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Technical Report

No. 12981

DEVELOPMENT OF LASER BEAM DELIVERY AND WELDING HEAD FOR THE INNER AND OUTER DIAMETER JOINTS OF THE AGT 1500 RECUPERATOR.

CONTRACT NO. DAAE07-84-C-R080

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AVCO LYCOMING TEXTRON
STRATFORD, CT 06497

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U.S. ARMY TANK-AUTOMOTIVE COMMAND
RESEARCH, DEVELOPMENT & ENGINEERING CENTER
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Attention: AMSTA-RCKM/Mr. Dave Pyrce

Subject: Final Technical Report
Contract DAAE07-84-C-R080
Laser Beam Weld Program

Reference: CDRL Item Number 004

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			Laser Welding	Outside Diameter (OD) Joint

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

The purpose of this TACOM project was to develop and demonstrate a production suitable laser welding head, which could successfully join the plate edges of the inner and outer joints of the AGT 1500 recuperator. This project investigated the laser welding process as a cost effective alternative for the resistance seam welding process currently used in production. The successful implementation of laser hole welder and the production inside diameter/outside diameter resistance welding machine provided background and insight necessary to develop a prototype laser welding head.

The project was conducted according to the project plan, which was based on technical tasks and corresponding acceptance criteria. These tasks followed a logical progression toward the development of the prototype welding head. The management philosophy stated that each tasks's acceptance criteria must be met before the next task could be undertaken. If the criteria could not be met, the project must either find an answer by some other approach or

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be discontinued.

Work in this TACOM project was divided into two competitive projects, Subproject A and Subproject B. Subproject A was based on a two-pass welding technique developed in a previous project. The first pass was a circularly deflected beam and the second pass was a higher power nondeflected beam. The welding head was designed to employ this technique on production recuperator plates. Subproject B focused on finding an alternative welding technique and qualifying it to the standards outlined in the feasibility study. If a successful approach was found, a second prototype welding head would be developed around this technique.

In Subproject B, a vendor market survey was completed and two vendors were selected to conduct feasibility studies. The first approach used a "donut" mode laser beam and the second approach used an oscillating laser beam. After extensive experimentation, an acceptable weld could not be produced in a production suitable manner.

In Subproject A, six major design iterations of the welding head were done. Four designs used the original edge welding technique and an arrangement of guide or grip wheels. Acceptable edges welds could not be produced due to joint separation, edge mismatch, and uncontrollable problems with the alignment between the plate edge and the laser beam spot. The other two designs used a lap welding technique and a sliding caliper tool. The sliding caliper tool showed more potential. However, acceptable welds could not be produced at a production suitable welding speed. The 45-degree laser beam impingement angle, which was necessary to produce the lap weld on the land of the joint, caused problems in parameter optimization. The reflected component of the beam was too great and reduced the power density at the joint surface causing insufficient or inconsistent coupling. At this time, the state of the art lasers cannot overcome this problem to weld the inner and outer diameter joint in a production suitable manner.

TABLE OF CONTENTS

Section		Page
1.0.	INTRODUCTION	9
1.1.	Description of Recuperator	9
1.2.	Purpose of the Project	9
1.3.	Purpose of this Phase	12
2.0.	PROJECT OBJECTIVES	12
3.0.	CONCLUSIONS	14
3.1.	Subproject B	14
3.1.1.	Laser Edge Weld - "Donut" Mode Beam	14
3.1.2.	Laser Edge Weld - Oscillating Beam	14
3.2.	Subproject A	14
3.2.1.	Laser Edge Weld	14
3.2.2.	Laser Lap Weld	15
4.0.	RECOMMENDATIONS	15
5.0.	DISCUSSION	15
5.1.	Current Manufacturing Technology	15
5.1.1.	Laser Hole Welding Machine	18
5.1.2.	Resistance I.D./O.D. Welding	18
5.1.3.	Quality Standards and Inspection	18
5.1.3.1.	Laser Welds	23
5.1.3.2.	Resistance Seam Welds	23
5.1.3.3.	Pressure Test	
5.2.	Project Management	23
5.2.1.	Philosophy of Project Plan Organization	27
5.2.1.1.	Organization of General Tasks	27
5.2.1.2.	Organization of Specific Tasks	29
5.3.	Phase 0 - IRAD Feasibility Study	29
5.3.1.	Objective of Feasibility Study	31
5.3.2.	Technical Approach	31
5.3.3.	Results and Discussion	32
5.3.4.	Conclusions	36
5.4.	TACOM Project Plan	36
5.5.	Background on Laser Technology	42
5.5.1.	Mode of the Laser Beam	42
5.5.2.	Power Density	43
5.5.3.	Operation Modes	44
5.5.4.	Other Items	47

TABLE OF CONTENTS (Continued)

Section		Page
5.6.	Subproject B	47
5.6.1.	Vendor Surveys	47
5.6.2.	Koppers Laser System	47
5.6.2.1.	Equipment	50
5.6.2.2.	Experimental Procedure	50
5.6.2.3.	Results and Discussion	50
5.6.2.4.	Conclusions and Summary	51
5.6.3.	Photon Sources, Inc.	51
5.6.3.1.	Equipment	51
5.6.3.2.	Experimental Procedure	51
5.6.3.3.	Results and Discussion	54
5.6.3.4.	Conclusion and Summary	54
5.7.	Subproject A	54
5.7.1.	Discussion of I.D./O.D. Welding Machine Design Concepts	55
5.7.1.1.	Concept A	55
5.7.1.2.	Concept B	55
5.7.1.3.	Concept C	55
5.7.1.4.	Evaluation	59
5.7.2.	Experimental Procedure	59
5.7.3.	Experimental Results	65
5.7.3.1.	Welding Head Design "A"	66
5.7.3.2.	Welding Head Design "B"	72
5.7.3.3.	Welding Head Design "C"	76
5.7.3.4.	Welding Head Design "D"	76
5.7.3.5.	Re-evaluation of Edge Welding Technique	82
5.7.3.6.	Welding Head Design "E"	85
5.7.3.7.	Welding Head Design "F"	87
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LIST OF ILLUSTRATIONS

Figure	Title	Page
1-1.	AGT 1500 Engine Schematic	9
1-2.	AGT 1500 Recuperator - Gas and Air Flow Diagram	10
1-3.	AGT 1500 Turbine Engine - Completed Recuperator Assembly	11
1-4.	AGT 1500 Recuperator - Cross Sectional Diagram	13
5-1.	AGT 1500 Recuperator - Welded Plate Pair	16
5-2.	Laser Hole Welding Machine	17
5-3.	I.D./O.D. Resistance Welding Machine	19
5-4.	I.D. Resistance Welding Position	20
5-5.	O.D. Resistance Welding Position	21
5-6.	Laser Weld - Top and Under Bead	22
5-7.	Resistance Seam Weld - Cross Section	24
5-8.	Schematic of Recuperator Pressure Test Rig	25
5-9.	Project Management Flow Chart	26
5-10.	Internal Pressure Fatigue Test Specimen	28
5-11.	Established S-N Curve for Pillow Specimen Tests	30
5-12.	Pillow Specimen - Sawtooth Edge Weld	33
5-13.	Pillow Specimen - Smooth Edge Weld	33
5-14.	Results of Straight, Vertical Single Pass Weld	34
5-15.	Result of Two Pass, Vertical Edge Weld	35
5-16.	Results of Two Pass, Horizontal Edge Weld	37
5-17.	Detailed TACOM Project Plan	38 - 42
5-18.	Gaussian Mode Laser Beam	44
5-19.	"Donut" Mode Laser Beam	45
5-20.	Operation Modes of the Laser	46
5-21.	Diagram of Laser Beam Splitting	48
5-22.	Acceptable Edge Weld - Transverse Section	52
5-23.	Unacceptable Edge Weld - Irregular Sawtooth Contour	53
5-24.	Welding Head Concept "A"	56
5-25.	Welding Head Concept "B"	57
5-26.	Welding Head Concept "C"	58
5-27.	Laboratory Workstation	60
5-28.	Schematic of Laser Beam Path	62
5-29.	Part Fixturing on Workstation	63
5-30.	Diagram of Alignment Stage	64
5-31.	Welding Head Design "A"	67
5-32.	Schematic of Guide Wheel	68
5-33.	Schematic of Grip Wheel	68
5-34.	New Fixture for Plate Pairs	70

LIST OF ILLUSTRATIONS (Continued)

Figure	Title	Page
5-35.	Welding Head Design "B"	73
5-36.	Schematic of Guide Slide	74
5-37.	Welding Head Design "C"	77
5-38.	Counterbalancing Weight System	78
5-39.	Welding Head Design "D"	79
5-40.	Schematic of Burr Crushing and Offset Wheels	80
5-41.	Pillow Specimen Tool and Prototype Tool	83
5-42.	Comparison of Pillow Specimen Tool and Prototype Tool	84
5-43.	Welding Head Design "E"	85
5-44.	Cross Section of Lap Weld	88
5-45.	Welding Head Design "F"	89
5-46.	Inserts for Sliding Caliper Tool	90 & 91

LIST OF TABLES

Table	Title	Page
5-1.	List of Vendors Surveyed	49
5-2.	Test Parameters - 3.75 in. Focal Length Lens (75 ipm) . .	94
5-3.	Test Parameters - 3.75 in. Focal Length Lens (60 ipm) . .	95
5-4.	Test Parameters - 5.0 in. Focal Length Lens	96
5-5.	Test Parameters - 2.5 in. Focal Length Lens	98

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1.0. INTRODUCTION

1.1. Description of Recuperator

Avco Lycoming's AGT 1500 turbine engine (Figure 1-1) uses a multiwave plate recuperator. The exhaust from the power turbine enters the center of the annular recuperator where it diffuses and turns radially to flow through the recuperator (Figure 1-2). Compressor air enters the front of the recuperator into the air inlet conduits or triangular holes, passes between the plates and leaves the front of the recuperator through the air exit conduits or elliptical holes. This raises the inlet air temperature into the combustor for more efficient engine performance.

The AGT 1500 recuperator is sized to meet the performance goals of the engine over the entire operating range. The core is 22 inches long with an inside diameter, (I.D.), of 15 inches and an outside diameter, (O.D.), of 27 inches. The plates are formed from 0.008-inch thick Inconel 625 material and embossed with 0.040 inch convolution to provide flow passages of suitable hydraulic diameter to achieve the desired thermal effectiveness, pressure drops, and convolutions stress levels.

The plates are assembled in pairs by first welding the joints around the air inlet and outlet holes. These two plates enclose the gas passages and have high pressure air bearing on the outside of them. Approximately 280 pairs of plates are then assembled and welded around the outer and inner diameters of the annulus to make a core. This welding operation encloses the air passages and serves to seal the air from the gas. Fabrication is completed by assembling and welding the core to the header and pressure testing the complete assembly (Figure 1-3).

1.2. Purpose of the Project

The purpose of this project is the production implementation of a laser I.D./O.D. welder of recuperator cores to provide improved joint integrity at reduced costs.

The inner and outer diameter joints present a complex welding problem because the weld integrity requirement, the limited accessibility of the joint, and the configuration of the recuperator place severe constraints on the welding system design. The welding technique and tooling are very different from existing laser welding systems and the current resistance welding system. The experience from these systems provides insight into the weld characteristics, tool design, and requirements for production suitability.

The production suitable system requires an integration of a dependable edge welding technique and tool design. The weld has to meet rigid requirements and hermetically seal the joint over almost a mile of weld per core. The weld has to be defectfree and the size has to be

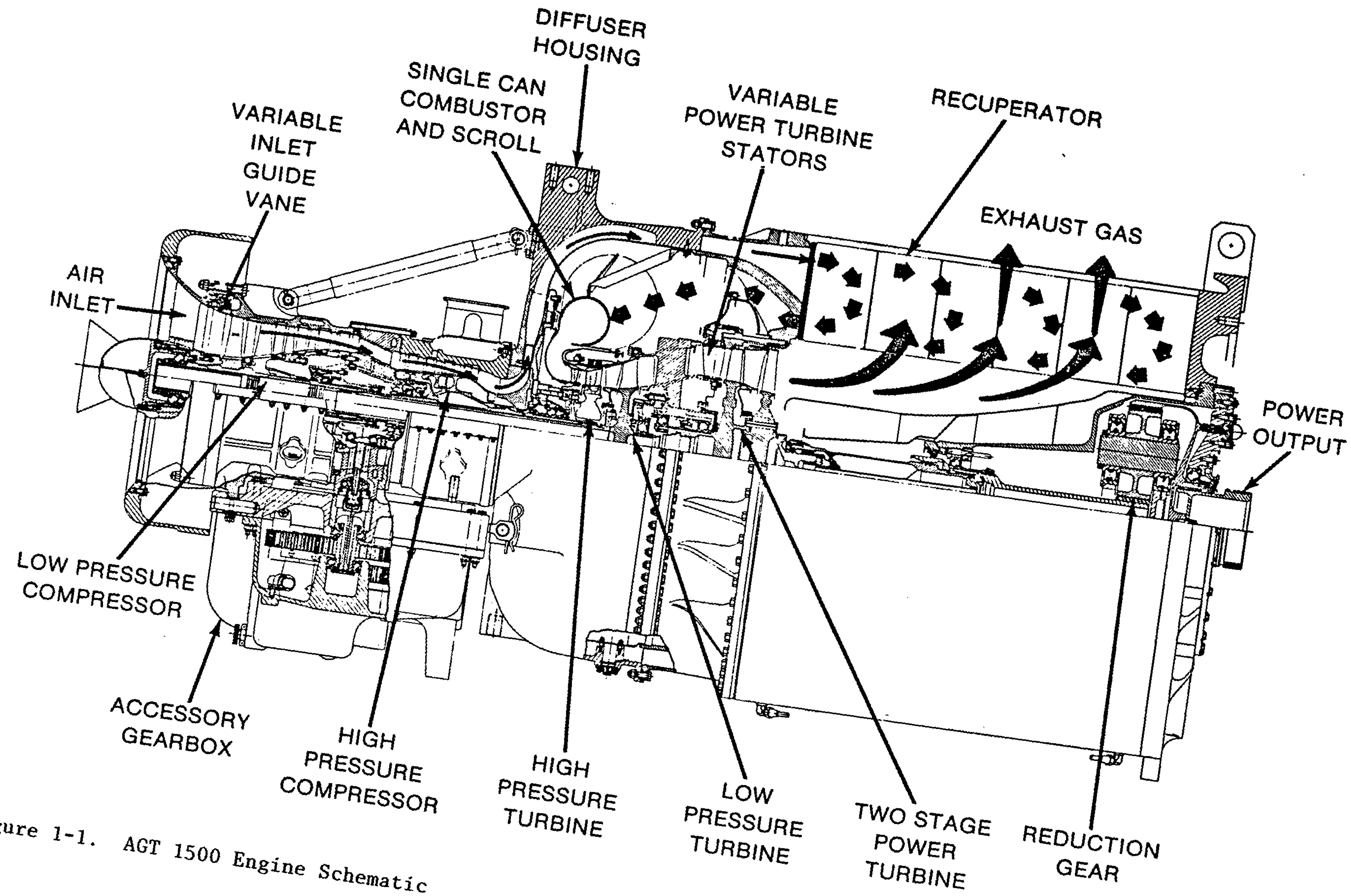


Figure 1-1. AGT 1500 Engine Schematic

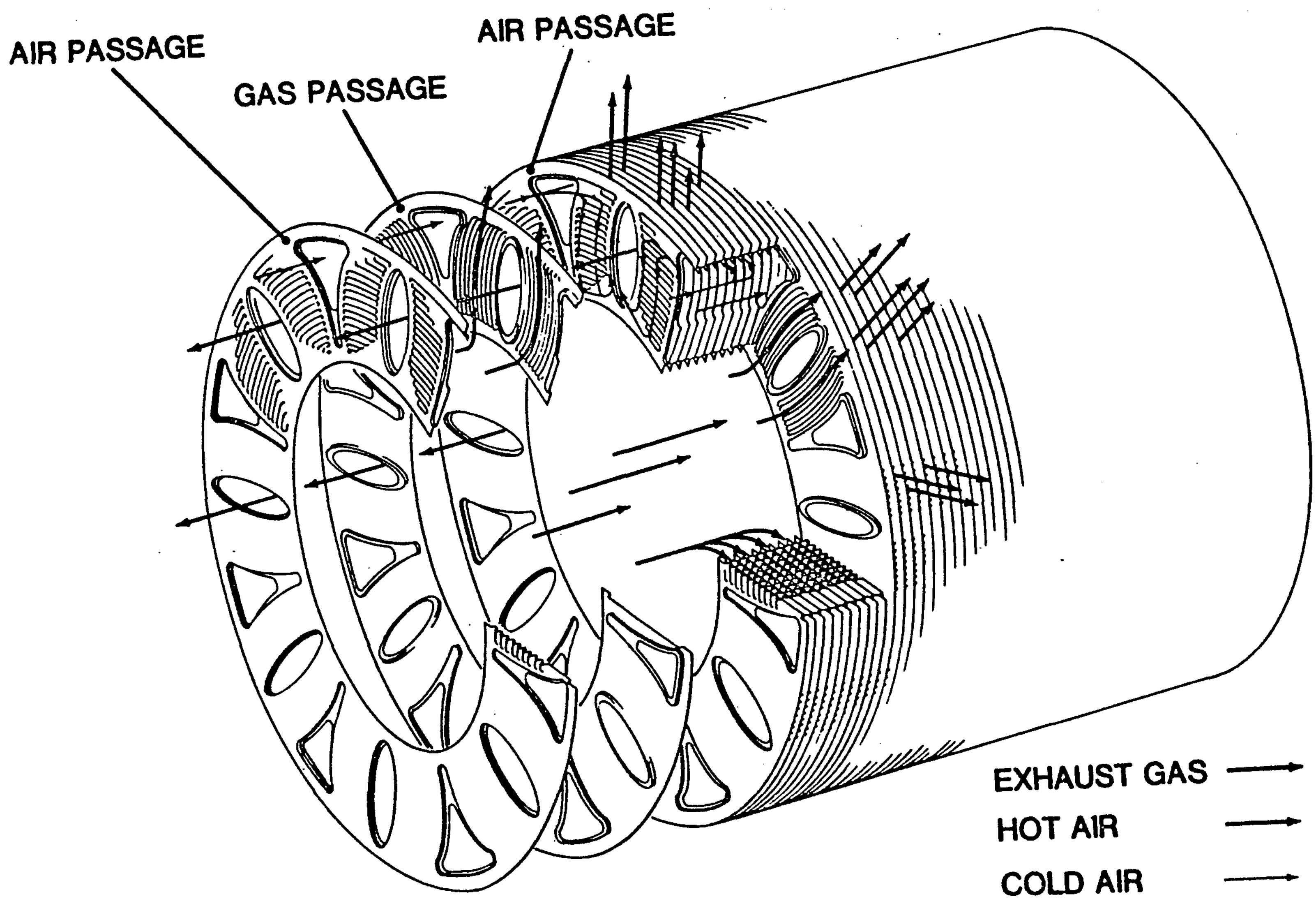


Figure 1-2. AGT 1500 Recuperator-Gas and Air Flow Diagram

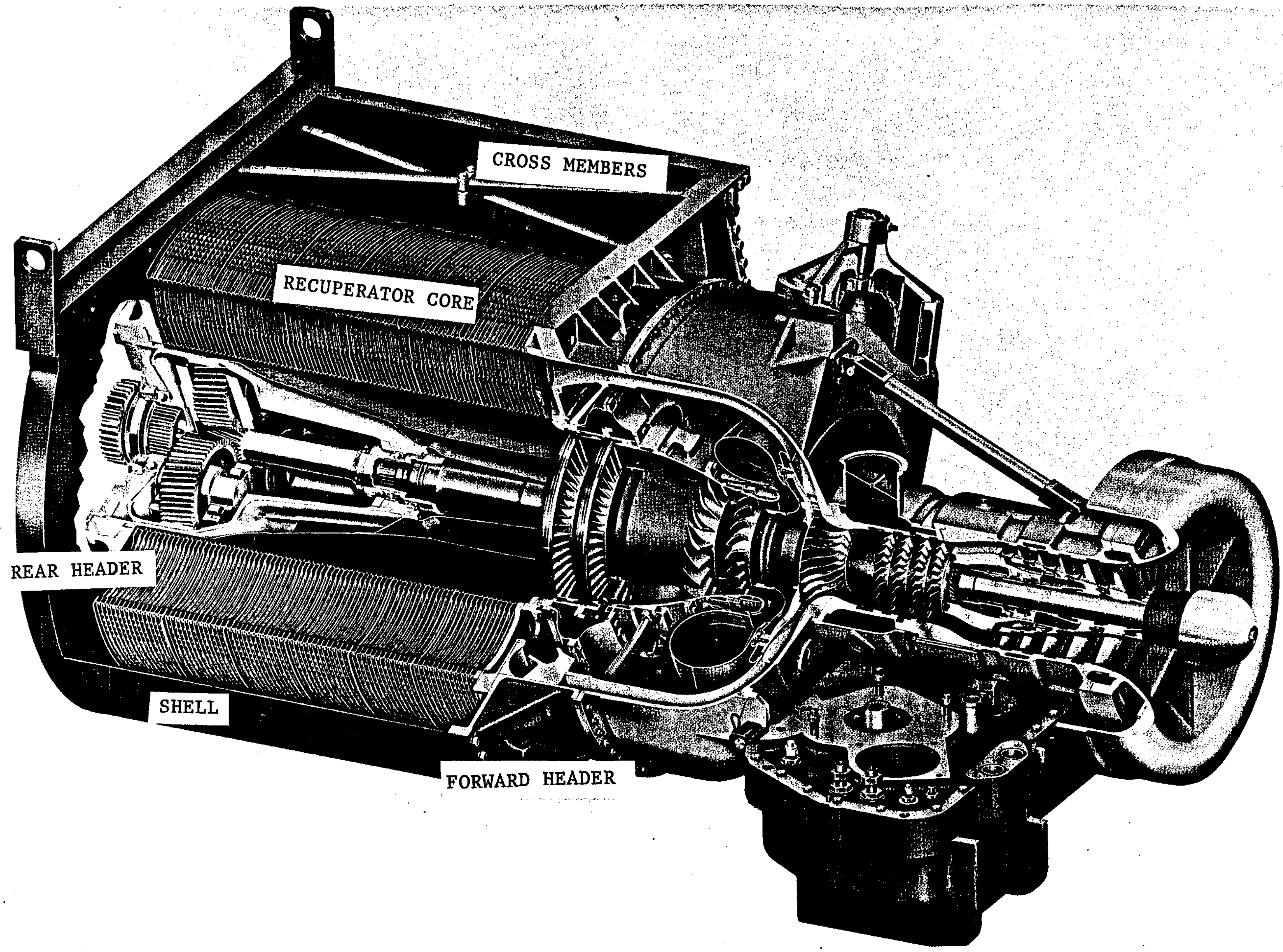


Figure 1-3. AGT 1500 Engine-Complete Recuperator Assembly

sufficiently large to meet the high temperature fatigue strength requirements.

The accessibility of the joint (Figure 1-4) is the limiting factor in the tool design. The welding head has to fit inside the 15-inch center annulus and deliver the beam to the 0.016-inch thick, two-ply joint. The tool has to hold the joint in perfect alignment with the beam and intimate sheet contact has to be maintained. This has to be accomplished by holding the 0.100-inch land of the joint together within the 0.080-inch space between adjacent joints.

1.3. Purpose of this Phase.

The purpose of this phase was to develop and demonstrate a production suitable welding head, which could successfully join the plate edges.

All options for the development of the welding technique and the head were investigated in this phase. Several designs were fabricated and tested on full-size production recuperator plate pairs. During the development project, the production suitability was continuously evaluated on the basis of the experimental results. For example, the welding speed has to be a minimum of 60 inches per minute to exceed the speed of resistance welding machines. Items such a system maintenance, tool wear, and system dependability were evaluated both quantitatively and qualitatively.

2.0. PROJECT OBJECTIVES

The overall project objective is the production implementation of a laser edge welder for recuperator cores to provide improved joint integrity at reduced costs.

- Phase 1 - Feasibility Study

  The objective is to develop and demonstrate a technique which successfully joins the plate edges, with welds having high temperature fatigue strength at least equivalent to resistance seam welds.

- Phase 2 - Pilot Plant System

  The objective is to develop and demonstrate the welding head which consists of a laser beam(s) delivery system and required joint tooling, by repeating the above high temperature fatigue requirements and welding a pack of 25 plate pairs for pressure test and metallurgical evaluation.

- Phase 3 - Prototype Production Machine

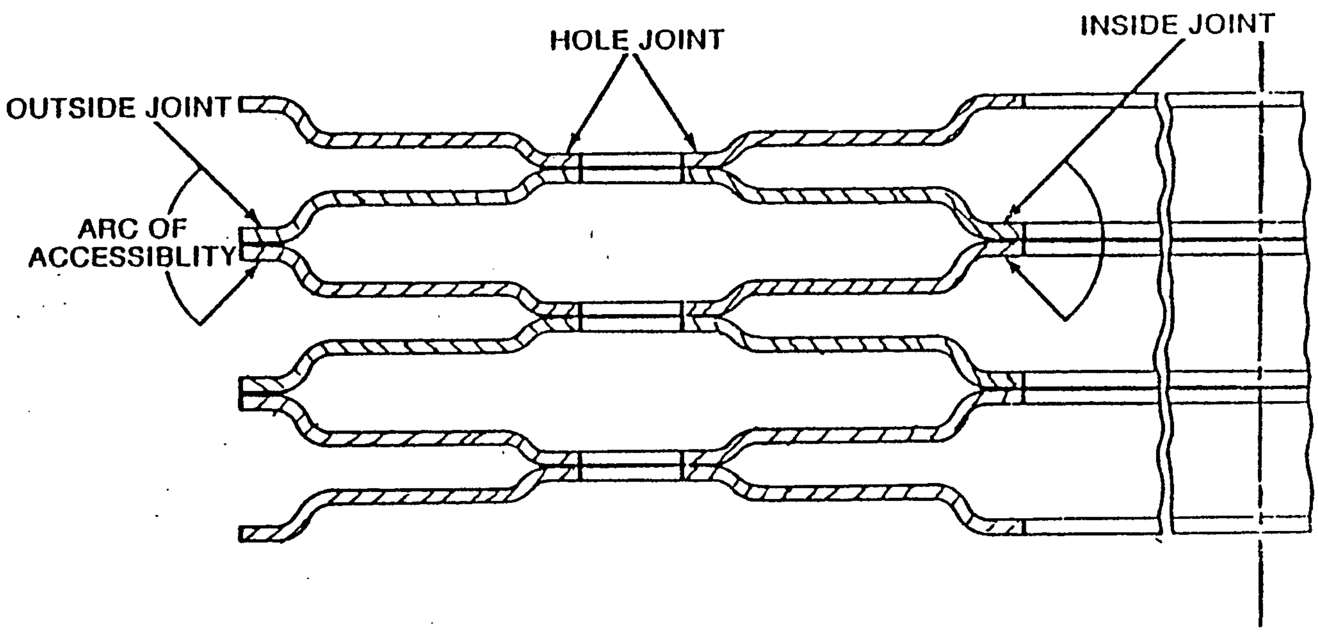


Figure 1-4. AGT 1500 Recuperator Cross-Sectional Diagram

The objective is to develop the production laser welding system for joining the AGT 1500 recuperator inner diameter and outer diameter joints and implement it into production.

NOTE: Each objective has specific tasks with tight technical requirements which must be met before proceeding to the next phase. If one of the task requirements is not met, for whatever reason, the program will be concluded at that point.

3.0. CONCLUSIONS

3.1. Subproject B.

3.1.1. Laser Edge Weld - "Donut" Mode Beam. Specimen joints simulating the recuperator plate outer diameter joints cannot be consistently joined with welds meeting the stated minimum size, quality, and surface contour requirements using the one-pass technique with any combinations of welding parameters evaluated. Therefore, this one-pass technique using the donut mode laser beam could not be developed for use in welding the recuperator plate inner and outer diameter joints.

3.1.2. Laser Edge Weld - Oscillating Beam. The specimen joints cannot be consistently laser edge welded meeting the specified weld size and surface requirements using the one-pass technique with any of the combinations of welding parameters evaluated. Based on the results of this feasibility study and those of the feasibility study conducted at Koppers Laser Systems, this one-pass technique using an oscillating gaussian mode laser beam could not be developed for use in welding the recuperator plate inner and outer diameter joints.

3.2. Subproject A.

The inner and outer diameter joints of the AGT 1500 recuperator in its current design configuration could not be welded using the present state-of-the-art industrial lasers.

3.2.1. Laser Edge Weld. Laser edge welding the full-size recuperator plates was more complex than laser edge welding the pillow specimens. The welding head tooling, which included different arrangements of grip and guide wheels, could not adequately accommodate the edge mismatch, plate run out and the alignment between the laser beam and the plate edge. The experimental work confirmed that parameter variations and even the circularly deflected beam could not overcome the problems associated with producing miles of weld in the recuperator assembly.

3.2.2. Laser Lap Weld. The laser lap weld, which was produced using the sliding caliper welding head, could not be made in a production suitable manner. The 45-degree laser beam impingement angle, which was dictated by the recuperator's configuration, caused problems that could not be overcome using the current generator of lasers.

4.0. RECOMMENDATION

This laser welding project for the inner and outer diameter joints of the AGT 1500 recuperator should not be pursued any further at this time. If and when a new industrial laser with suitable capabilities becomes available on the market, a new study should be initiated. This study should also include an evaluation of the design of the recuperator and the possible modifications, which could be made to improve its compatibility with the laser welding process.

5.0. DISCUSSION

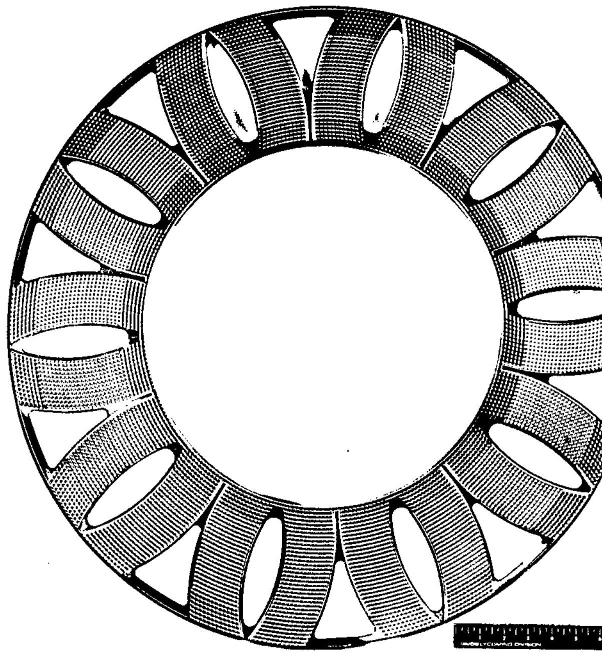
5.1. Current Manufacturing Technology for Recuperator Cores

In an earlier TACOM-funded project, the techniques and equipment for laser welding the air inlet and outlet hole joints of the recuperator were successfully developed and implemented into production. The laser welded recuperator plate pair is shown in Figure 5-1. That project resulted in significant reduction of recuperator manufacturing costs.

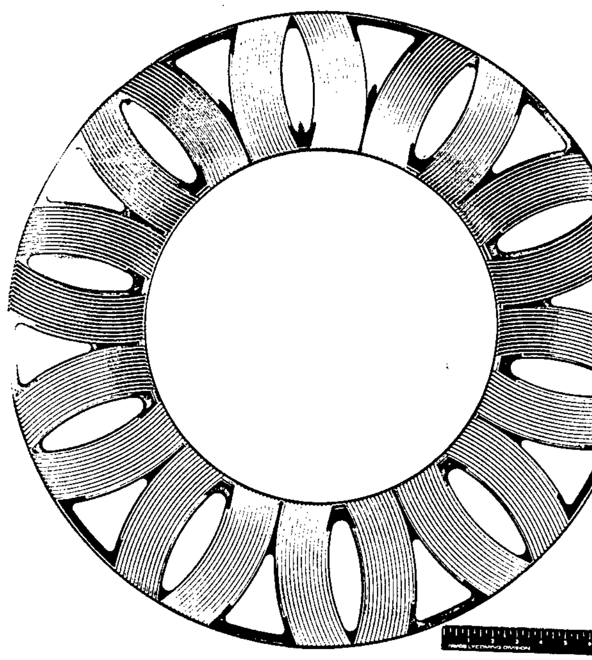
5.1.1. Laser Hole Welding Machine. The production recuperator welding machine, which resulted from that project and is shown in Figure 5-2, has two 525 watt pulsed CO_2 lasers each with a moving mirror system, a controller, and a work station. A single swing arm load/unload mechanism is shared between the two laser stations. The welders run out of phase so that while one laser is welding, the other is being unloaded and then loaded. This allows the load/unload mechanism to be time-shared but provides maximum redundancy in the more complex portions of the system.

Two lasers, each welding at 80 to 100 inches per minute, are needed in order to join the large volume of plate pairs required by the production schedule. Each laser has its own moving mirror and computer system as well as a complete tooling package. When the system was being designed, it was suggested that each laser weld five hole pairs in each plate, thus saving one indexing table. This would provide no true system redundancy. The lasers would be so close together that it would be impossible to repair most parts of one while the other was running. The use of separate indexing and tooling packages provides a system which can run at 50 percent throughput while being serviced. The machine has seven axes of motion; X & Y on each moving mirror system, a rotary stage for indexing in each welding station, and the robot rotary stage. All use the same motors, encoders and tachometers. All are connected by identical plug connectors. This concept of system and spare parts simplification and redundancy is basic to developing a machine, which can function successfully in a production environment, while operated and serviced by production personnel. This is an important factor in production suitability.

The laser hole welding system is capable of welding the hole joints of one recuperator for over $500 less than the currently used resistance



a) View of "A" Plate



b) View of "B" Plate

Figure 5-1. AGT 1500 Recuperator-Welded Plate Pair

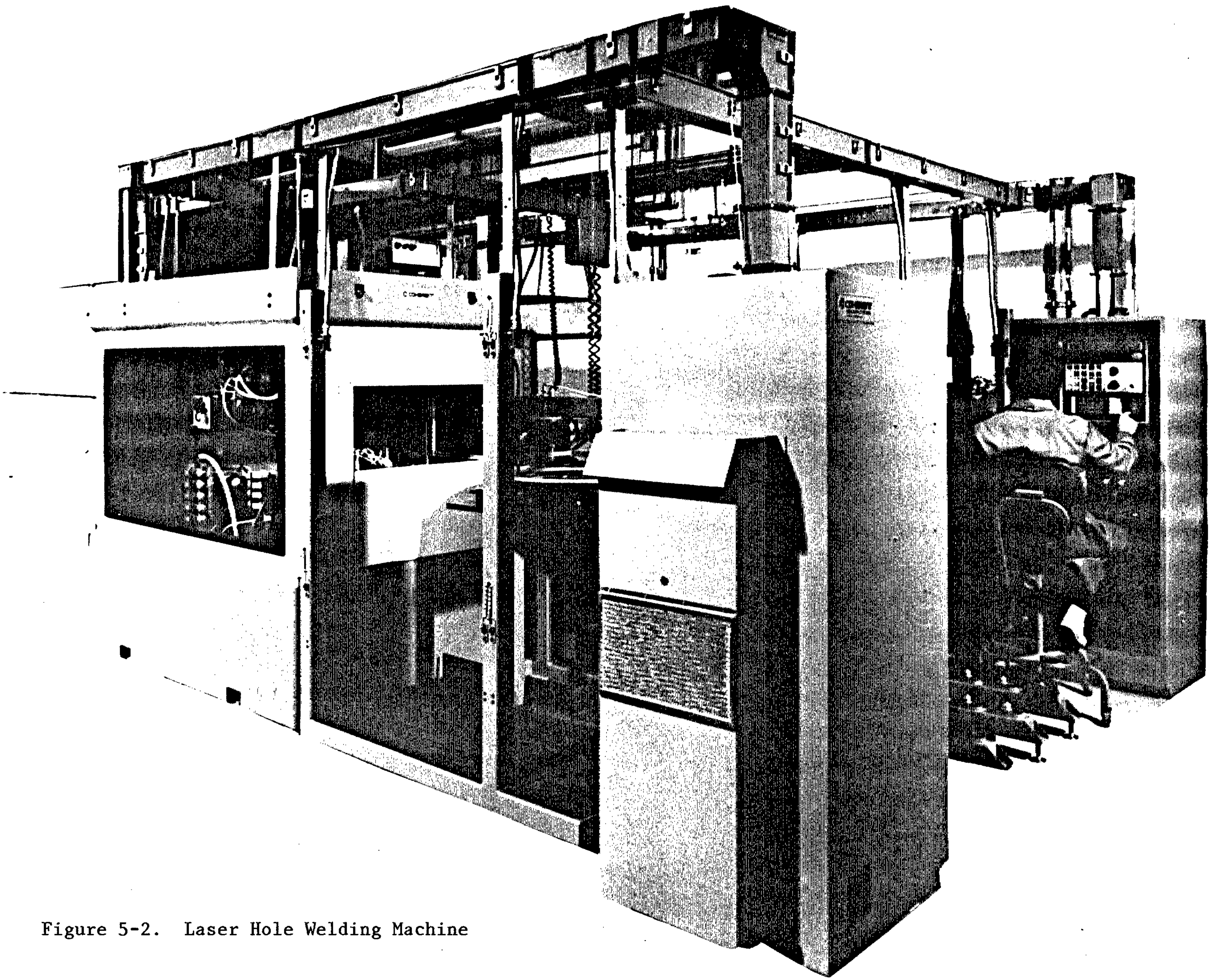


Figure 5-2. Laser Hole Welding Machine

welding facility of equal capacity. Results of field testing and inspection of in-service parts also indicates the life may be improved considerably.

5.1.2. Resistance I.D./O.D. Welding Machine. Resistance seam welding is currently used to hermetically seal the inner and outer diameter joints. The machine in operation on the production floor is high volume, high speed, metallic foil joining systems. This machine is shown in Figure 5-3. The resistance seam welding process is compatible with requirements such as precision alignment and limited accessibility of the inner and outer diameter joints. The nature of this process limits the travel speed to about 50 inches per minute. The resistance welding machine tracks the joint during welding by moving the recuperator core up and down, while holding the welding head vertically stationary. Because of the weight of the core, this presents inherent problems in joint tracking.

This machine has a single welding head, which is used to make both the inner and outer welds. To reduce the repositioning time, all of the joints on the inner periphery, as shown in Figure 5-4, or all of the joints on the outer periphery, as shown in Figure 5-5, are welded at once. This complicates rework of defective inner welds because the core must be cut apart to gain access to them. The inner diameter welds are made blindly because no real time viewing system is designed into the resistance welding head. This increases the frequency of weld rework. The resistance welding process requires that external cooling water be used on the electrode wheels to increase their life. This complicates equipment design, operation, and maintenance.

The resistance welding process is dependent on the electrode wheels, which both position the parts for welding and conduct the electrical current to make the weld. The high conductivity required is only possible with copper alloys having relatively poor abrasion resistance. Thus, the constantly changing wheel condition is a difficult to control variable of the process.

5.1.3. Quality Standards and Inspection. The fabrication of the recuperator core involves preparing and joining the details and pressure testing the completed assembly. In-process inspection of the joining processes is done as part of the overall manufacturing process. An inspection of the elliptical and triangular welds and of the inner and outer diameter welds is done prior to pressure testing.

5.1.3.1. Laser Welds. The elliptical and triangular hole laser weld is a full penetration lap weld. This weld, shown in Figure 5-6, is visually inspected by looking at the weld's top and under bead. This inspection detects any defects before the plate pairs advance to the next assembly level. Because this welding process has consistently met the quality standards over a period of time, a quality control sample plan was instituted into the production sequence.

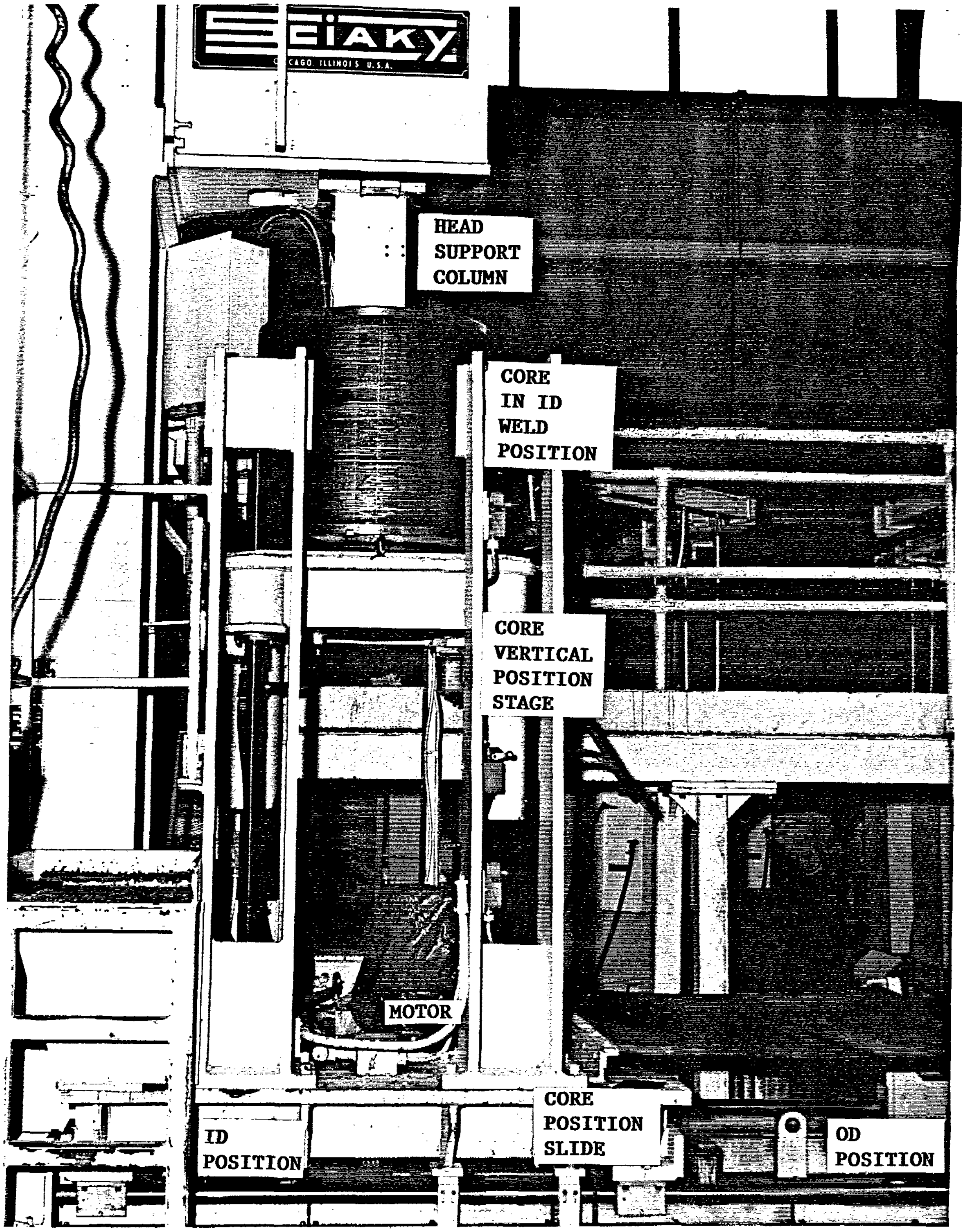


Figure 5-3. I.D./O.D. Resistance Welding Machine

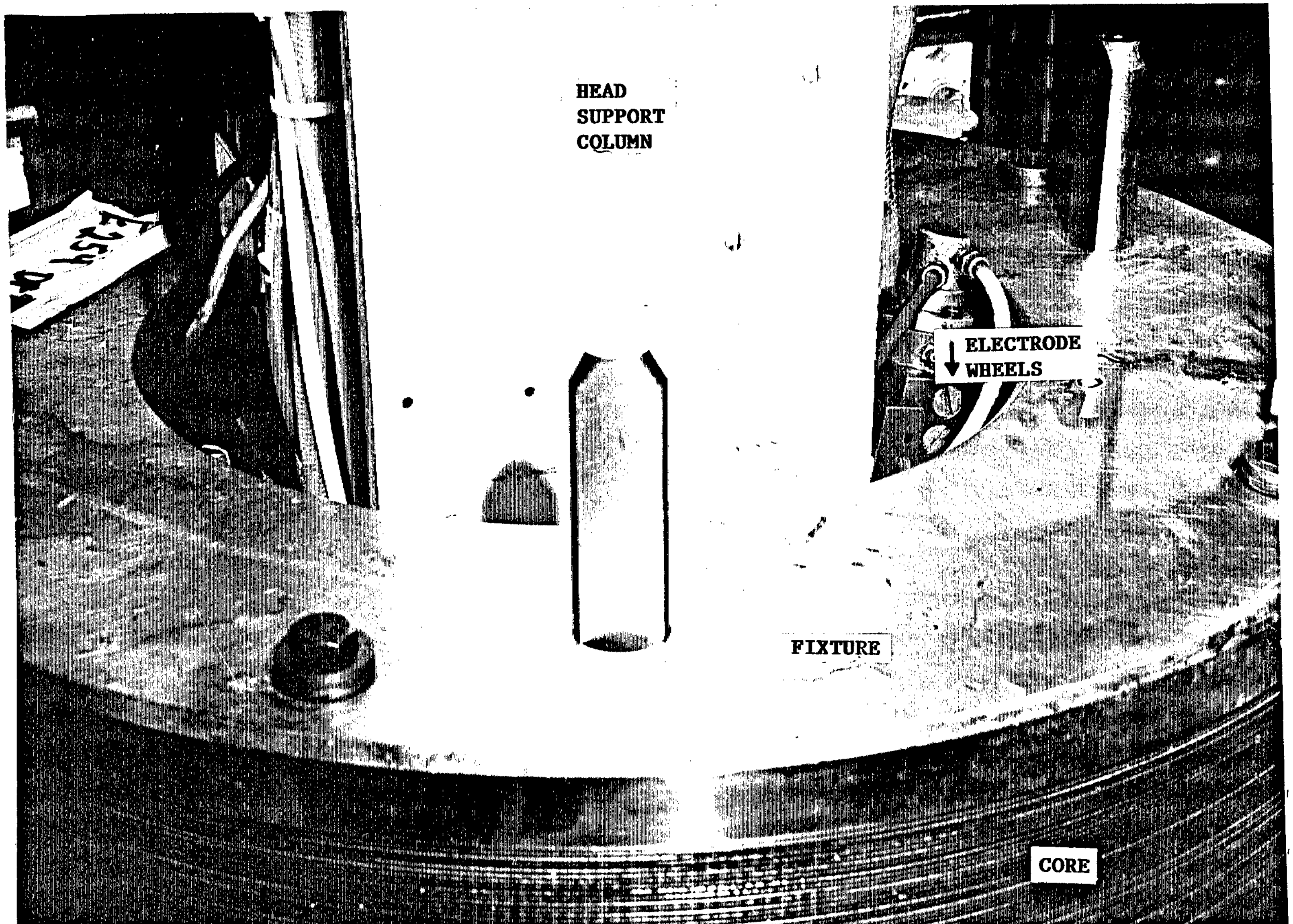


Figure 5-4. I.D. Resistance Welding Position

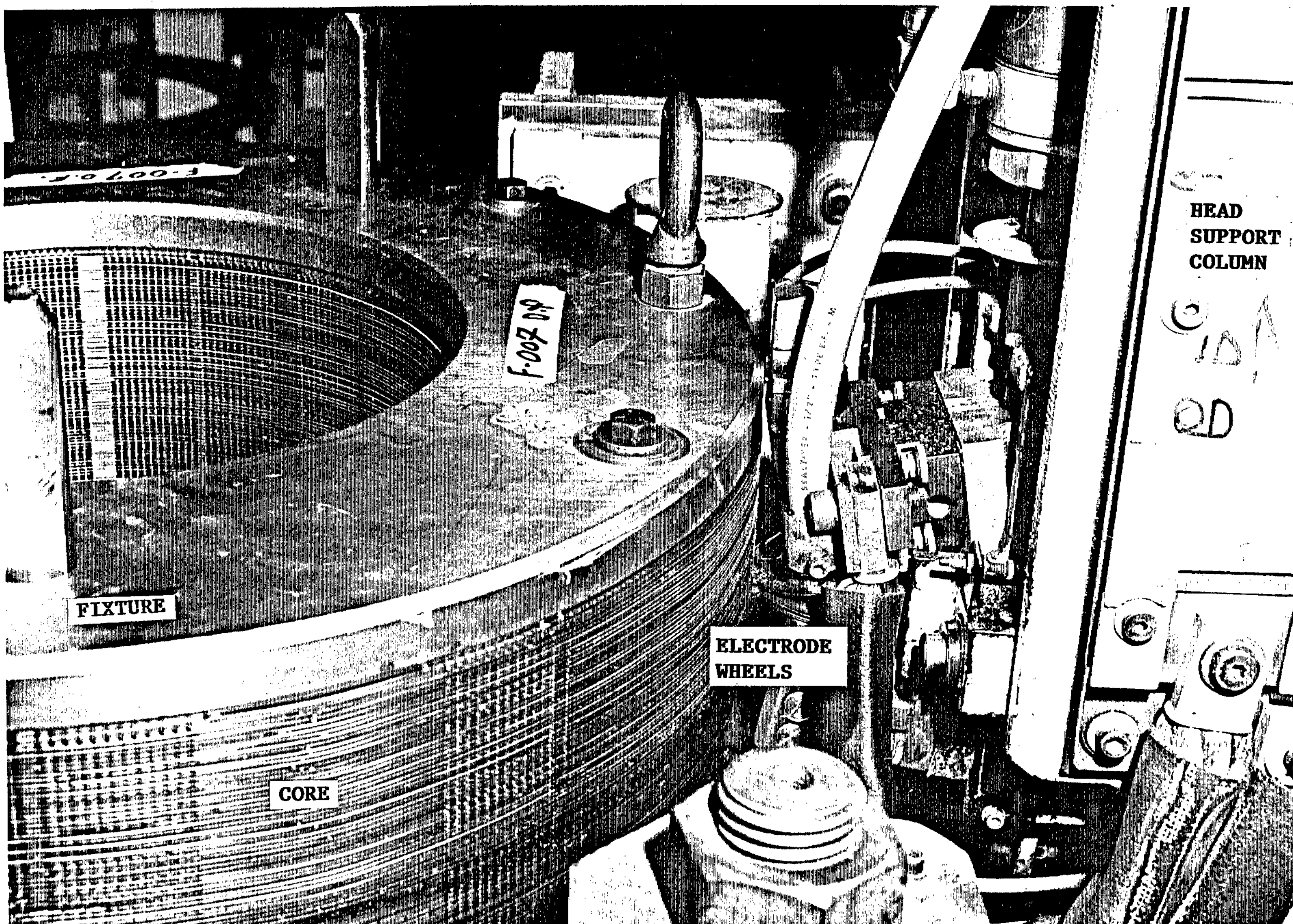
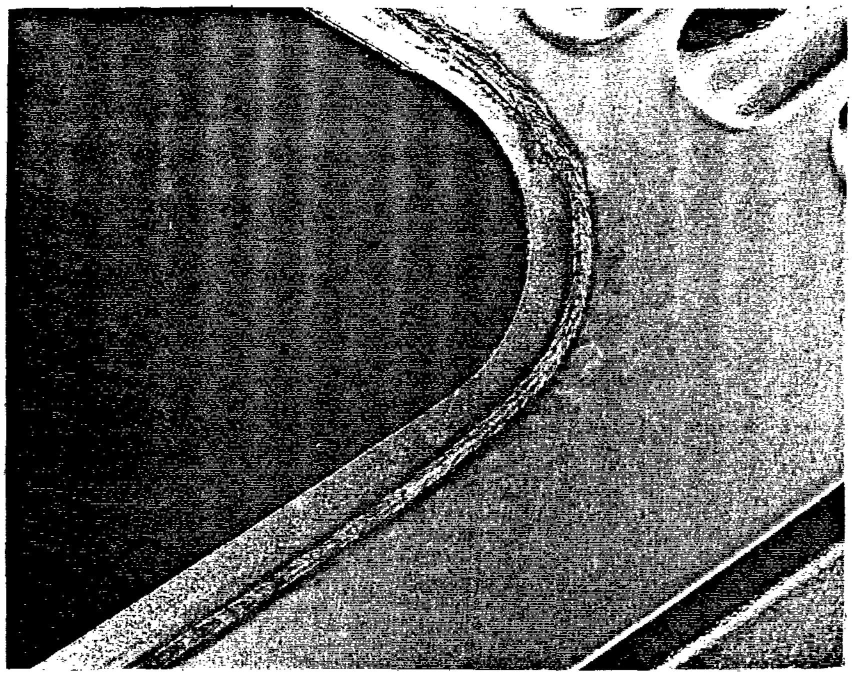
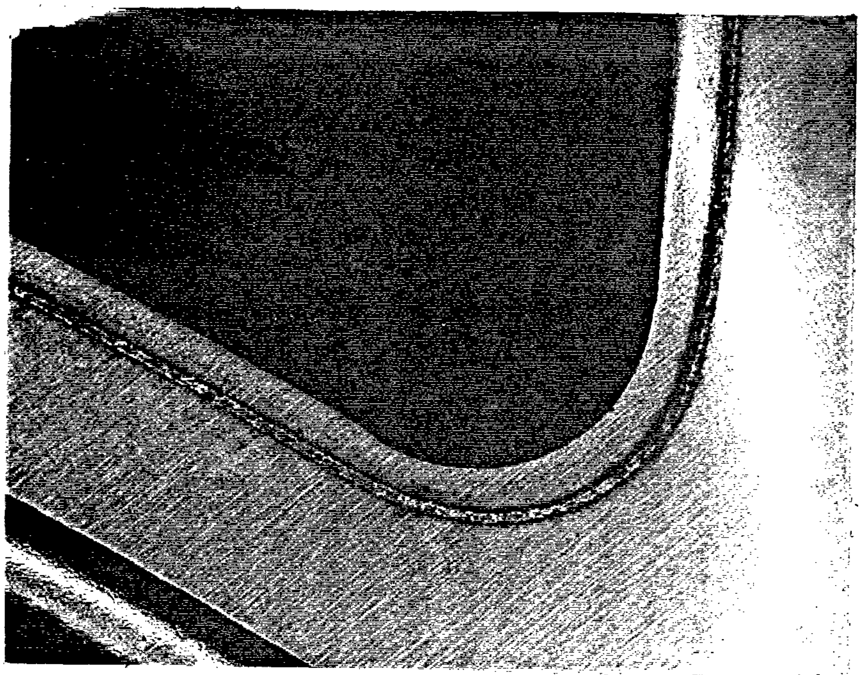


Figure 5-5. O.D. Resistance Welding Position



a) Top Bead



b) Under Bead

Figure 5-6. Laser Weld Top and Under Bead

5.1.3.2. Resistance Seam Welds. The inner and outer diameter weld is a resistance seam weld. The resistance weld, which is shown in Figure 5-7, is totally enclosed in the two-ply joint and is not readily nondestructively inspected. In the resistance welding process, the electrode wheels tend to wear due to the low abrasion resistance of the copper alloy. This leads to degradation in the weld's size and strength. The inspection, which periodically monitors the process, is done using representative test coupons and full size recuperator plates. The test coupons, which are the same material and thickness as the recuperator plates, are made and evaluated every two hours. These coupons are destructively tested for weld size and strength. The results from the test coupons are recorded and kept on file for future reference. Upon the completion of each half pack (135 to 140 plate pairs), an extra inner and outer diameter joint is welded specifically for destructive testing. The joint is cut in several locations and the weld's size is verified for conformance to specification requirements. This extra joint represents the worst case condition. Therefore, if it is acceptable, all the joints welded prior to this time are also acceptable. These results are also recorded and filed for future reference. The careful monitoring of the weld quality and timely maintenance of the electrode wheels and machines are essential to the quality control and inspection procedure for the inner and outer diameter joints.

5.1.3.3. Pressure Test. The final inspection for the recuperator core is pressure testing. The core is placed in a specially designed rig (Figure 5-8), which tests the core at three different pressure levels, i.e., 20 psig, 100 psig, and 250 psig. The pressure test checks for leakage by measuring and recording the pressure drop across an orifice gage. If the core does not meet the requirements, the defective joints are marked for rework. The rework procedure is relatively complicated and time consuming. Once the rework is completed, the core is pressure tested again. A core, which meets the specification requirements, is forwarded to the next assembly level, i.e., installation in the recuperator can.

5.2. Project Management.

The project management approach (Figure 5-9) used in this project is one which has proved successful in previous projects to develop complex, advanced technology welding systems. It is based upon defining tasks and the minimum criteria for their successful completion so that objectives are concisely and rigidly defined, but the greatest possible flexibility in the technical means of meeting those objectives if permitted. Tasks are scheduled in a sequence which assures that each project decision is based on experimental evidence acquired in tasks which are completed before that decision must be made. For example, no production system will be designed and built until a pilot plant demonstrating its essential concepts, has been built and successfully tested by welding recuperator plate test packs. No pilot plant is built until a feasibility study showing that the proposed laser and welding

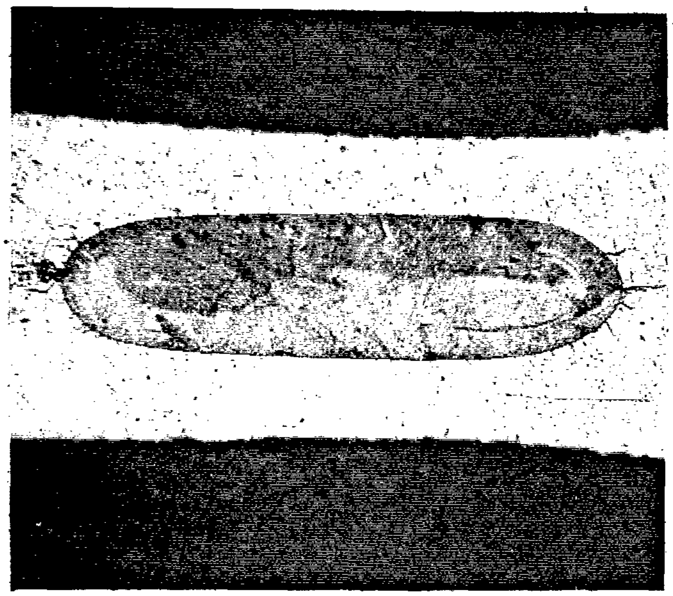


Figure 5-7. Resistance Seam Weld Cross Section

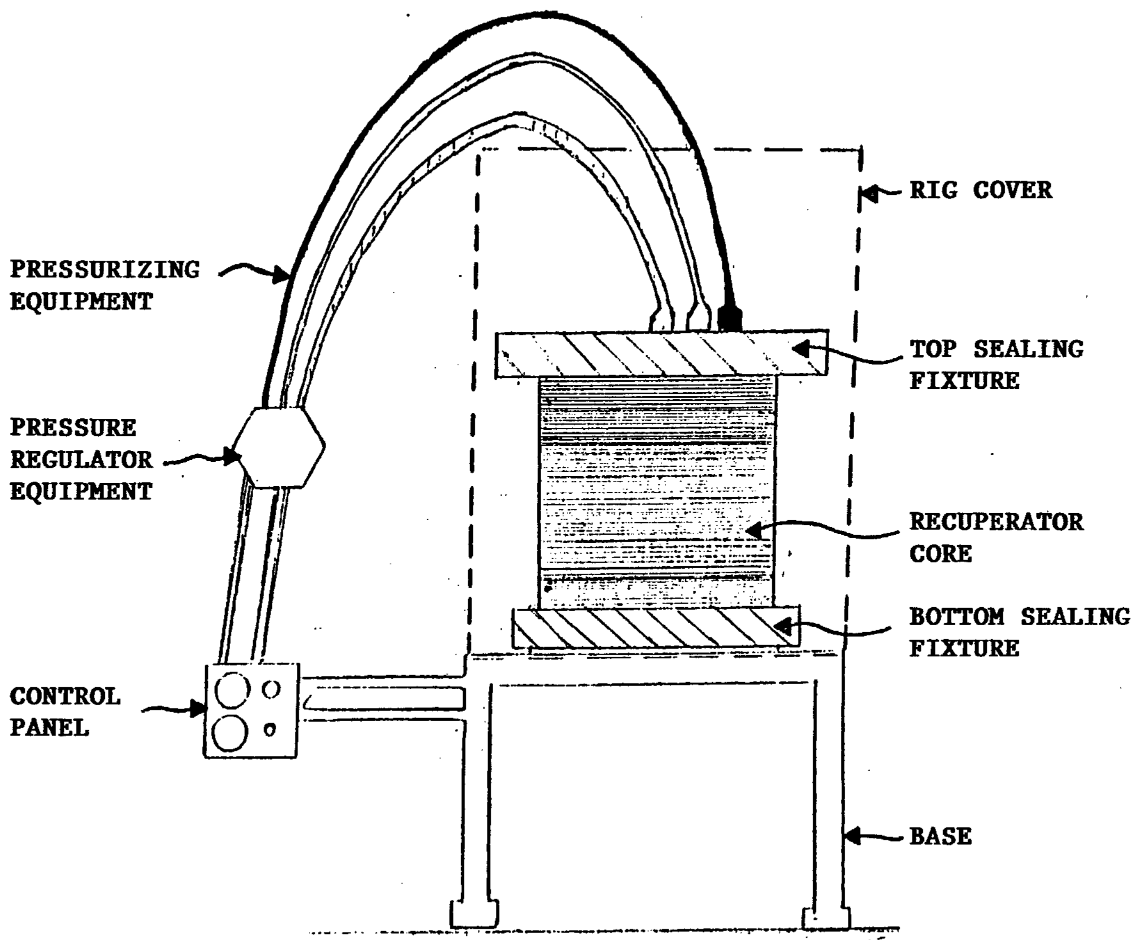


Figure 5-8. Schematic of Recuperator Pressure Test Rig

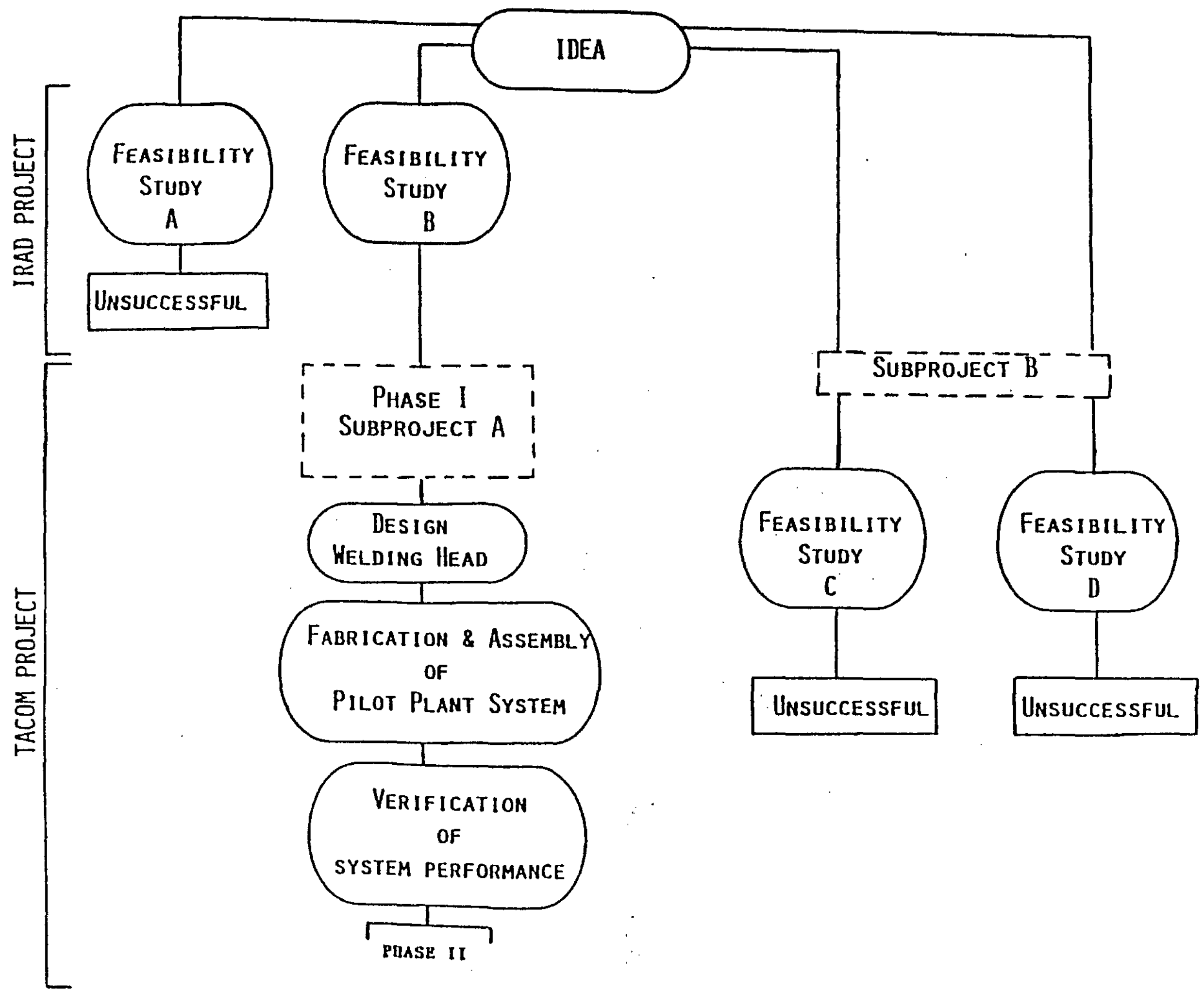


Figure 5-9. Project Management Flow Chart

head design concept can consistently produce welds meeting stated minimum quality and low cycle, high temperature fatigue properties.

5.2.1. Philosophy of Project Plan Organization.

5.2.1.1. Organization of General Tasks. This project is divided into three major phases: (1) the feasibility study, (2) the development of a prototype system and (3) the development and implementation of the production system. Each phase leads logically to the overall project goal, which is a system working on the production floor, manufacturing parts to the production schedule.

The feasibility study is a simple experiment, which validates the basic concept or welding technique. This project uses internal pressure fatigue test or pillow specimens (Figure 5-10) to demonstrate the basic welding technique. A simple fixture was designed to hold the edges of the specimen details in intimate sheet contact. These edges, which must be in the horizontal plane, are rotated in front of a stationary laser beam. The resulting edge weld is evaluated for metallurgical quality and high temperature fatigue strength.

Once an acceptable technique is demonstrated in the feasibility study, it is used as the basis for the development of the prototype welding head. In this phase, the welding head is designed, built and tested. A nonproduction suitable model, which clearly shows the concepts of a welding head, is built at minimal cost and equipment investment. Development of the head may require extensive iterative modification, therefore, the model must be easy to modify. It should be built with inexpensive components adequate for its short duty cycle (for example, the use of sleeve bearings instead of ball and roller bearings). Other processing functions such as plate positioning and joint incrementing should be done manually, concentrating the design effort on the head itself. Evaluation of the welding head design will be done by welding pillow specimens for fatigue testing and A-B plate pairs.

Once the head design concept is established, a pilot plant system is built and tested. The first production suitable welding head is built using the concepts developed in the prototype model. Since it is required to produce miles of good quality welds, components of the head are optimized to withstand the demands of a high duty cycle. The head design will be evaluated by welding pillow specimens for fatigue testing and A-B recuperator plates (25 plate-pair stack) for pressure and engine tests. In the next phase of the project, this welding head will be incorporated into the production system to manufacture AGT 1500 recuperator assemblies.

The objectives for each phase are rigid and cannot be altered in any way during the project. These include production of welds to stated quality standards. However, the path that is taken to meet these objectives may be changed as often as necessary. The welds must have acceptable size

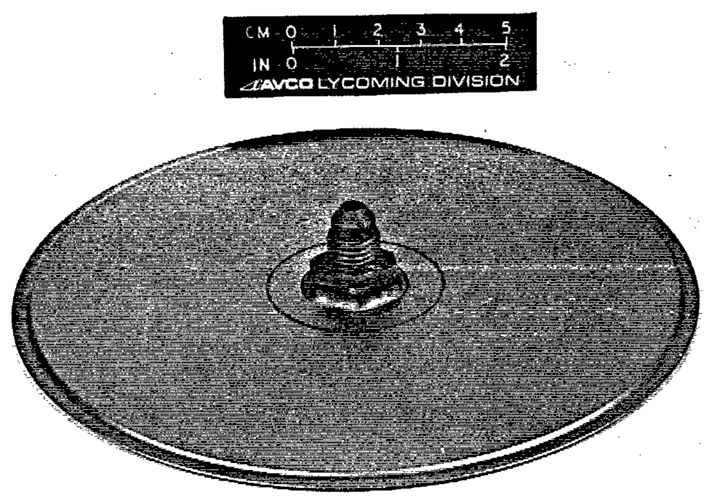


Figure 5-10. Internal Pressure Fatigue Test Specimen ("Pillow" Specimen)

and appearance and no other defects. Welds on pillow specimens must have a low cycle fatigue (LCF) life equal to or exceeding the established scatter band based on resistance welded specimens (at infinite life, fatigue strength greater than or equal 215 psig). This criteria, which is shown in Figure 5-11, was established in the infancy of recuperator design and manufacturing technology and has provided an accurate comparison between welding techniques and actual component operation.

5.2.1.2. Organization of Specific Tasks. The project plan is the technical milestone chart and it relates the logistics, budget, and time table of the project to technical tasks. This deviates from conventional plans, which tend to intertwine logistics with the technical goals. This allows a checklist approach to be used for the logistics without interfering with the technical acceptance standards.

The Central Technical Question (CTQ) provides the basis for the project's specific tasks and corresponding acceptance criteria. The CTQ is strictly a technical item and has a direct bearing on the future of the project. The series of CTQ's follow a logical progression to achieve the overall goal. This division helps to establish specific tasks and derive experimental evidence proving that the technology is possible in the real world. This experimental work also provides the hardware and demonstration of the technology to evaluate the production suitability of the proposed process or method. If a CTQ is not answered and the acceptance criteria is not met, the project must either find an answer by some other approach, or be discontinued. This is not the same as project failure. Project failure is the building and failed implementation of a production system that does not work on the production floor.

The project management approach uses the program plan as the basis for decisions affecting the current status and future of the project. Because the design process is iterative, the acceptance criteria must be rigid. This allows the engineer to use insight and experience from other welding process to determine the production suitability of the approach. In judging the approach, factors such as welding speed are quantitative and others such as ease of day to day maintenance and operator friendliness are qualitative. The project plan also forces the equipment vendor and project engineer to agree on the specified tasks and goals ahead of time, and realistically estimate the resources needed to accomplish them. A contract between the two parties involved can be easily formulated using the tasks as the guideline. The criteria for fulfilling the contract obligation can be determined by using the task acceptance standards as the work completion point.

5.3. Phase 0 - IRAD Feasibility Study.

Prior to this TACOM contract, the original feasibility study for the laser edge welding of the AGT 1500 recuperator inner and outer diameter joints was done. The project was funded in Avco Lycoming's 1984 Independent Research and Development (IRAD) budget. Its purpose was to

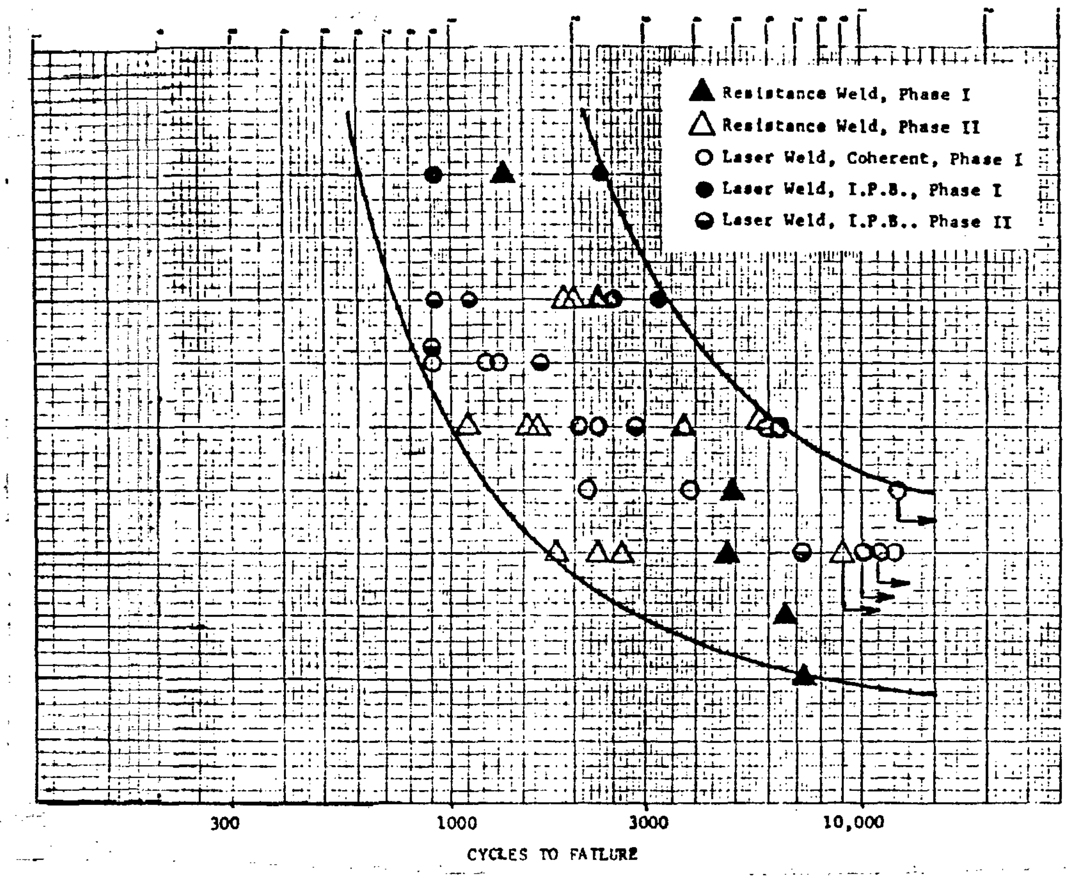


Figure 5-11. Established S-N Curve for Specimen Tests

investigate laser welding as an alternative process to the resistance seam welding process currently used to weld the inner and outer diameter joints. This improved joining technique had to work within the access limitations and design requirements of the joint and incorporate higher welding speeds while producing a readily inspectable weld. The results of this work were in the procurement of this TACOM contract for the development of a production suitable welding head for the inner and outer diameter joints.

5.3.1. Objective of the Feasibility Study. The objective of this project was to demonstrate the feasibility of laser edge welding as a production method for joining the inner and outer diameter joints.

5.3.2. Technical Approach. The feasibility study simulated the inner and outer diameter joints of the AGT 1500 recuperator plates using an internal pressure or pillow test specimen (refer to Figure 5-10). These were made from two 6-inch diameter plates of 0.008-inch thick Inconel 625, one of which incorporates the pressure test fitting.

The pillow specimens were laser welded in two vendor's laboratories using 375, 525, and 800 watt lasers and specially designed breadboard tooling. Various laser welding parameters were used to join the plate pairs and the resulting specimens were tested in low cycle fatigue for comparison to baseline resistance and laser seam weld data. The low cycle fatigue test subjects the pillow specimens to conditions similar to those met by the recuperator during engine operation. The specimen is restrained in a special test fixture and is then tested at 1300°F (704°C) by pressurizing the specimen with nitrogen gas at 360 cycles per hour until failure or run-out. All specimens were tested at 500 psi, maximum pressure, and held between restraining plates to a maximum deflection under pressure of 0.075 inch.

The mean infinite pressure (fatigue strength) was calculated for the laser edge welded specimens using the standard S-N curve fitting method shown below, and compared to the baseline results for resistance and laser seam welded specimens, similarly calculated.

$$Pi = \frac{Pt}{1 + \frac{\beta}{(N/10 \exp 3)}\ \gamma}$$

where Pi = The pressure at which infinite specimen life can be expected (endurance limit).

Pt = Test pressure

N = Number of cycles to runout or failure

β = Curve fit parameter = 2.0

γ = Curve fit parameter = 0.5

NOTE: γ and β were selected to minimize individual variations from points fitted to the mean S-N curve.

Scatter in the data within each of the two populations was due to the range of the weld parameters used. To supplement the fatigue testing, a metallurgical analysis of the welds was performed and the causes and modes of failure were evaluated.

5.3.3. Results and Discussion. The first weld trial was performed on parts with various conditions of edge mismatch (up to 0.020-inch), burred corners, and distortions and dents, all likely to be encountered in production. A straight laser beam directed vertically downward to the rotating pillow test specimen was used. The edge mismatch caused the beam to be randomly reflected, resulting in poor energy coupling, a very inconsistent weld size and a humped bead profile. This condition, shown in Figure 5-12, could not be eliminated by increasing the energy density or altering the focal length to increase the width of the laser beam.

Based on Lycoming experience in electron beam edge welding of thin sheet metal, a means of circularly deflecting the laser beam was devised. It used a rotating lens to produce a circular deflection of the beam which alternately directed it between the two plate edges. The system was set up with a 375 watt laser and lens that rotated at 17 Hertz through an 0.008 inch circular deflection. The resulting edge weld, shown in Figure 5-13, exhibited a smooth, continuous weld bead surface in one welding pass and successfully eliminated the energy coupling problem caused by edge mismatch. However, low cycle fatigue testing of these specimens (refer to Figure 5-14), yielded values below the minimum of the S-N band for resistance and laser seam welded specimens. The failures occurred through the weld, indicating the overall weld size was insufficient to withstand the required cyclic loads.

The mean internal pressure fatigue strength was 32 psig whereas the baseline value for resistance seam welds is 215 psig. To compensate for the lower overall power density from the rotating lens and the resulting small weld size, a double-pass weld technique was subsequently developed. The first pass used the rotating lens circular beam deflection to fuse the mismatched plate edges. The second pass used a straight, higher energy density beam to make a weld of the required penetration and cross section. The resulting match head shaped welds, shown in Figure 5-15, are much larger than the single pass weld, yet still retain the smooth weld surface. Four of the six low cycle fatigue test values for the double pass welds fell within the established S-N band for resistance and laser seam welded plates, while the remaining two failed substantially below this scatter band.

The mean fatigue strength of these six specimens was 138 psig. Failures occurred through the weld, and an investigation of several specimens indicated that in each case the failure initiated at a cold shut weld crack defect at the bottom of the weld. This cold shut is found on the

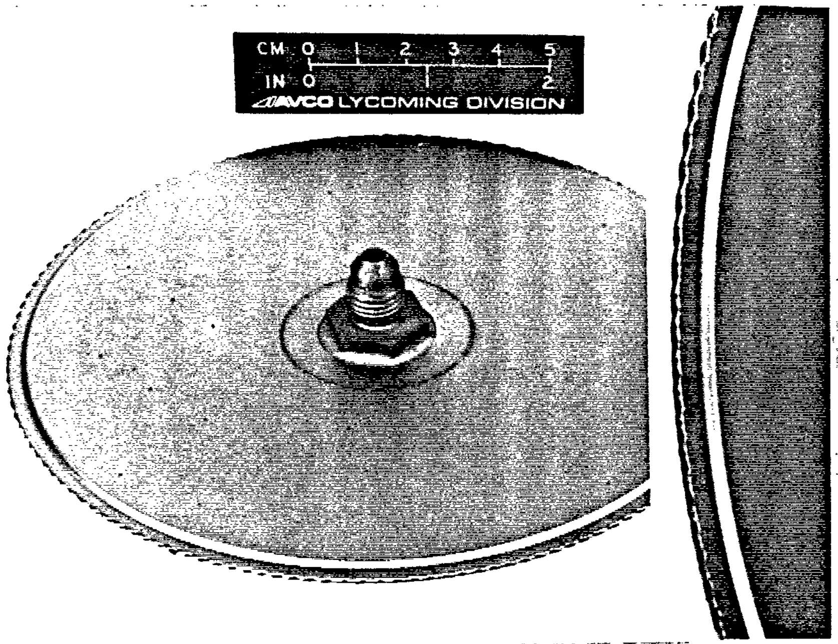


Figure 5-12. Pillow Specimen, Sawtooth Edge Weld

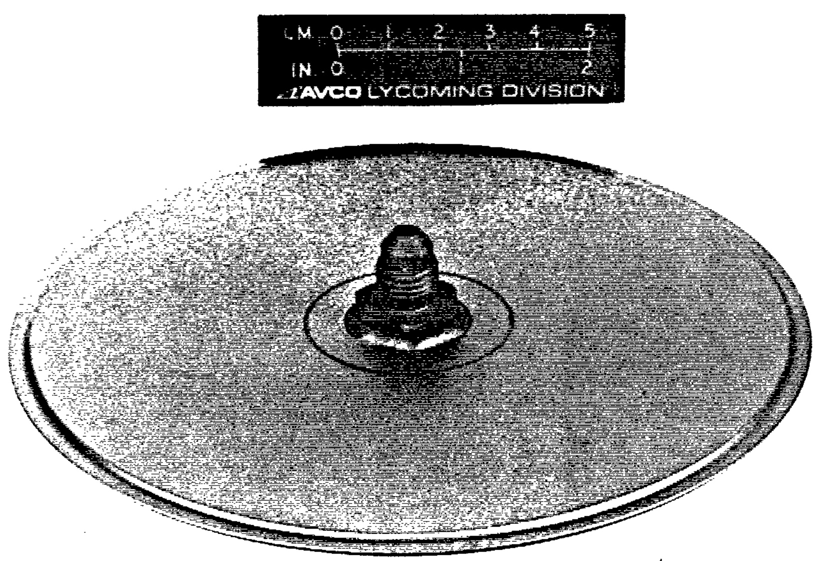
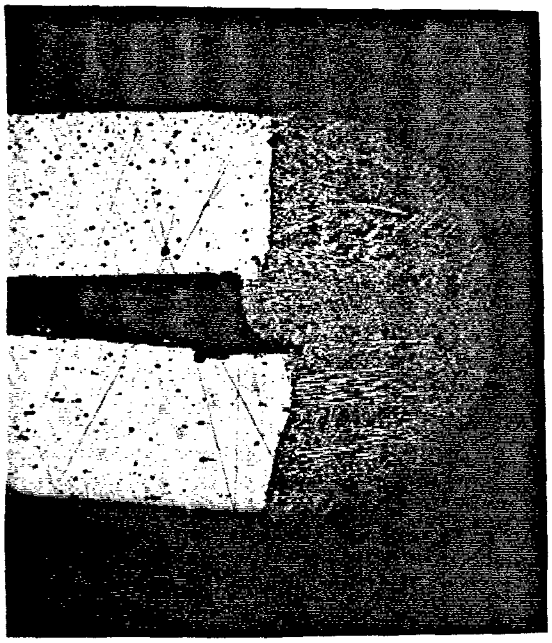
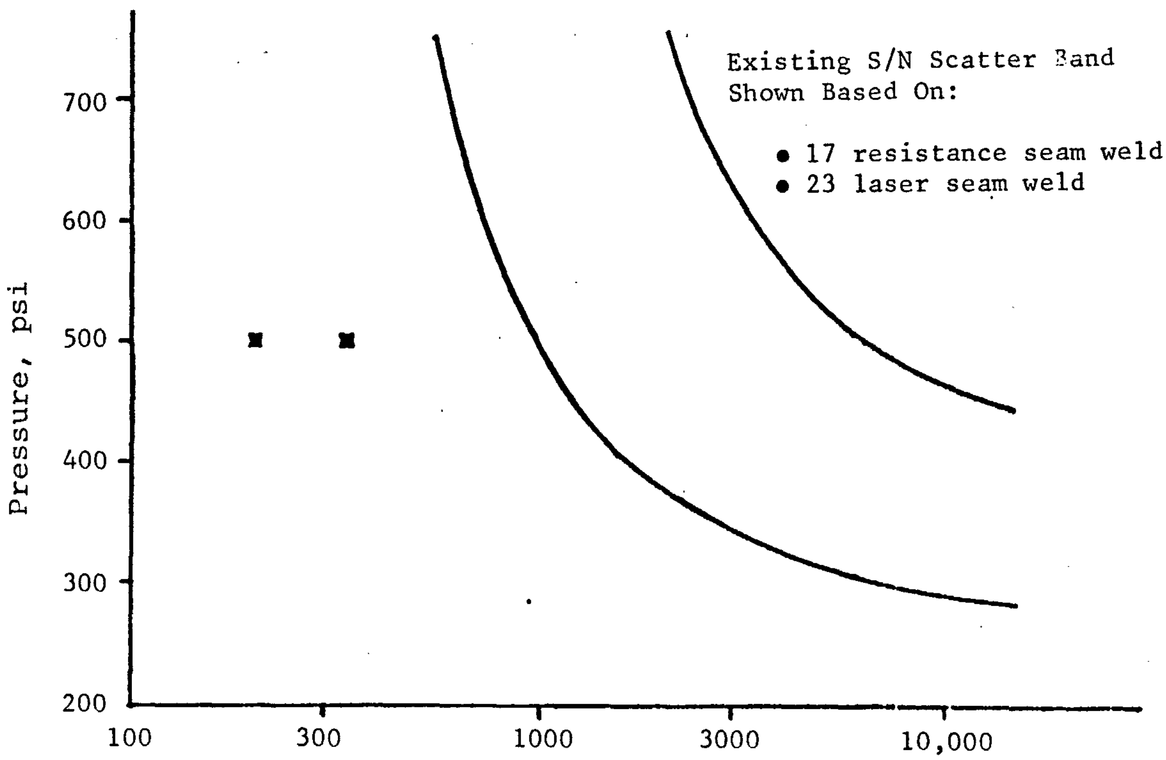


Figure 5-13. Pillow Specimen, Smooth Edge Weld



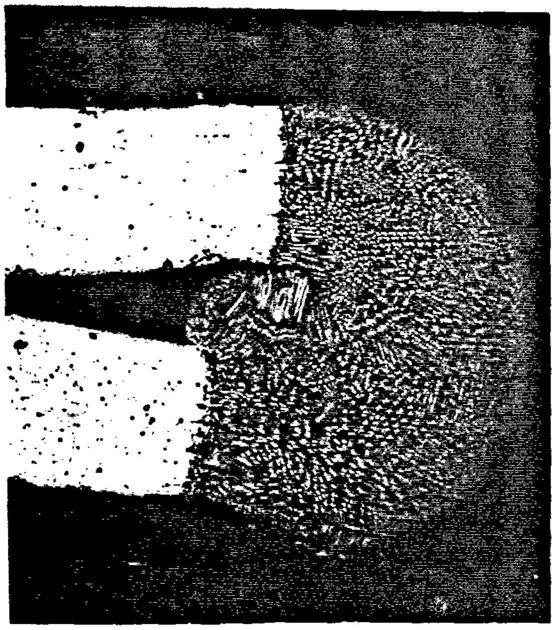
(a) As welded

(b) Fracture

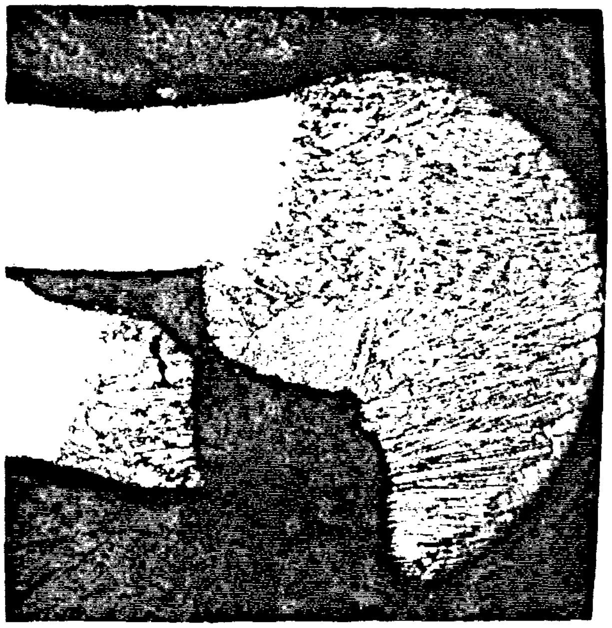


(c) S-N Curve

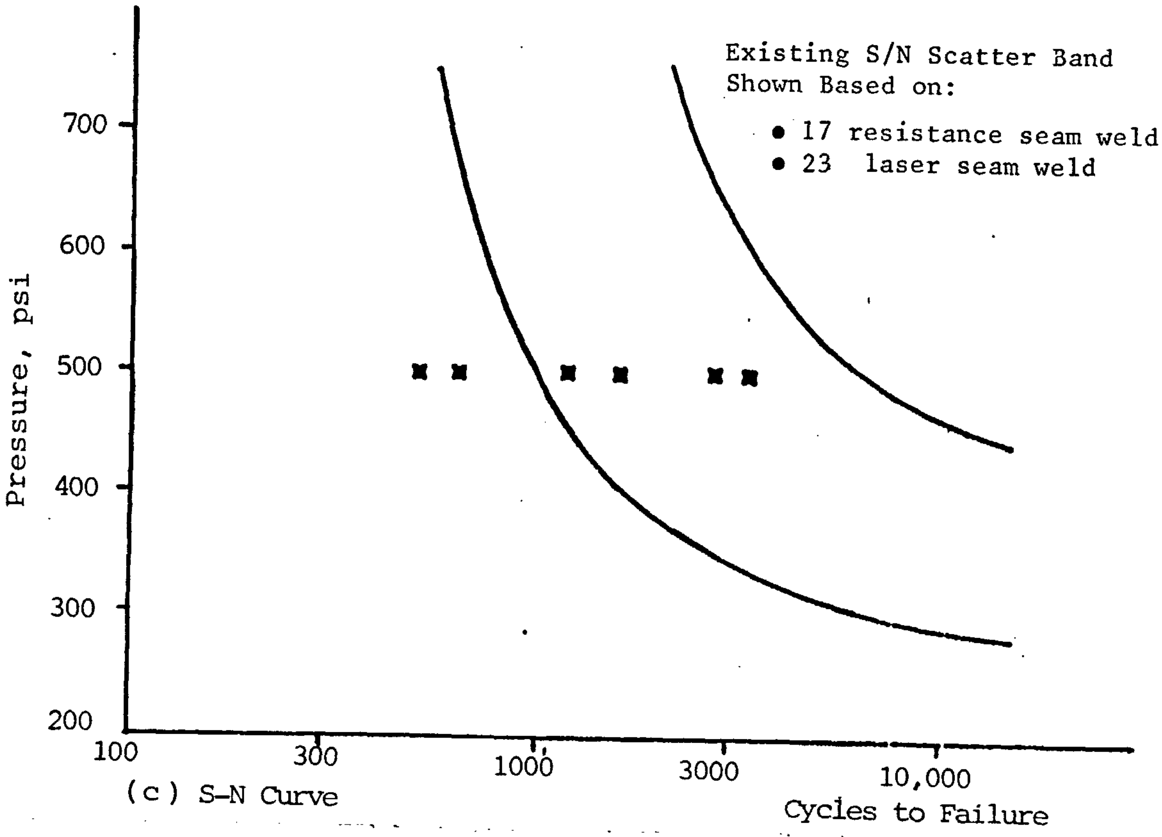
Figure 5-14. Results of Straight, Vertical Single-Pass Weld



(a) As welded



(b) Fracture



(c) S–N Curve

Figure 5-15. Results of Two-Pass, Vertical Edge Weld (Circular Deflection Plus Penetration Pass) inside edge of one plate next to the bottom of the weld puddle which collapsed between the two separated plates. On the first pass, the tooling did not provide a fit up tight enough to avoid this separation. When the second laser beam was applied, a larger molten weld puddle formed on the plate edges and flowed between the plates where it came in contact with the cold plate surfaces, and solidified.

In any case, the recuperator must be welded with a horizontal beam for production due to its large dimensions and mass. A rig to horizontally deliver the laser beam to horizontal plate edges was built. Pillow test specimens were joined with it using the double pass weld technique. Due to tooling limitations, the two plate edges of the pillow specimens were laser tack welded in several places to ensure intimate contact before the two-pass welding. The resulting weld had a match-head shape, and a smooth, uniform, and visually inspectable contour as shown in Figure 5-16. The fatigue testing of these specimens yielded the best results of the study with values in the mid-to-upper ranges of the S-N scatter band for resistance and laser seam welds. The mode of failure was along the fusion line of the laser edge weld to the base metal, or at the pressure fitting (run-out). The metallurgical evaluation of these horizontal double-pass welds showed no evidence of the cold shut condition which propagated into a weld crack. The elimination of this stress riser resulted in an improvement in the weld strength in fatigue for the six specimens to 230 psig.

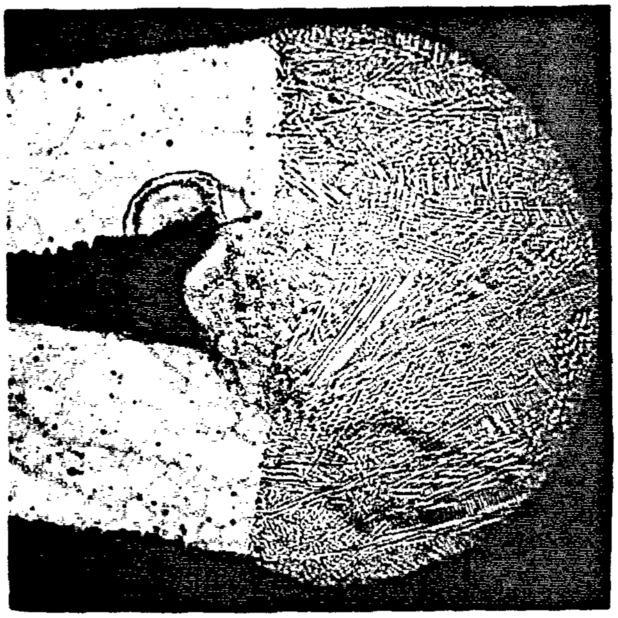
5.3.4. Conclusions. The technique of laser welding the AGT 1500 recuperator plates was shown to be feasible, having met the objectives for low cycle fatigue strength and metallurgical evaluation.

The prototype production facility had been defined. It would incorporate two adjacent laser beams. The first beam would be circularly deflected to ensure laser energy coupling to mismatched and distorted plate edges. The second beam would be a straight, higher energy density beam needed to increase the weld's size and penetration.

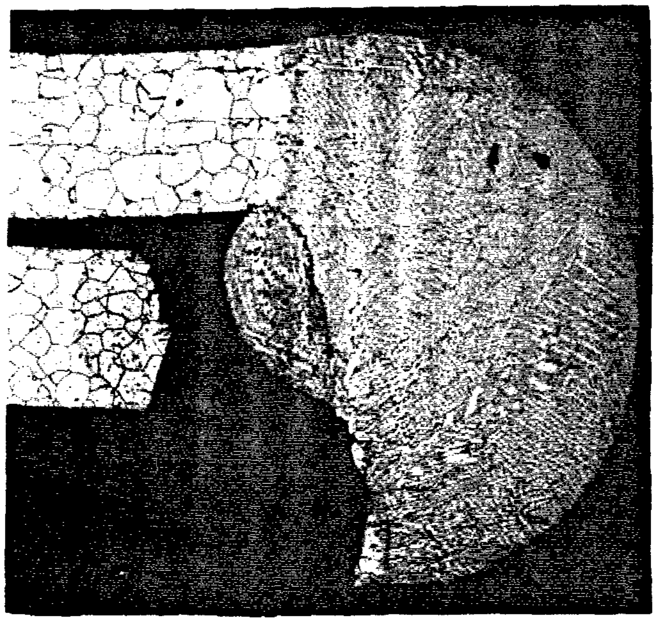
5.4. TACOM Project Plan.

The goal of this project was to develop a prototype production laser welding head for joining the AGT 1500 recuperator inner and outer diameter joints. The TACOM project is a competitive project where multiple sources do simultaneous development projects to investigate different approaches. These different approaches use different laser beam techniques, i.e., mode, deflection, and type of laser. All vendors had to complete each task in the project plan, including the feasibility study, before qualifying for the development project.

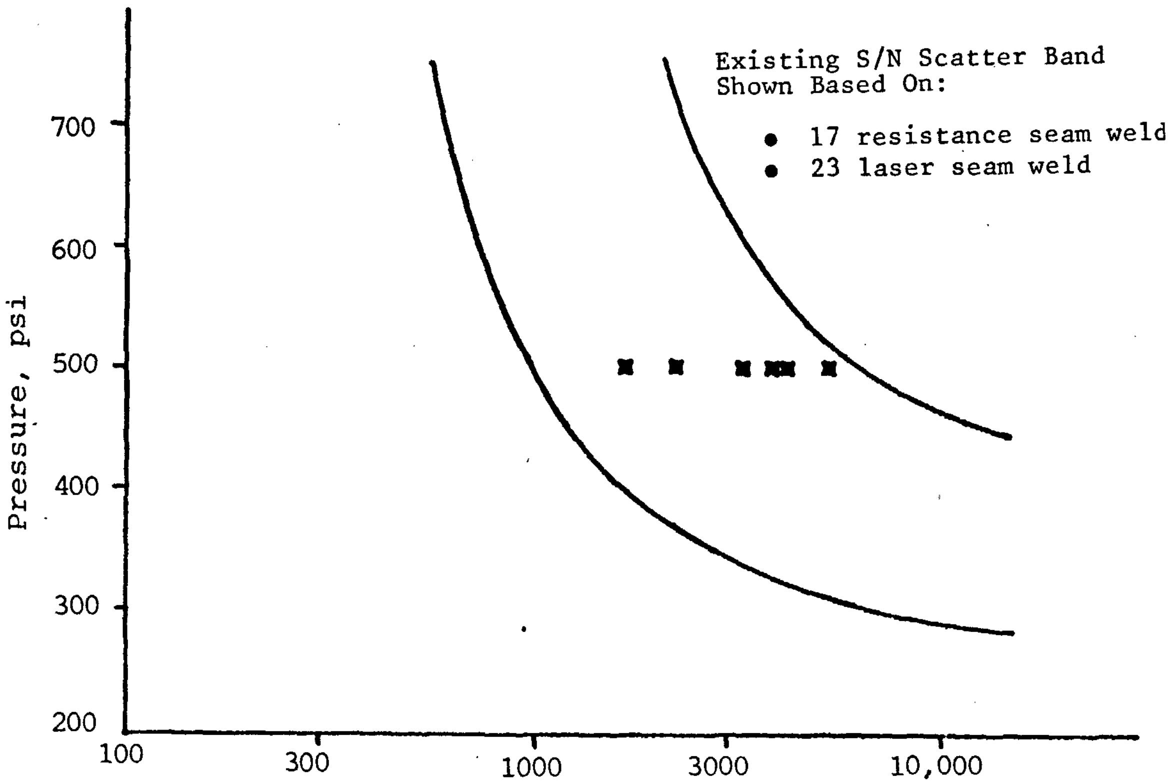
The first task in the project plan, (refer to Figure 5-17) was to determine the welding technique for the inner and outer diameter joint, which produced a weld with acceptable metallurgical characteristics and fatigue strength. (Refer to Tasks 1.1 and 1.2 in the project plan.)



(a) As welded



(b) Fracture



(c) S-N Curve

Figure 5-16. Results of Two-Pass, Horizontal Edge Weld (Circular Deflection Plus Penetrating Pass).

DETAILED PROGRAM PLAN - LASER RECUPERATOR I.D./O.D. PROGRAM - PHASE I
October 3, 1984

OBJECTIVE OF PHASE I

To develop a prototype production laser welding head for joining the AGT 1500 recuperator inner and outer joints

FEASIBILITY STUDY

C T Q	T A S K	TASK ACCEPTANCE CRITERIA
1. Is it possible to develop a welding technique suitable for the ID/OD joints which gives acceptable fatigue strength?	1.1 Conduct vendor survey. 1.2 Perform welding trials and weld pillow specimens for fatigue testing and metallographic examination.	1.2 Acceptable micros and pillow specimens that have an LCF life in the established scatter band based on resistance welded specimens. (Average fatigue strength at ∞ life = 215 psig.)

DEVELOPMENT PROGRAM

2. What is the best basic design concept for welding head?	2.1 Design breadboard welding head. 2.2 Build breadboard welding head, test by welding pillows and scrap plate pairs and modify until acceptable test results are obtained. (Iterative development process). 2.3 Design and build pilot plant head and verify performance.	2.2 Welds must have acceptable size, appearance and no cold shut, i.e., micros as good as 1.2 and concept must be adaptable to a production machine in a manufacturing environment.
3. What is the best welding technique using the device from CTQ #2?	3.1 Optimize welding techniques using prototype welding head and weld 10 pillow specimens for fatigue testing and 5 ID and 5 OD joints on scrap plate pairs. 3.2 By welding 20 pillow specimens for fatigue testing.	3.1 Pillow specimens must have an LCF life as in 1.2 & micros of plate section welds in both transverse and longitudinal direction must be acceptable. 3.2 Pillow specimens must meet requirements in 1.2 and micros of plate section welds in both transverse and logitudinal direction must be acceptable.

SUBTOTALS AT FINANCIAL DECISION POINT

4. How should a high volume machine to weld the ID/OD joints be designed and built?	4.1 Weld test pack of 25 plate pairs for pressure and engine tests.	4.1 Test pack must meet pressure and engine test requirements.

Figure 5-17. Detailed Project Plan

SUBPROGRAM A				SUBPROGRAM B			
Time Sched.	Vendor $	Engr. Time	Travel	Time Sched.	Vendor $	Engr. Time	Travel
				2 mos.	$6,000 Review program when 80% of the time and/or funds are used.	80 hrs.	$2800 4 trips of three (3) working days to vendor
LOGISTICS SUPPORT for both SPA and SPB 80 hrs.							
	$56,250 Review program progress when 80% of time and/or funds are used.	160 hrs.	$5400 4 trips of four (4) working days to Palo Alto, Ca.	(4 mos.)		(160 hrs.)	
	$56,250	240 hrs.	$5400				

Figure 5-17. Detailed Project Plan (Continued)

PROGRAM MANAGER

LOGISTICS SUPPORT

Time	Travel	ITEM	Dependent Task	Totals
110 hrs. for first six months of program	Kick off meetings $1350 1 trip of four (4) days to Ca.	1. Review contract for gov't. requirements and procedures.	N/A	
		2. Obtain pillow details a) Procurement of mat'l. for pillow details (issue P.O.) b) Fabrication of pillow test details c) Set up pillow test rig, order required equipment and schedule testing.	 1.2B 2.2A, B 3.1A, B 4.1A, B	
		3. Obtain scrap A-B plate pairs and 0.008" thickness Inco 625 sheet stock for weld tests.	1.2B 2.2A, B 3.1A, B 4.1A, B	
	$700 1 trip of four (4) days to Detroit (midwest)	4. Kick-off meetings	1.1B, 2.1A	
		5. Issue P.O. to vendors (In "Not to exceed" format)	N/A	
		6. Record in log books - time, $, travel, equipment, testing, results, etc..	N/A	
		7. Prepare quarterly progress reports to gov't. (15th of December, March, June) plus draft of final report (October 6, 1985).	N/A	
		8. Obtain materials and prepare visual aids for various types of presentations.	N/A	
110 hrs.	$2050	9. Receivables: . pillows welded with selected parameters for metallography . blueprint of welding head design (concept and final design) . photos, etc. of development setup . vendor reports	 1.2B, 2.2A,B 3.1A,B, 4.1A,B 2.2A,B 4.1A,B 1.2B, 2.2A,B, 3.1A,B, 4.1A,B, 4.2A,B N/A	First 6 mont Vendor $62,2 E.T. 590 h Travel $10,.
		10. Procure 50 (total) A-B plate pairs for laser ID/OD welding	4.1A,B	Remainder Vendor $57, E.T. 880 h Travel $10,
		11. Schedule engine test and record performance results.	4.2A,B	Total(progra Vendor $120, E.T. 1570 Travel $21,

Figure 5-17. Detailed Project Plan (Continued)

PHASE I - TASK SCHEMATIC

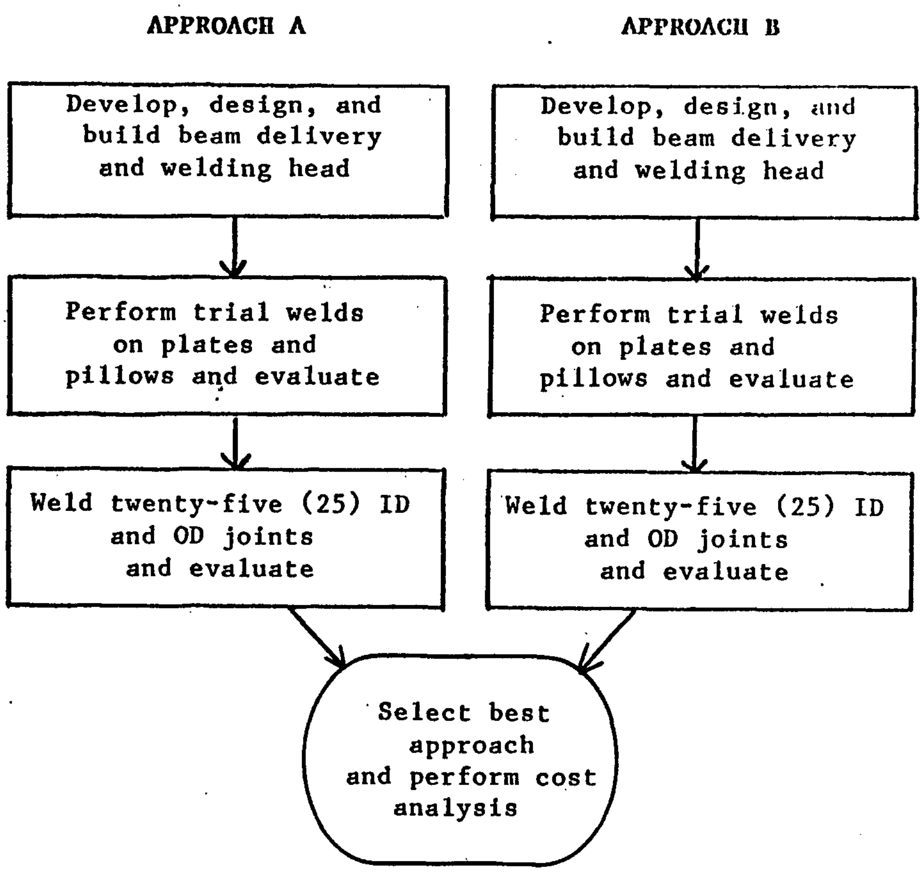


Figure 5-17. Detailed Project Plan (Continued)

Because different lasers have different mode characteristics and different system houses have unique ideas, a comprehensive vendor survey was planned. Any vendor with the apparent capability to weld the joint was given the opportunity to do a feasibility study for a small amount of funds ($3000 maximum). Each vendor's results was evaluated independently on the basis of its own technical merit. The acceptance criteria stated that the vendor must make pillow test specimens, which met the metallurgical and high temperature fatigue strength requirements. If a possible production suitable technique existed, it was evaluated competitively with other approaches. Vendors whose technique met the task objectives were selected to participate in the development project. A Lycoming engineer worked with the vendors on these feasibility studies to gain insight on the process and evaluate, first hand, the potential production suitability of the technique.

The first Central Technical Question in the development project focused on the tooling portion of the welding head design. (Refer to Task 2.1). The head was built and demonstrated on a work station, which is capable of handling full size recuperator plates. (Refer to Task 2.2). The tool and the welding technique had to be demonstrated on ordinary production plate pairs. (Refer to Task 2.3).

The second Central Technical Question focused on the optimization of the welding head and process. (Refer to Tasks 3.1, 3.2 and 4.1). This presents a clear picture of the production suitability of the complete approach and its potential benefit to the manufacture of recuperator cores. This work also verified the parameters that would be used in the production prototype system. The task acceptance criteria simulated a production environment and gave insight into the welding head's operation in this type of environment. There are certain variables in the welding technique which were nonnegotiable. These were items that make the technique uneconomical or too complicated for everyday operation. This technique was required to be demonstrated on a test pack, which met the visual inspection and pressure test requirements of the production recuperator.

5.5. Background On Laser Technology Relevant To Edge Welding.

The laser edge welding of the inner and outer diameter joints of the recuperator is a complex process. This edge weld presents a unique problem because the laser beam must not only fuse the plate edges but the resulting weld must meet the high temperature fatigue strength requirements. This task involves the state-of-the-art laser technology. It is essential to be familiar with the factors important to parameter selection and optimization.

5.5.1. Mode of the Laser Beam. The mode of the laser beam is a critical variable in materials processing. It is defined as the cross-sectional shape of the working laser beam and technically called the transverse electromagnetic mode (TEM). The shape of the mode is dependent on the photon wavelength, mirror alignment, curvature and bore on the photon wavelength, mirror alignment, and curvature and bore diameter of the laser tube, i.e., the construction and design of the basic laser. The following analogy can be made: the sharpness of the mode has the same effect on material as the sharpness of the cutting tool. The two modes most commonly used in materials processing applications are the gaussian mode (TEM00) and the donut mode (TEM01).

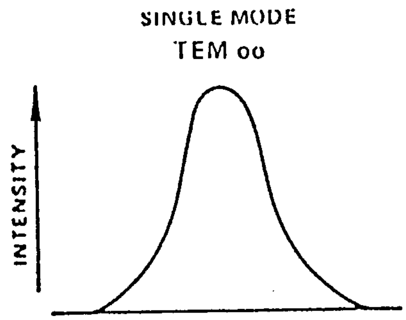
The gaussian mode (TEM00), which is illustrated in Figure 5-18, maximizes the power density, concentrating the energy in a small spot. This energy is able to overcome the surface reflectivity to produce a deep penetration weld. The heat-affected zone and distortion associated with the heat input are minimized when the weld is produced using a gaussian mode laser beam. This mode is used for welding, cutting, and drilling applications.

The donut mode (TEM01), which is illustrated in Figure 5-19, produces a larger laser beam spot than the gaussian mode beam. A beam in this mode has most of its energy concentrated near the periphery of the focused area. This mode distributes the heat over a larger beam spot. This mode is used primarily for specific welding applications and localized heat treating.

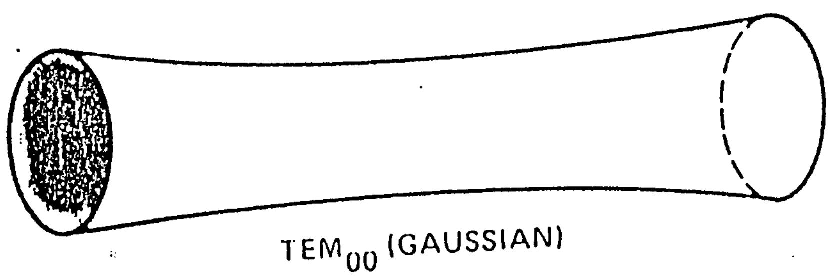
5.5.2. Power Density. The power density is defined as the amount of radiant energy concentrated on a surface. The level of the power density is related to the focal length lens and the focal spot size. The focusing lens selection determines the power density at the surface of the joint. For example, the power density, which can be achieved with a 2.5-inch focal length lens is greater than that of a 5-inch focal length lens. A longer focal length lens reduces the relative power density which occurs on the material surface. A slower welding speed must be used to compensate for the reduced power density. A gaussian mode beam and a 2.5-inch focal length lens is the optimum combination for penetrating highly reflective materials. However, once the weld is initiated, this high energy beam may vaporize the molten metal (with very low surface reflectivity) and cause excessive weld spatter. Therefore, the variables effecting the power density on the surface of the joint must be considered in the development and optimization of the laser welding parameters.

5.5.3. Operation Modes. The energy from the laser can be delivered to the material in different ways or operation modes. The operation modes, which are illustrated in Figure 5-20, are described below and can be selected according to the application. Depending on the surface reflectivity, material thickness, beam angle, etc., the operation mode must be selected accordingly. The three operation modes are as follows.

For welding applications, it is important to have a high enough peak power which will overcome the surface reflectivity and maintain the weld around the entire joint. A high peak power initiates rapid vaporization



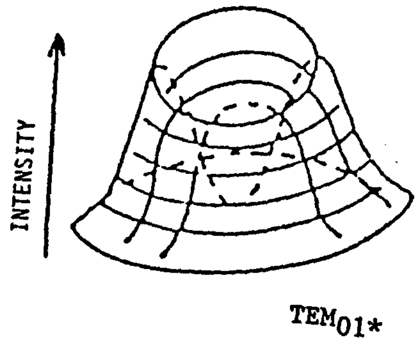
a) Power Distribution for Beam



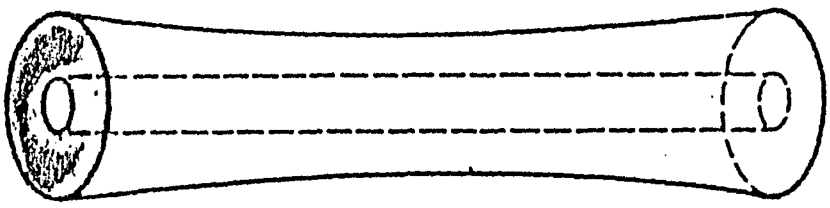
b) Transverse Beam Mode

c) Beam Spot Configuration

Figure 5-18. Gaussian Mode Laser Beam



a) Power Distribution for Beam



b) Transverse Beam Mode

c) Beam Spot Configuration

Figure 5-19. Donut Mode Laser Beam

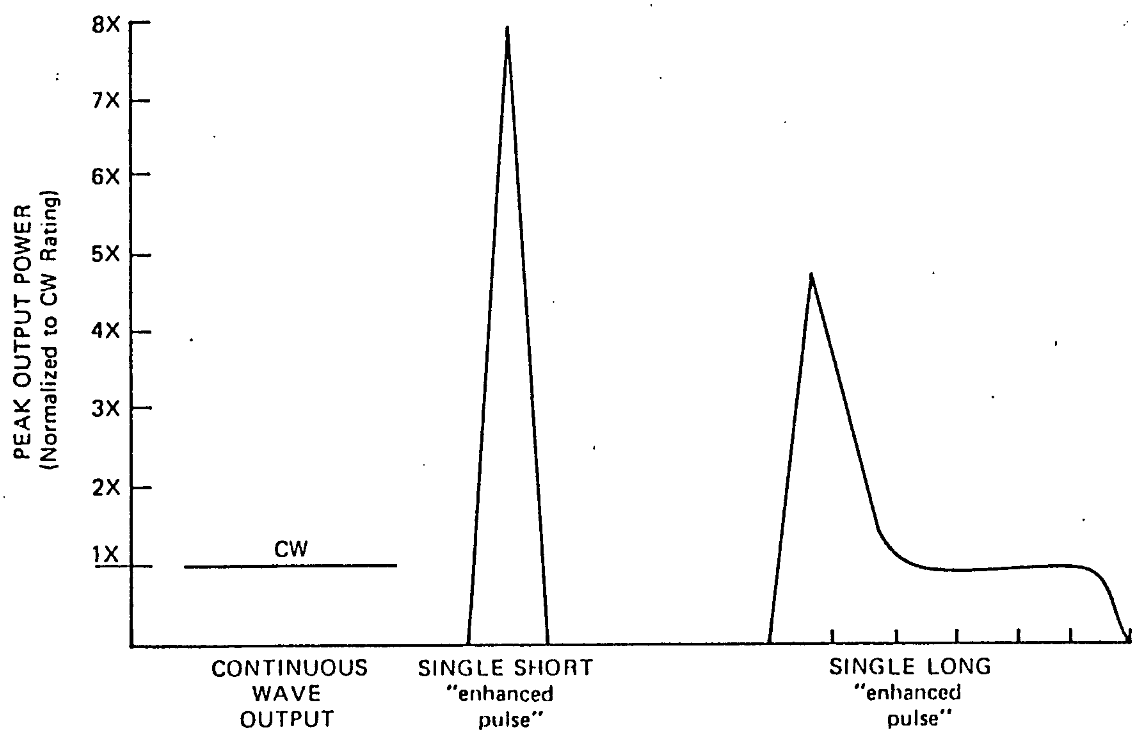


Figure 5-20. Operation Modes of the Laser

of material when the beam interacts with a substance. This creates a minimal melting of material surrounding the beam spot and a reduced heat-affected zone.

The short pulse has a leading edge spike. This enhanced pulse rapidly overcomes surface reflectivity to produce deep penetration welds with minimal thermal damage to surrounding material. The peak power can be 5 to 8 times the continuous wave output level.

A longer pulse length is a pulse at a level four to five times the continuous wave output level followed by decay of power below the continuous wave level for the remainder of pulse duration. The leading pulse is used to initiate the reaction and the following decay is used to maintain the reaction.

5.5.4. Other Items. The rotating lens is a device that typically rotates a focusing lens in the plane of the lens on an axis coincident with the incoming stationary beam. The focused spot will always be on the axis of the lens. The axis will be rotated in a circle with the lens. This can increase the effective diameter of the beam.

The beam splitter was discussed as an alternative in the production system. In Figure 5-21, the beam is divided by using special lenses and mirrors. It is a flat optical element that is coated to reflect a defined proportion of incident light and to transmit the remainder. Standard beam splitters have reflection/transmission ratios of 50, 30/70, or 10/90.

5.6. Subproject B.

The purpose of Subproject B was to investigate alternative laser edge welding techniques for the inner and outer diameter joints. To be selected for development, an alternative approach must also demonstrate feasibility by producing welds of acceptable quality and high temperature fatigue strength. The welds had to be smooth and continuous and have a minimum size, i.e., radial dimension of 0.016-inch and a low cycle fatigue at least equal to the previously established baseline resistance weld fatigue strength at 1300°F.

5.6.1. Vendor Surveys. Twelve potential subcontractors (Table 5-1) to investigate alternative welding concepts were contacted. Visits were made to three of them to discuss the project in detail and survey their technical capabilities. Two were selected to perform feasibility studies. Koppers Company's Laser Systems Division of Glen Arm, Maryland was selected to investigate a one-pass weld technique using the TEM01 (donut) mode beam. Photon Sources, Inc. of Livonia, Michigan was selected to investigate a one-pass weld technique using an oscillating gaussian mode beam.

5.6.2. Koppers Laser System.

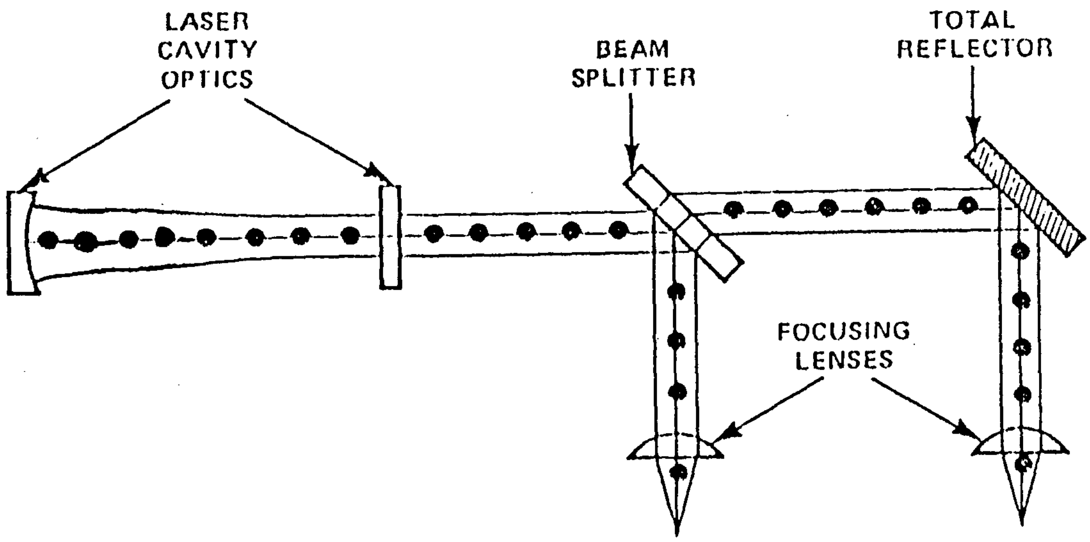


Figure 5-21. Diagram of Laser Beam Splitting

TABLE 5-1. LIST OF VENDORS SURVEYED

1. COHERENT GENERAL
2. SPECTRA-PHYSICS, INC.
3. SCIAKY BROS.
4. PHOTON SOURCES, INC.
5. KOPPERS LASER SYSTEMS DIV.
6. ACME TECHNOLOGIES GROUP
7. LASER CORP. OF AMERICA
8. PENN RESEARCH CORP.
9. MIDWEST LASER
10. RAYTHON CO.
11. INTERNATION LASER MACHINES CORP.
12. LASERMATION, INC.
13. FERRANTI PIC

5.6.2.1. Equipment. A 1,200 watt CO_2 laser (Photon Sources' Model V1200) was used with a five-inch focal length lens. The laser beam produced was nongaussian, i.e., a donut mode. Such a beam was used because it has a larger spot size than a gaussian beam. The nongaussian beam spot size was 0.010 inch in diameter compared with 0.003 to 0.005-inch diameter for a gaussian beam produced by a laser of comparable power rating. Results of the previous feasibility study indicated that adequate coverage of the width of the edge joint by the laser beam was important to achieving the required energy coupling and weld quality.

5.6.2.2. Experimental Procedure. Welding experiments were conducted on specimen joints. Each joint was formed by two 0.008-inch thick, 6-inch diameter Inconel 625 plates, as was shown in Figure 5-10 to simulate the recuperator plate outside diameter joint. The joint mismatches were from 0 to 0.020 inch to simulate production part joints. The specimen contained a pressure fitting to allow fatigue testing of the welded joint under conditions simulating those experienced by the recuperator plate outside and inside diameter joints during engine operation.

In preparation for welding, the plates were degreased and then placed in a welding fixture. The plate position was horizontal. The laser beam positions included 0 and 20 degrees for the horizontal position combined with either 60 or 90 degrees from the tangent point where the beam impinged the joint. During welding, the plates were rotated with the beam kept stationary. Both argon and helium were evaluated as shielding gasses. The welding speed was 100 inches per minute, which is about twice the current production resistance welding speed. Different levels of beam power ranging from 600 to 1000 watts were used. The beam was either focused or nonfocused, with or without pulsing, with or without vertical or horizontal oscillation. The vertical oscillation frequency was from 100 to 150 Hertz with an amplitude of 0.040 inch, while the horizontal oscillation frequency was from 150 to 350 Hz with an amplitude of 0.100 inch. These different types of beam were used in an effort to obtain uniform and sufficient melting over the entire edge width of the joint. All joints were welded with a single pass.

Welded specimen joint quality was evaluated visually and metallographically.

5.6.2.3. Results and Discussion. Based on the weld surface geometry and cross section size, the best combination of welding parameters evaluated was a nonpulsed horizontal beam perpendicular to the tangent of the point where it impinged on the joint, with a 350 Hertz horizontal oscillation rate, a 0.10-inch oscillation amplitude, a focal point 0.030 inch in front of the joint, 750 to 800 watts beam power, 100 inches per minute travel speed, and argon shielding gas. Several joints with a mismatch of less than 0.010 inch were welded using this combination of parameters. A smooth continuous weld was obtained in these joints. Metallographic examination of transverse weld sections from one of these joints revealed a maximum weld size about 0.017 inch, as shown in Figure

5-22, which is only 0.001 inch above the minimum acceptable size established during the previous in-house feasibility study.

The weld pool tended to bead up, resulting in an irregular weld, as shown in Figure 5-23, when attempts were made to increase the weld size on the joints with a plate edge mismatch of less than 0.010 inch, or to weld a joint with a plate mismatch of less than 0.010 inch, or to weld a joint with a plate mismatch of 0.020-inch. The problem is primarily attributable to the small edge width of the plates. The experimental results indicated that a consistently smooth continuous weld meeting the required weld size could not be achieved with a one pass welding technique.

No fatigue testing was performed on the specimens welded during this feasibility study because of the welding problem described above.

5.6.2.4. Conclusion and Summary. Specimen joints simulating the recuperator plate outer diameter joints cannot be consistently joined with welds meeting the stated minimum size, quality, and surface contour requirements using the one-pass technique with any combinations of welding parameters evaluated. Therefore, this one-pass technique using the donut mode laser beam will not be developed for use in welding the recuperator plate inner and outer diameter joints.

5.6.3. Photon Sources, Inc. Only preliminary welding experiments were conducted in this feasibility study. The remaining experiments were later cancelled because of the unavailability of a beam oscillator with a high enough oscillation rate and suitable laser system to allow the study to be completed on schedule. At the same time, while awaiting for availability of the oscillator and laser system, beam oscillation was included in the feasibility study at Koppers Laser Systems as previously discussed.

5.6.3.1. Equipment. A 500 watt (Photon's Model V500) and a 1,200 watt (Photon's Model V1200 CO_2 laser were used with a 3.75-inch focal length lens. The laser beam produced was gaussian. The system was equipped with a beam oscillator with a maximum oscillation rate of 60 Hertz. Beam oscillation was used because the previous feasibility study indicated that sufficient coverage of the width of the edge joint by the laser beam was important to achieving the required energy coupling.

5.6.3.2. Experimental Procedure. Welding experiments were conducted of specimens simulating the configuration of the recuperator outer diameter joints. Each joint was formed by two 0.008-inch thick, 6-inch diameter Inconel 625 plates as was shown in Figure 5-10. The joint mismatches were less than 0.010 inch. The specimen contained a pressure fitting to allow fatigue testing of the welded joint under conditions simulating those experienced by the recuperator plate inner and outer diameter joints during engine operation.

Recuperator welding specimen, .5X.

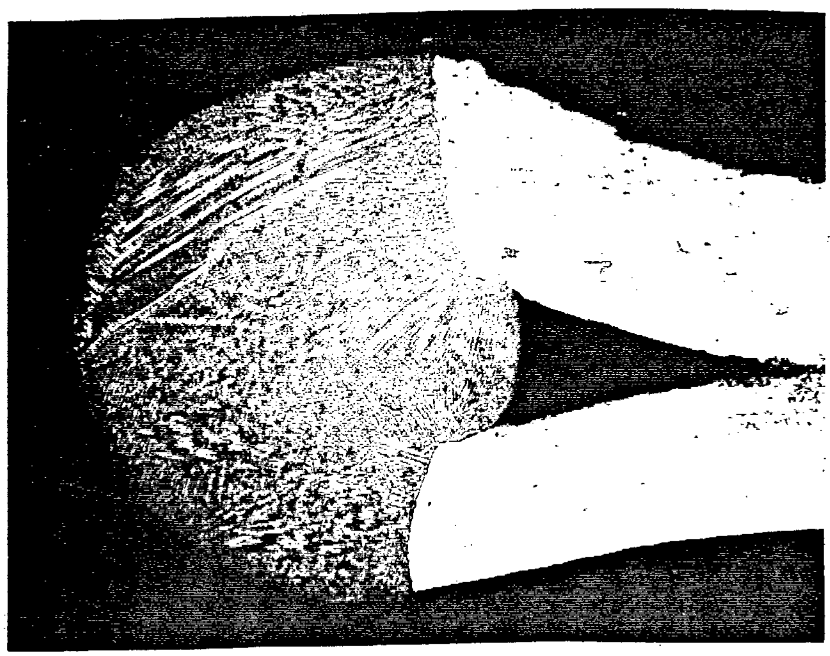


Figure 5-22. Acceptable Edge Weld Transverse Section (100X)

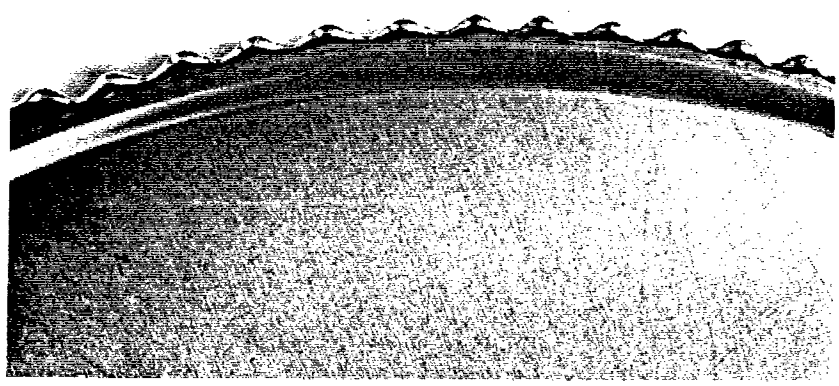


Figure 5-23. Unacceptable Edge, Weld-Irregular, Sawtooth Contour

In preparation for welding, the plates were degreased and then placed in a welding fixture. Both the plate and laser beam positions were horizontal. The laser beam was perpendicular to the tangent to the point where the beam impinged of the joint. During welding, the plates were rotated with the beam kept stationary. Both argon and helium were evaluated as shielding gases. The welding speed was 100 inches per minute. The speed was lowered to 50 inches per minute when the beam oscillated perpendicular to the welding direction because the oscillator did not have a high enough oscillation rate to allow a continuous weld to be made at 100 inches per minute. Different levels of beam power ranging from 350 to 850 watts were used. The beam was either focused or nonfocused, with or without pulsing, and with or without vertical or horizontal oscillation. These different types of beams were used in an attempt to obtain uniform melting over the entire edge width of the joint. All joints were welded with a single pass.

Welded specimen joint quality was evaluated visually and metallographically.

5.6.3.3. Results and Discussion. The weld pool tended to bead up and solidify into a sawtoothed configuration when attempts were made to produce an edge weld of 0.016-inch minimum size in the joints using various combinations of welding parameters with both lasers. Postweld metallographic examination revealed a weld size of about 0.010 inch or less in all the joints that showed a smooth continuous weld. The difficulty of producing a smooth continuous one-pass weld meeting the 0.016-inch minimum size in the joints was not significantly lessened by any of the changes of welding parameters.

An irregular weld surface was obtained when a joint was welded at 100 inches per minute using either horizontal or vertical beam oscillation was 60 Hertz. Therefore, further welding experiments were delayed until an oscillator with a high enough oscillation rate was obtained. As previously indicated, additional experiments were subsequently cancelled because of unavailability of such an oscillator and suitable laser system.

5.6.3.4. Conclusion and Summary. The specimen joints can not be consistently laser edge welded meeting the specified weld size and surface requirements using the one-pass technique with any of the combinations of welding parameters evaluated. Based on the results of this feasibility study and those of the feasibility study conducted at Koppers Laser Systems, this one-pass technique using an oscillating gaussian mode laser beam will not be developed for use in welding the recuperator plate inner and outer diameter joints.

5.7. Subproject A.

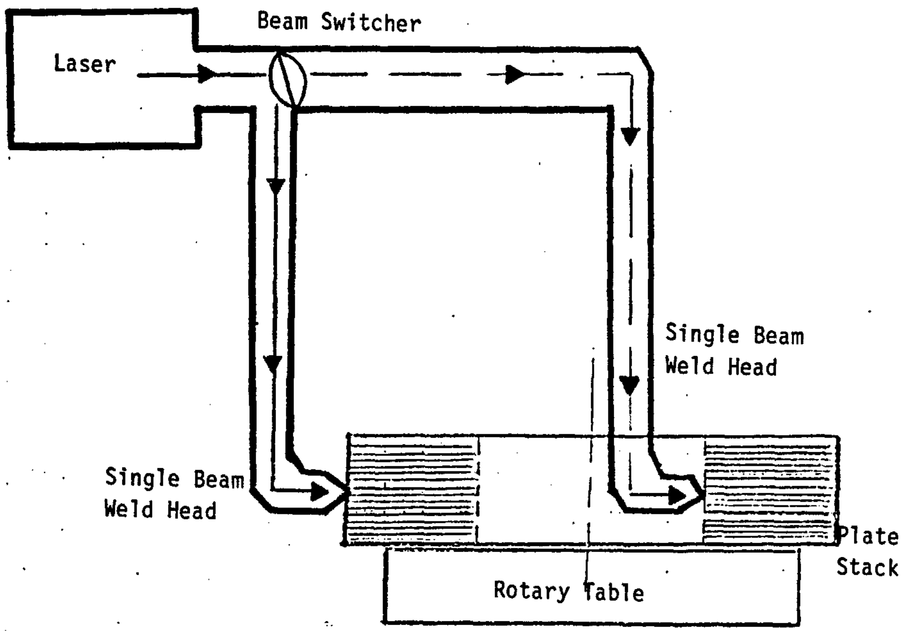
Subproject A was based on the results of the 1984 IRAD feasibility study. The feasibility of the edge welding the inner and outer diameter joints using a two-pass technique with a gaussian mode beam was demonstrated. The welds produced met the metallurgical and high temperature fatigue strength requirements. The first weld pass was made with a circularly deflected beam and the second weld pass was made with a nondeflected beam. The welding head was designed to accommodate this two-pass welding technique. The production suitability of this welding technique was evaluated in conjunction with the tooling on full size recuperator plates.

5.7.1. Discussion of I.D./O.D. Welding Machine Design Concepts. There are a number of basic layout and functional concepts for a laser I.D./O.D. welder. These were first defined and then evaluated in terms of Lycoming's experience both with resistance welding of these joints and in the design of automated production laser systems. An explanation of the possible concepts follows.

5.7.1.1. Concept A. This concept, which is shown in Figure 5-24, would use a single beam delivery welding head to weld the inner diameter joint and a second similar head to weld the outer diameter joint. Each would have permanent tooling matching the curvature of the inner and the outer diameter, respectively. Each joint would require two separate welding passes, if the welding technique was finally proven production suitable, the first using the circular deflection of the beam and the second using the nondeflection beam. A beam from a single laser would alternately weld the inner diameter joint then the outer diameter joint of a single plate pair, by being switched between the heads. The individual welding heads would independently move to the next joint upon completion of the weld while the other head was welding. Optimum welding parameters would be used for each joint, i.e., power and rotational speed would be adjusted independently.

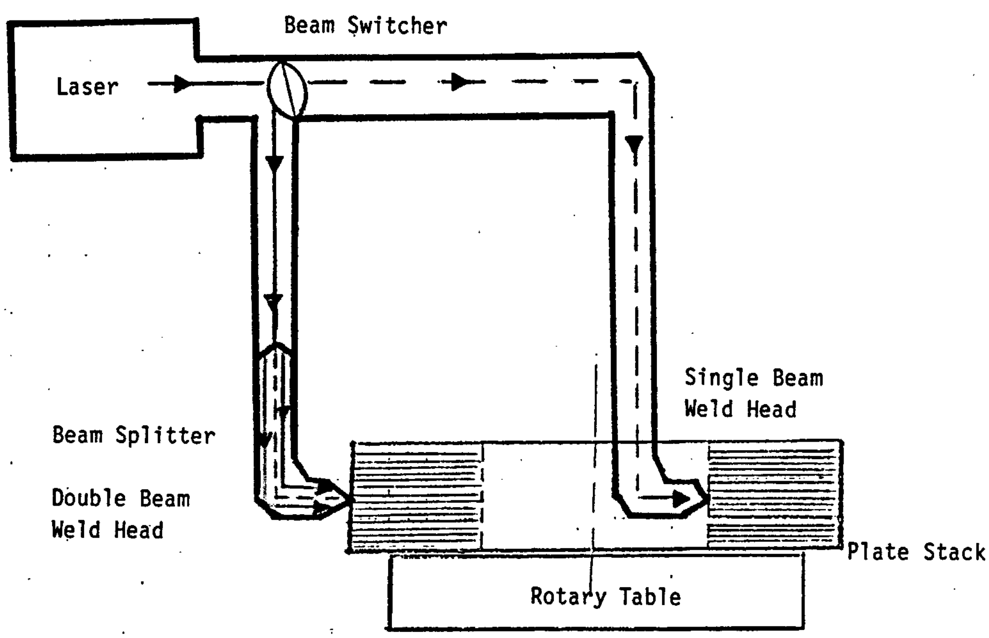
5.7.1.2. Concept B. This concept, which is shown in Figure 5-25, would use a single beam delivery head to weld the inner diameter joint and a double beam head to weld the outer diameter joint, if a two-pass technique was finally selected. The curvature of each head's tooling would be fixed to the inner and outer diameter, respectively. The inner diameter joint would be welded in two separate passes using optimum welding parameters, and then, the outer diameter joint would be welded in one-pass. The outer diameter double beam welding head would deliver two beams, i.e., a rotating beam directly followed by a non-deflected beam, to the joints using optimum welding parameters. A single laser producing two beams would be used with only one beam output connected to the inner diameter welding head. But both beams would be used simultaneously in the outer head. As in concept A, each head would move to the next joint while the other head was welding.

5.7.1.3. Concept C. This concept, which is shown in Figure 5-26, would use a welding head with a single beam delivery to weld the inner diameter and a similar head to weld the outer diameter. The permanent tooling would fit the inner and outer diameter curvatures, respectively.



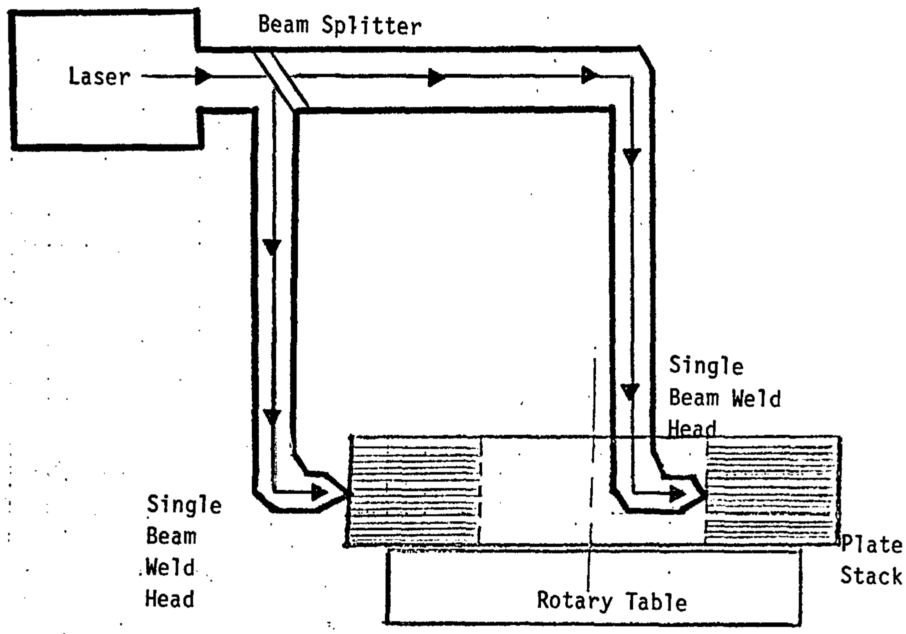
- Weld I.D. (two passes) while indexing O.D. head
- Weld O.D. (two passes) while indexing I.D. head

Figure 5-24. Welding Head Concept "A"



- Weld I.D. (two passes) while indexing O.D. head
- Weld O.D. (one pass) while indexing I.D. head

Figure 5-25. Welding Head Concept "B"



- Weld I.D. and O.D. simultaneously
- Index both heads simultaneously

Figure 5-26. Welding Head Concept "C"

Each joint could require two separate welding passes, if a two-pass technique was finally adapted. Both the I.D. and O.D. joints would be welded simultaneously using a constant stack rotation speed. The laser beam would be split between the inner and outer diameter welding heads. Upon completion of the welds, both heads would independently index to the next joint. The welding speed would be in the ratio of the diameters for the inner and the outer diameter joints. Therefore, the power would have to be adjusted accordingly.

5.7.1.4. Evaluation. Design concepts A, B, and C were evaluated by calculating the machine theoretical production rate capability, assuming a welding speed of 100 inches per minute. This showed that the machine based on concept A would take 13.75 hours to process a complete core. A machine based on Concept B would take 10.0 hours to accomplish the same task. A machine based of Concept C would take 9.5 hours. The significant increase in the equipment complexity of Concept C did not appear to justify its 5 percent increase in the theoretical production rate. Therefore, pending experimental evidence from operating the pilot plant, Concept B appeared to be the best approach.

NOTE: This is calculated theoretical capability only for purposes of comparison and should not be used to estimate the actual production rate of a production system.

5.7.2. Experimental Procedure. The welding head was tested on a laboratory work station, which closely simulated production conditions. The work station, which is shown in Figure 5-27, was designed to be the skeleton of a future production machine. The entire experimental setup was flexible enough to accommodate many design iterations with a minimum of effort and cost. The iterative design process was essential to the development of the production suitable welding head. The design of the laboratory work station incorporated the welding head, beam delivery apparatus, and plate handling equipment. The components of the work station were compatible with the recuperator assembly, including the limited space of the inner and outer diameter.

The foundation of the laboratory work station was an x-y table with a 60-inch by 40-inch travel range and a 30-inch by 30-inch vertical frame. A variable speed rotary table was permanently mounted on the x-y table. The rotary table was capable of linear travel speeds ranging from 0 to 100 inches per minute. The plate stacking fixture was bolted to the top of the rotary table. A single axis table, which was mounted on the vertical frame, held the beam delivery apparatus and support plate. This table, which was operated manually, provided the z-axis motion required to locate the head on the specific joint.

The Coherent EFA 51 laser was selected for this work because it had a higher power rating than the 525-B laser used in the feasibility study. The EFA 51 laser was rated at 1500 watts and produced a beam with a gaussian mode, TEM00. A 3.75-inch focal length lens was selected for

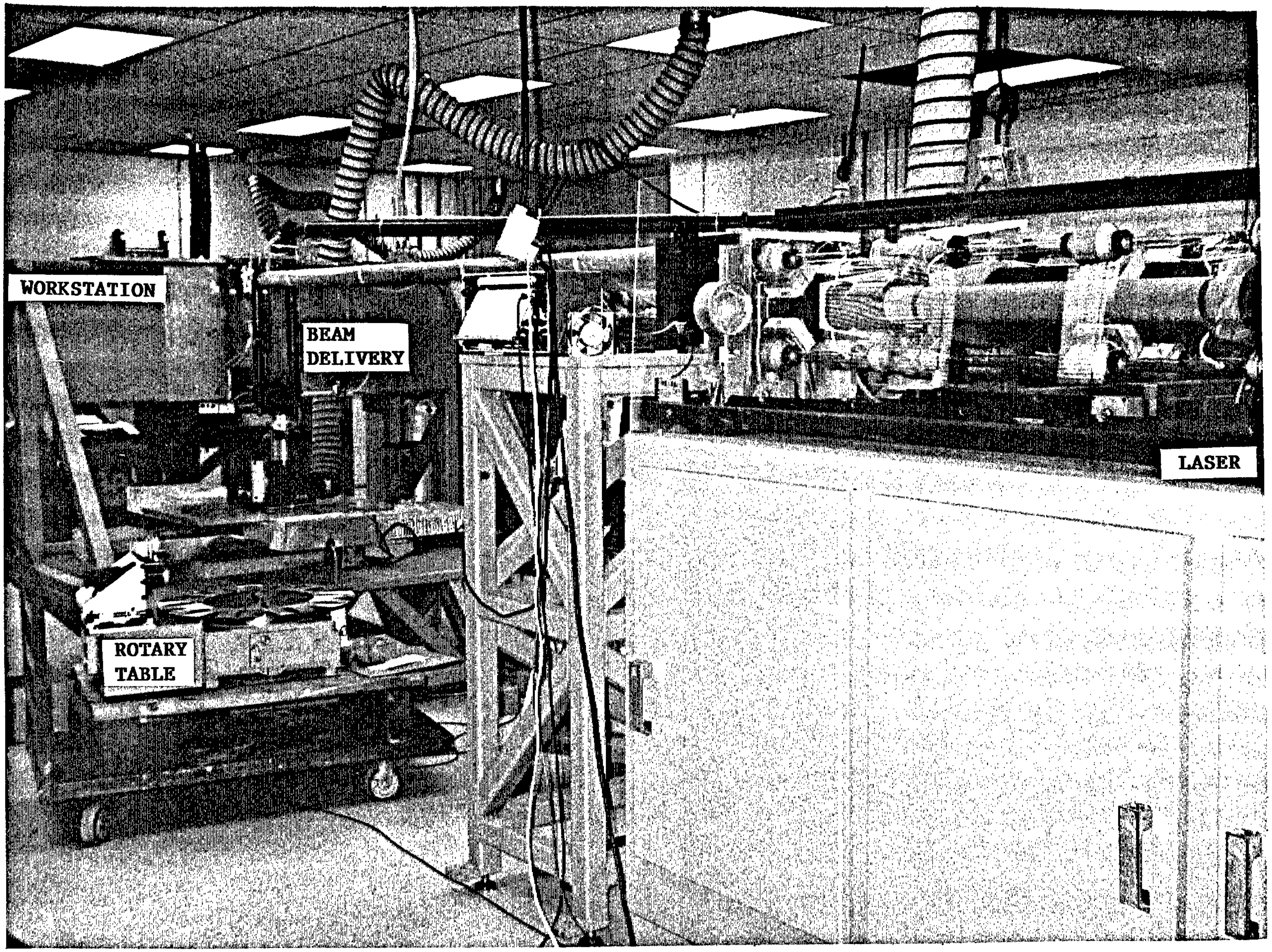


Figure 5-27. Laboratory Work Station

this application because it could be easily integrated with the other components of the welding head and meet the size limitations of the 15-inch diameter annulus. This lens produced a medium range power density and was located far enough away from the work to avoid severe contamination. A rotating mirror was installed in the beam path just before the beam was turned to the horizontal plane, as shown in Figure 5-28. The rotating mirror was used instead of the feasibility study's rotating lens for simplicity. The deflection of the beam by either the rotating mirror or lens would distribute the heat across both plate edges with equal efficiency. The speed of the circular deflection, which ranged from 0 to 2,000 revolutions per minute, was adjusted manually. The helium shielding gas was delivered to the workpiece through tubes placed around the tooling and workpiece. Also, a 10x magnification microscope was installed to aid with the alignment the beam to the joint and observation of the welding process and the resulting weld.

The support plate, which was bolted to the vertical table, held the beam delivery apparatus. This included a turning mirror, the focusing lens, and the welding tool. This entire assembly fit inside the 15-inch annulus of the recuperator core. The support plate maintained the alignment and distance relationship between the focusing lens, the tool, and the workpiece.

The tool's function was to hold the joint in the beam path. The entire laser beam delivery system was mounted in a fixed position to maintain this alignment. The tooling was adjusted to match the curvature of the inner diameter or the outer diameter by changing its location at the end of the support plate. The delivery tube was mounted on the vertical plate, which could be adjusted to the desired joint.

A fixture to hold the plates on the rotary table was designed and fabricated (see Figure 5-29). It is a 1.00-inch thick aluminum jig plate with a 26-inch outer diameter and 14-inch inner diameter, a configuration slightly smaller than recuperator plate. It was mounted on a square stage on top of the rotary table. The square plate allowed the welding head to reach the joints on the bottom of the stack without any interference from the fixturing. Dowel pins were located in several places in the plate provided the reference from the elliptical holes for plate location. An alignment stage, shown in Figure 5-30, was designed to hold a stack of recuperator plates and fixture them with respect to their outside diameter. This would minimize the edge mismatch. The plates were locked in position and then transferred to the rotary table. Another plate, which was similar to the bottom plate, was placed on the stack over the locator pins. It was then bolted to the fixture's bottom plate to achieve the 0.080-inch spacing between the joints. This would minimize the separation between the two plates in the joint and facilitate joint tracking.

This pilot plant system, which included the work station components and welding head, operated using a basic process sequence that could be

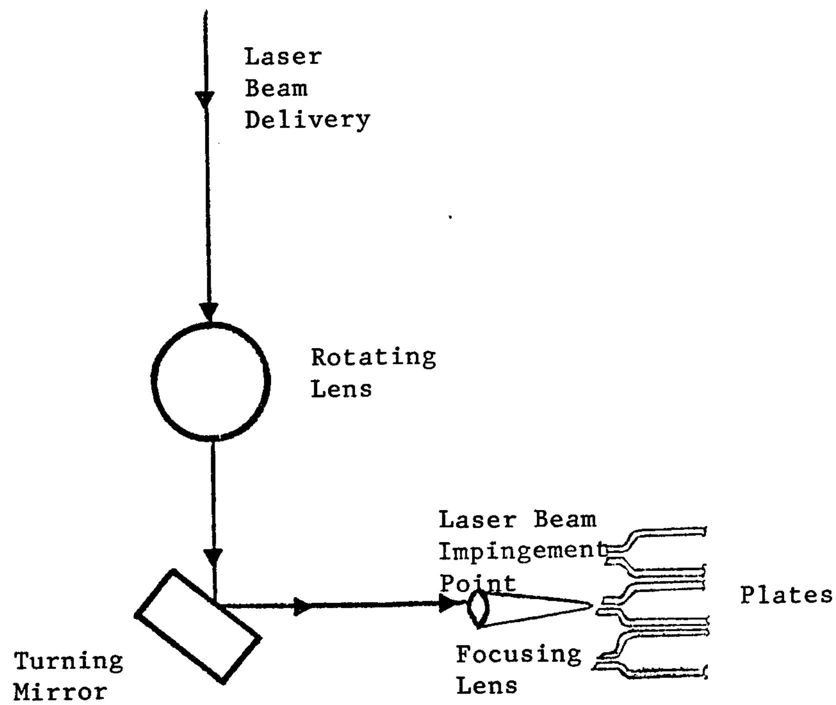


Figure 5-28. Schematic of Laser Beam Path

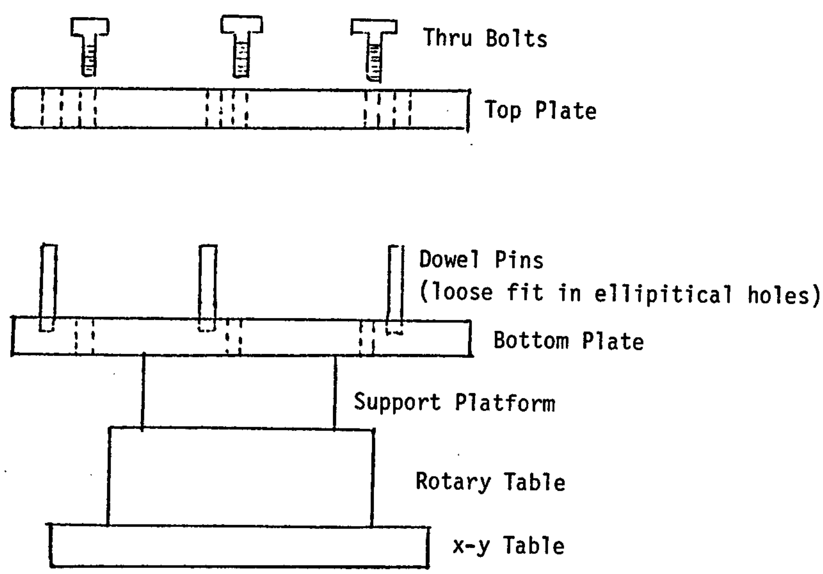


Figure 5-29. Part Fixturing on Work Station

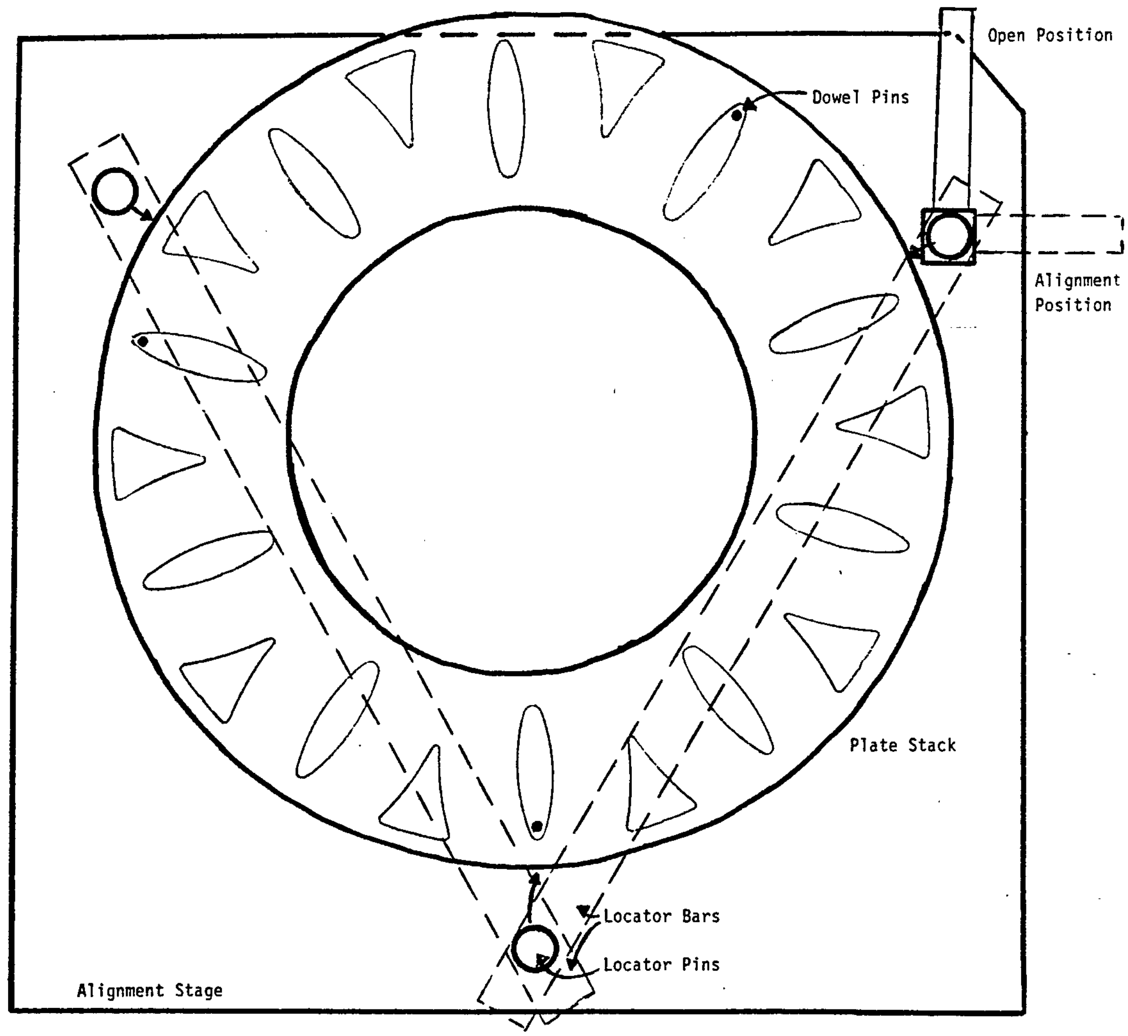


Figure 5-30. Diagram of Alignment Stage

adapted to the future production system. The plate pairs were stacked on the alignment stage to minimize the mismatch in the periphery joints. The small stack of plates was then transferred to the permanent fixture on the rotary table. The top plate was placed on the stack and bolted to the bottom plate of the fixture. The head was positioned on either the inner or outer joint by changing the coordinates of the x-y table. The welding head was manually located on the selected joint location and the tool was adjusted for proper joint tracking. The process parameters such as welding speed, power, pulse length and frequency, and laser beam focus were set manually. The flow of the helium shielding gas was adjusted manually. This process sequence was repeated for each joint, varying the welding parameters until the optimum combination was found.

All testing of the welding head was done on full size recuperator plate pairs. These parts were representative of the type which would have to be welded by a future production system. The evaluation of this experimental work was stated in the project plan, which outlined the specific tasks and acceptance criteria (refer to section 5.4).

5.7.3. Experimental Results. The work focused on testing the proposed welding head design on production recuperator plates and using the results for design modifications or optimizations. Because the design process is iterative, the steps toward the development of a production suitable welding head are described in detail.

The laser welding head tooling must hold the two plate edges together as they pass through the laser beam impingement point. The limited accessibility of the joint being welded is the controlling factor in the tool design. The tool must hold the joint along the 0.100-inch land and fit into the 0.080-inch space between each joint. The tool must adjust to the different curvature of the inner or outer diameters. To achieve optimum laser beam coupling, the tool must maintain intimate sheet contact between the two plate edges to the joint. Difficult conditions such as the curved edges at the outside of the triangular hole (called smiles), separation between the two plates of the joint, heavy burrs, and edge mismatch must be accommodated by the tool. The welding head with this tooling must hold the joint in a constant location with respect to the focal length and focal spot size of the beam. It is imperative that the location variances of the joint were minimized because of their direct effect on the welding parameters and the consistency of the resulting edge weld. As the beam couples into the joint, the tool must hold the plates together until the weld solidifies completely. Because the welding technique developed in the feasibility study required two welding passes, the tool must accommodate the first pass weld bead and hold the joint in position for the second weld pass. The tool must be flexible to accommodate the larger second weld bead, particularly around the start-stop point in the joint's circumference. The tool must be designed to avoid interference with the beam path. This considers the optical characteristics of the lens and the shape of the focusing cone. Other considerations in the tool design are the future integration of a real-time viewing and inspection system, and other accessories associated with a production system.

5.7.3.1. Welding Head Design "A." The original design of the tool was a wheel arrangement consisting of one leading guide wheel and two pairs of grip wheels, as shown in Figure 5-31. The purpose of the leading guide wheel was to align the edges and minimize the separation of the plate edges, particularly in the section where smiles are present. The purpose of the two pairs of grip wheels was to hold the edges in intimate sheet contact. The laser beam impingement point was between the two grip points. The grip wheel concept was similar to the resistance seam welding electrodes currently used in production but it was modified for the laser beam welding process.

The guide wheel, shown in Figure 5-32, was 1.5 inches in diameter and fabricated in two halves. Each half was beveled on the outside diameter forming a 0.100-inch deep V-groove when joined through their center by a sleeve bearing. This should accommodate any edge mismatch. Each wheel half was 0.075-inch thick to fit into the space between the adjacent joints. The guide wheel was attached to the end of a cantilever beam, which was mounted to the end of the support plate. This assembly was located approximately 1.5 inches away from the first pair of grip wheels and was adjusted to match either the inner or outer diameter curvature.

The grip wheels, shown in Figure 5-33, were two (2) inches in diameter and fabricated from mild steel. The axis of the top wheel was plus 45 degrees from the joint and the axis of the bottom wheel was minus 45 degrees from the joint. One wheel entered from the top of the joint and the other entered from the bottom of the joint, thus pinching the joint between them. This allowed 0.090-inch flat surface on the outside diameter to contact and track along the 0.100-inch land of the plate edge. This flat area was inserted into the joint approximately 0.080 to 0.090 inch from the outside edge. Each wheel rotated on a sleeve bearing that was attached to the 45 degree face of a holding block. The top and bottom holding blocks were bolted together to form a gripping pair. Partially threaded bolts with expansion springs were used to apply pressure to the joint. The pressure was adjusted by tightening or loosening the bolts. The bottom holding block had a series of threaded bolt holes for attaching the grip wheel pairs to the support plate. Using these holes, the tool was set to match either the inner or outer diameter curvature.

The intent of this design was for the two pairs of grip wheels to maintain intimate sheet contact for a two-inch section between the grip points. The laser beam would impinge the joint from a horizontal direction and weld the edges as the plates were rotated through the tool. A low pressure was necessary to maintain sheet contact. The pressure applied to the joint should be sufficient to grip the plate edges and allow the wheels to turn as they track around the joint. Also, the pressure applied using the expansion springs was variable so

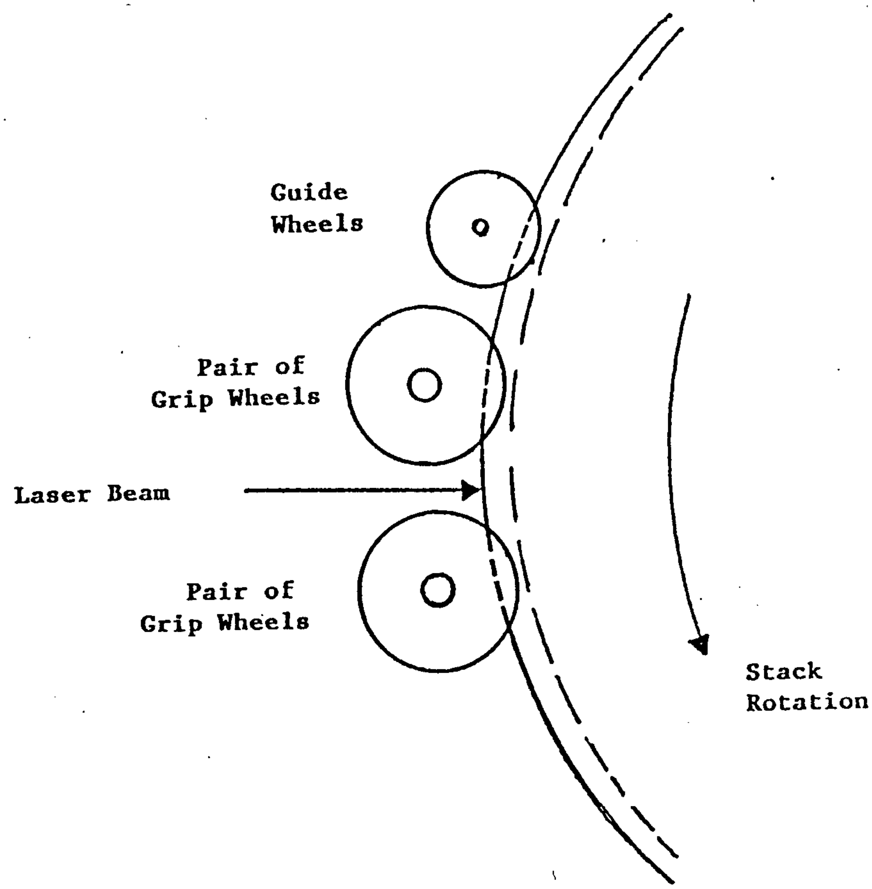


Figure 5-31. Welding Head Design "A"

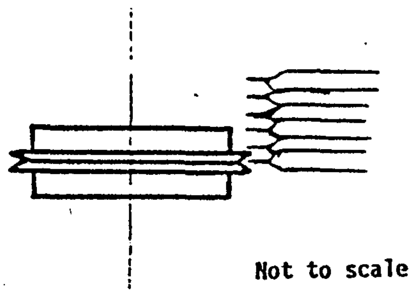


Figure 5-32. Schematic of Guide Wheel

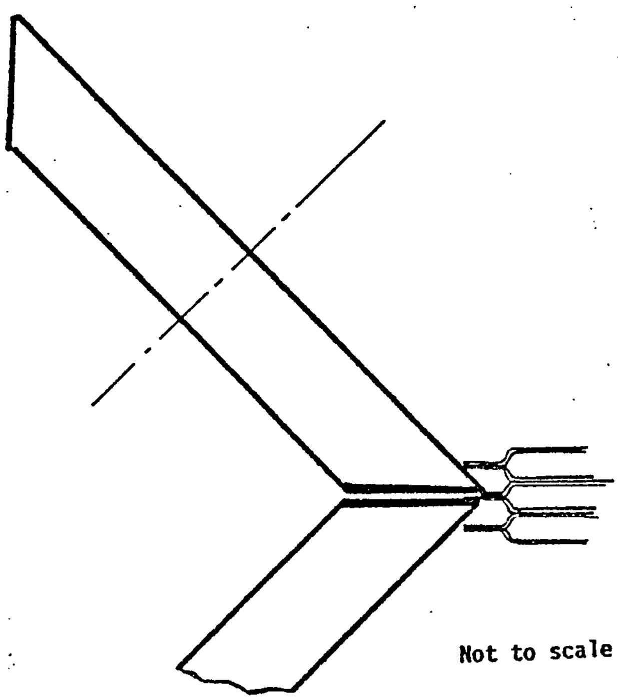


Figure 5-33. Schematic of Grip Wheel

the first-pass weld bead and the start-stop point could be easily accommodated. (The pressure was not a process variable in the laser welding process as it is in the resistance seam welding process.)

Each component of the welding head was fabricated according to the blueprint specifications. These components were assembled and attached to the support plate of the work station. Fine adjustments were made to the wheel's location and alignment using the inner diameter joint of the recuperator plates, which were fixtures on the rotary table. It was very difficult to perfectly align all the wheels because of the tight work space and poor visibility into the 15-inch diameter annulus. The guide wheel, which played a secondary role in the process, was eliminated for simplicity in the initial trials. After evaluation the results of the initial trials, the guide wheel would be added, if necessary.

The first tracking trials were done on the inside joint using the two pairs of grip wheels. The wheel arrangement matched the curvature of the inner diameter. The pressure was applied to the plate edges approximately 0.080 inch into plate land. The stack of plates was rotated through the tool at a linear speed of 50 inches per minute.

The results of these joint tracking trials were unsuccessful. Either one or both pairs of grip wheels skipped to an adjacent joint. That is, the tool jumped the track and fell off the joint. The grip wheels randomly grabbed extra plates, creating a three-ply joint. These problems are similar to the "crashes," which frequently occur in the resistance seam welders. A slower speed was used to determine the causes of the problems. It was very difficult to closely observe the operation or set up an observation system to do so, because the welding head was inside the 15-inch annulus of the recuperator.

The trials were moved to the outer diameter joint because it was easier to view the tool's operation. The two pairs of grip wheels were set up in a manner similar to that used on the inner diameter joint trials except the tool matched the outer diameter curvature. The tracking trials confirmed the observations made on the inner diameter joint trials. The tool skipped plates, cut through the edges of adjacent plates, picked up extra plates unexpectedly, and jumped off the track or land. This problem was found to be caused by the run-out in the stack of plates. Because the plate edges could not be held together properly, welding trials were not attempted until the joint tracking problems were corrected.

The problem of plate run-out, which caused the wheels to jump off the joint, was traced to the stacking method. The plates were stacked on a specially designed alignment fixture which used the outer diameter as the reference dimension. As part of the fixture, loose fitting pins on the outer diameter end of the elliptical hole were used as a rough guide for alignment. Once the stack of 10 to 15 plate pairs was aligned and transferred to the rotary table on the work station, a small amount of slippage occurred between the plate pairs. This movement created an intolerable amount of run-out in the joint.

This problem was corrected by changing the stacking tool to use the radius of the outer diameter end of the elliptical hole as the reference. The existing guide posts were fitted with sleeves having a radius slightly smaller than the radius of the elliptical hole. This modified fixture, shown in Figure 5-34, was permanently mounted on the work station's rotary table. The run-out was minimized to a tolerable limit of less than 0.005 inch, and allowed the grip wheels to track around the joint without jumping off the landing. It also facilitated the stacking and removal of the plate pairs because the transferring of plate pairs between the alignment fixture and the work station was eliminated.

The problem of cutting adjacent plates was caused by the sharp edges on the wheels. The flat area of the wheels, which tracked on the joint, had been machined to a sharp point to maximize the wheel's contact with the joint. This sharp edge got caught on the heavy burrs on the large smiles and cut the adjacent plates. The cutting problem was corrected by grinding a small curvature into the wheel edge to form a blunted edge.

The tracking trials were repeated on the outer diameter joint using the modified tooling. The two pairs of grip wheels tracked all the way around the plate's circumference at a travel speed of 50 inches per minute, without problem.

A microscope with 10x magnification was set up to observe the joint as it moved the through the two pairs of grip wheels. Observation of the interaction between the wheels and the joint was done over a series of joints. The sheet contact was closely observed to determine the optimum point for laser beam impingement. The plates separated in the section between the grip wheels. An accurate observation to determine the extent of this separation in the joint could not be made because a clear view of the joint was not possible between the grip wheels. The separation in the joint had to be negligible or the laser beam would not couple into the joint.

To determine exactly what the wheels were doing, the rear pair was removed. This simplified the tracking operation and a clear view of the entrance to and exit from the grip wheels was possible. The best sheet contact was found in a 0.250-inch section on the exit side of the wheels.

The welding trials were done using one pair of grip wheels. The circularly deflected beam was aimed at the joint approximately 0.200-inch away from the exit side of the pinch point. The welding parameters used for the trials were 900 watts, continuous wave and 100 inches per minute. The circular deflection of the rotating mirror was 2,000 revolutions per minute and 0.008-inch circular deflection.

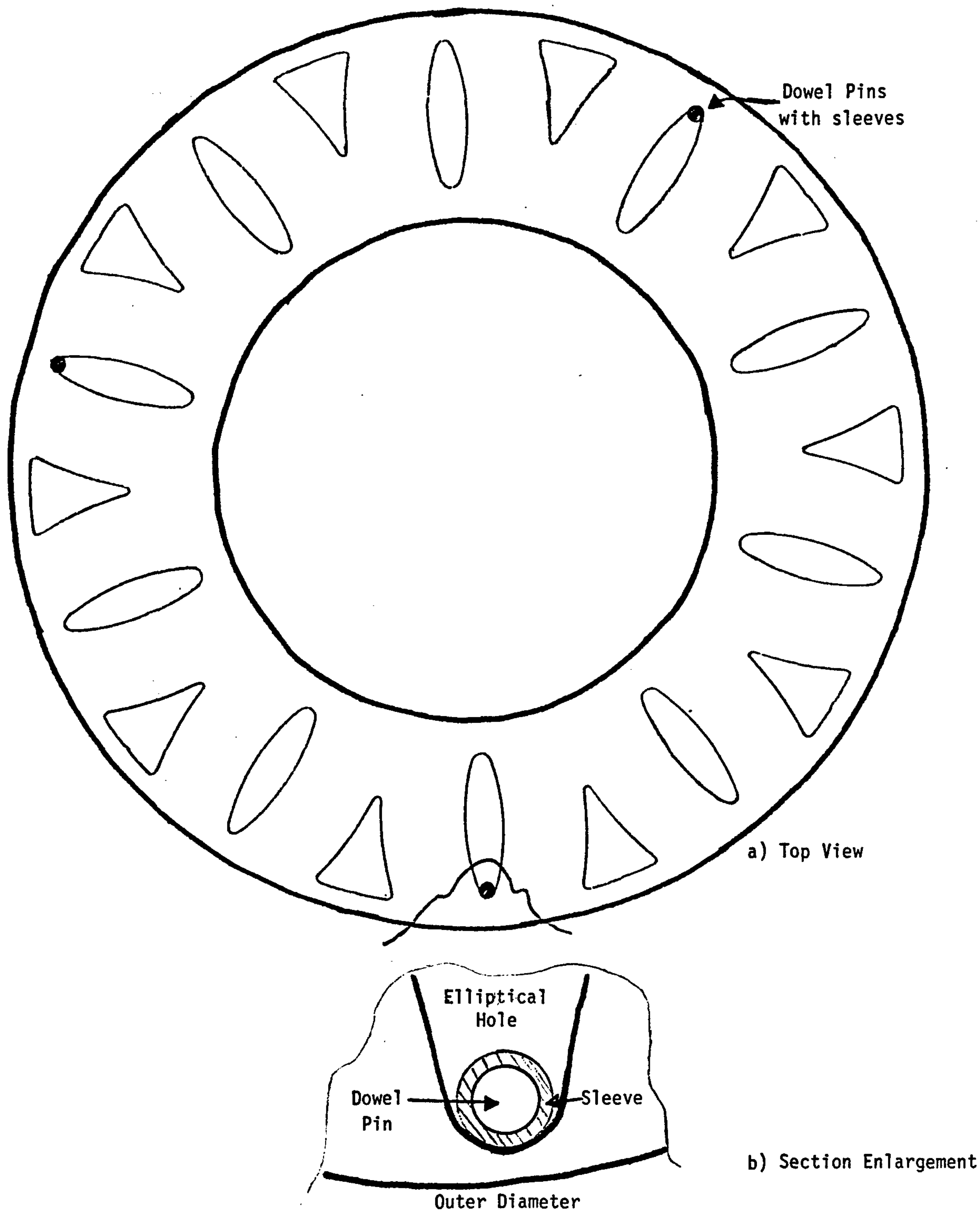


Figure 5-34. New Fixture for Plate Pairs

There was no laser beam coupling into the joint. The problem was traced to a lack of sheet contact at the laser beam impingement point. The heat of the laser beam aggravated the joint separation. The laser beam energy was reflected in an uncontrolled manner and damaged the adjacent plates and cut holes through the convolutions. Where the beam coupled into the joint, the weld contour was irregular and jagged. The weld had many assorted defects including lack of fusion and holes.

The second pair of grip wheels was installed. However, the guide wheel was eliminated from the tool because tracking trials showed it to be unnecessary. The two pairs of grip wheels and the section between the pinch points were observed closely as they tracked around the joint. The point of greatest separation was found at the center of this section. The separation seemed to begin immediately after the joint moved through the pinch point. It was determined that the laser beam impingement point should be as close to the pinch point as possible. The original design, based on the welding point being in the middle of the area between the two pairs of grip was, therefore, disregarded.

The problems with this tool design were analyzed to determine the modifications required in the next design iteration. The major problem was that the tool did not maintain sheet contact at the laser beam impingement point. A design based on a pinch area rather than a pinch point was therefore contrived.

5.7.3.2. Welding Head Design "B." The new welding head design, which was based on the results of the previous trials, consisted of one pair of grip wheels and a guide slide. This tool, shown in Figure 5-35, used a combination of a pinch point and a pinch area to maintain sheet contact at the laser beam impingement point. As the plate edges rotated through the tool, the grip wheels would pinch the plate edges together and the guide slide would support the joint as it exited from the pinch wheels. This additional support would keep the plate edges together during the welding process, including the solidification period. Welding would take place in the 0.250-inch section between the pinch point and the guide slide.

The grip wheels were the same ones used in the original design and trials. Their tracking capability, which was demonstrated in the previous trials, was adequate for this application.

The guide slide, which was shaped like a boot, allowed the plate edges to slide through a 0.020-inch space and be supported for about a 1.0 inch section. It is shown in Figure 5-36. A 0.020-inch shim separated the two halves of the guide slide to accommodate the 0.016-inch joint thickness. This minimized the separation between the plate edges and allowed the laser beam to couple into the joint. The edge thickness of the slide was 0.075 inch to fit into the 0.080-inch space between the joints. The guide slide was mounted on the end of a cantilever beam

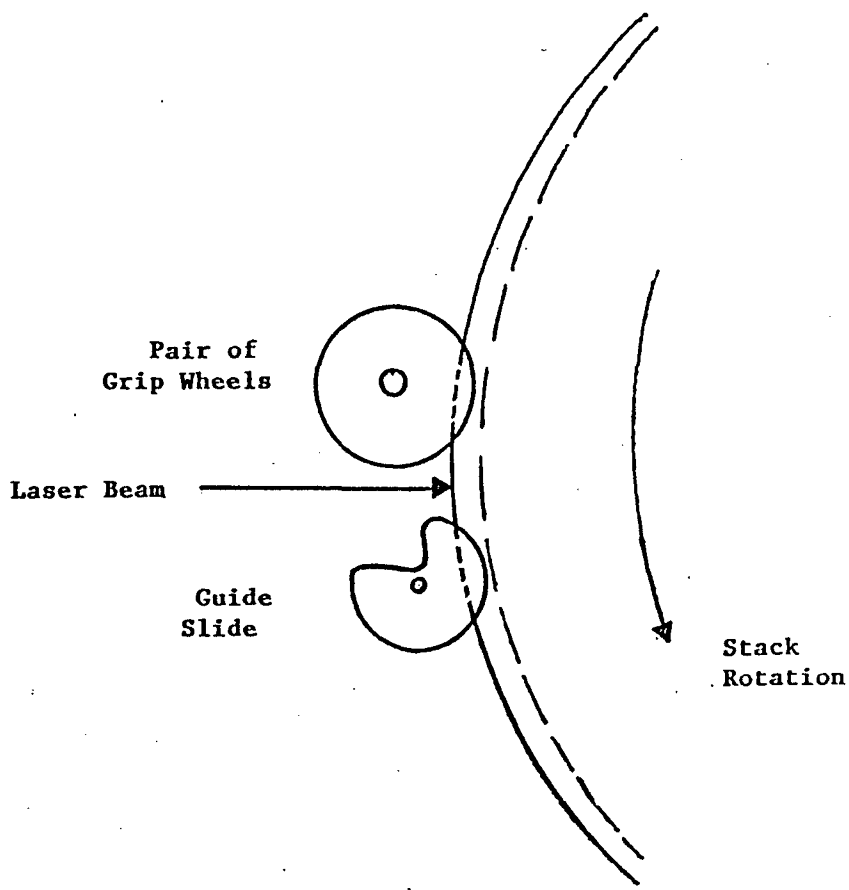


Figure 5-35. Welding Head Design "B"

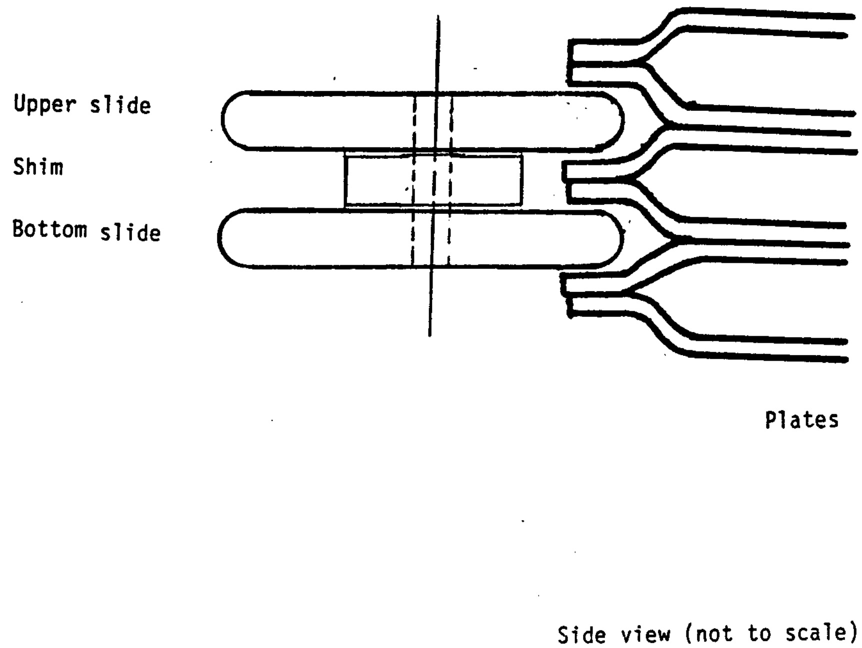


Figure 5-36. Schematic of Guide Slide

which was bolted to the support plate. The edges of the slide were inserted into the joint approximately 0.085 to 0.090 inch over the land.

The tracking trials were done on the outer diameter joint. This tool tracked around the circumference of the joint at 60 inches per minute. The grip wheels jumped off the joint when a heavy burr or very stiff smile was encountered. The guide slide tracked without any problems and did not jump off the joint or grip extra plates.

The welding trials were conducted on the outer diameter joint. The joint separation at the weld point was much less than the previous tool. The circularly deflected beam impinged the joint and produced a very irregular weld. The resulting weld had a large number of defects including holes in the convolutions, pin holes and a saw-toothed weld contour. Using the macroscope for observation, the joint was seen moving in and out of the laser beam impingement spot. The plate edges separated from each other as the heat was applied. The focus of the beam was varied to increase or decrease the spot size, however, separation of the edges still occurred. The parameters, such as power, focus and circular deflections, were varied. An acceptable weld could not be produced. The lack of success was thought to be associated with the edge mismatch, and the laser edge welding process not tolerating any sheet separation.

The next welding trials were done by visually tracking the joint and manually adjusting the turning mirror to follow the variations in the joint passing through the welding head. The welding speed was 20 inches per minute. The welding parameters were similar to those used in the feasibility study. A small section of weld (15 linear inches) was produced. Visual inspection showed that the weld had a smooth bead contour. Several attempts to weld around the circumference of the plate were made, but, an acceptable weld could not be produced. Separation in the joint was the major problem which prevented effective laser beam coupling. This separation, which ranged from 0.005 to 0.020 inch, was greatest in the section on the outer diameter side of the elliptical hole. This separation between the two plates would increase and decrease at this section passed through the welding head. The separation was minimal (less than 0.005 inch) in other sections of the joint. This observation indicated that residual stresses in the plate pairs (i.e., due to forming and welding) accumulated in this section and created an unsatisfactory condition for laser welding.

The major problem with the tool was that it could not consistently maintain intimate sheet contact at the laser beam impingement point. The observations indicated that the pinch point was the only point where sheet contact was guaranteed. The next design would take this in account and redesign the grip wheels in such a way that the plates edges would be exposed while the pressure was applied to the back of the land.

Modifying of the tracking system was necessary to improve the sheet contact in the joint. The lack of sheet contact was thought to be caused by the fixed position tooling, which forced the plate edges through a stationary point. This possibly contributed to the accumulation of residual stress in the joint section discussed above. A floating or counterbalanced z-axis, which would enable the welding head to track the joint variations, would be designed for this purpose.

5.7.3.3. Welding Head Design "C." This welding head design, shown in Figure 5-37, was based on the experimental evidence gained from the two previous designs. The tool consisted of one pair of grip wheels fabricated from a highly reflective material. The basic grip wheel design was modified to expose 0.050 inch of the joint for laser edge welding. A groove was machined in the outside diameter of each wheel in the pair. The 0.040-inch flat section on the outside diameter of the wheels would track and apply pressure to the back portion of the land. Two materials, tungsten and copper, were discussed for wheel fabrication. Copper was selected because it was readily available and would adequately demonstrate the design concept.

The joint tracking trials were done at 60 inches per minute. The installation of the counterbalancing weight system, shown in Figure 3-38, improved the tracking capability of the wheels. The wheels followed the variations in the joint very smoothly, particularly in the outer diameter section of the triangular holes. Also, the separation in the joint was reduced.

The welding trials were done using the parameters developed in the feasibility study. The result was that the plate edges fused to the wheels. The heat of the laser beam, which was required to weld the plate edges, was too high to be readily reflected off the copper wheels. Different parameter combinations were tried to no avail. The excess energy of the laser beam could not be controlled or reflected back into the joint at the laser beam impingement point. This tool design showed no potential as a production suitable method, therefore, edge welding at the pinch point, even with tungsten wheels, was eliminated as a possible design concept.

5.7.3.4. Welding Head Design "D." The design of this welding head, shown in Figure 5-39, was based on the results of the previous trials. This design, which was a printing press concept, attempted to minimize the problems associated with the plate edge burrs, smiles and joint separation. This tool consisted of a pair of burr crusher wheels and two offset wheels. The burr crusher wheels had a 0.125-inch flat section on the wheel's the outside diameter. The burr crusher wheels, which applied high pressure to the plate edges, were fabricated from hardened steel. The wheels were similar to the grip wheels except they were mounted at a 35 degree angle from the horizontal plane of the joint as shown in Figure 5-40. The flat section of the wheels covered the entire 0.100-inch land. The offset wheels produced a 0.070-inch

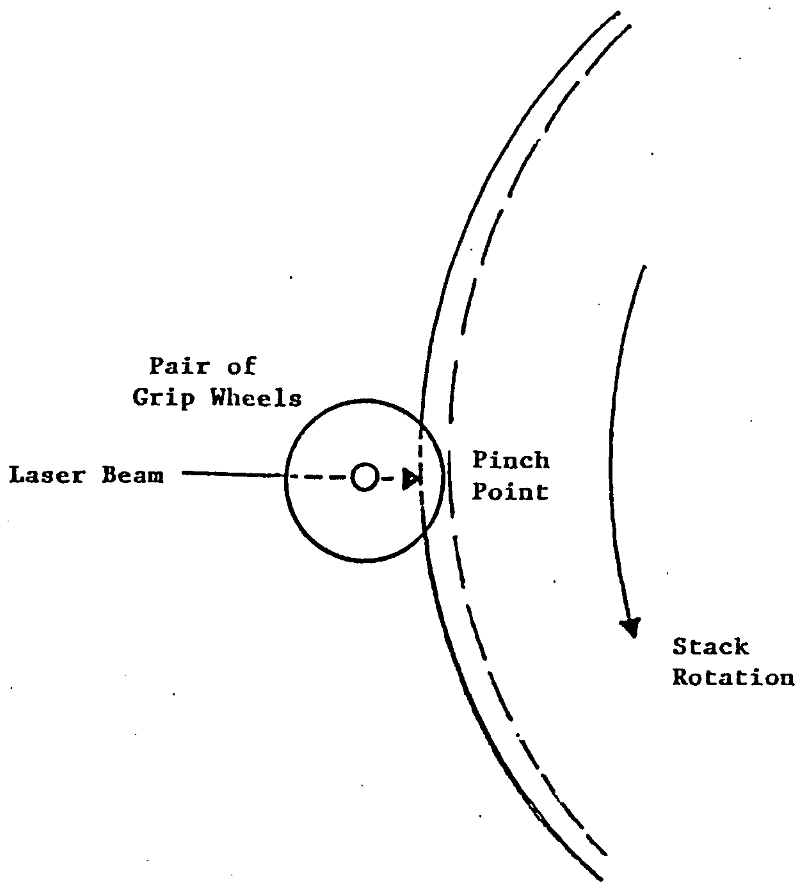


Figure 5-37. Welding Head Design "C"

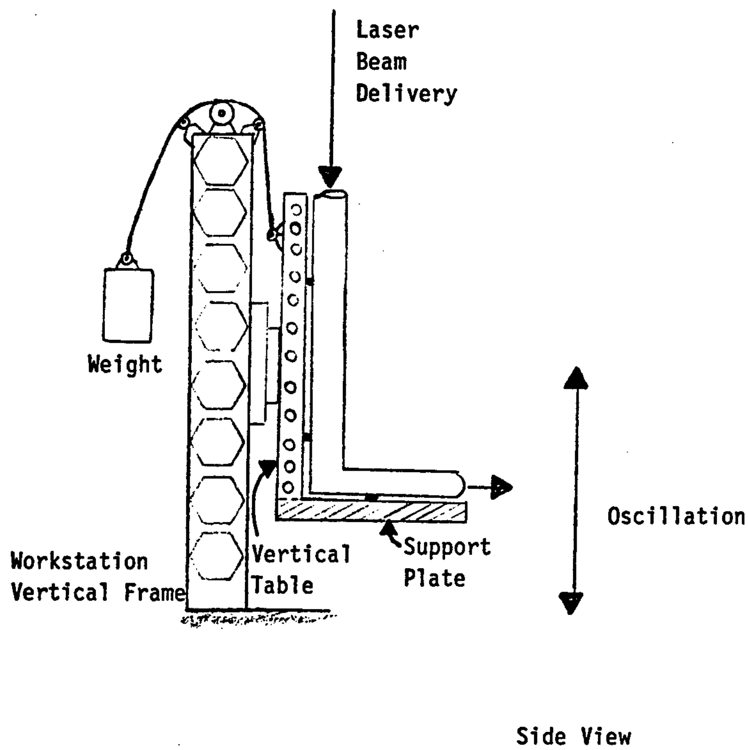


Figure 5-38. Counterbalancing Weight System

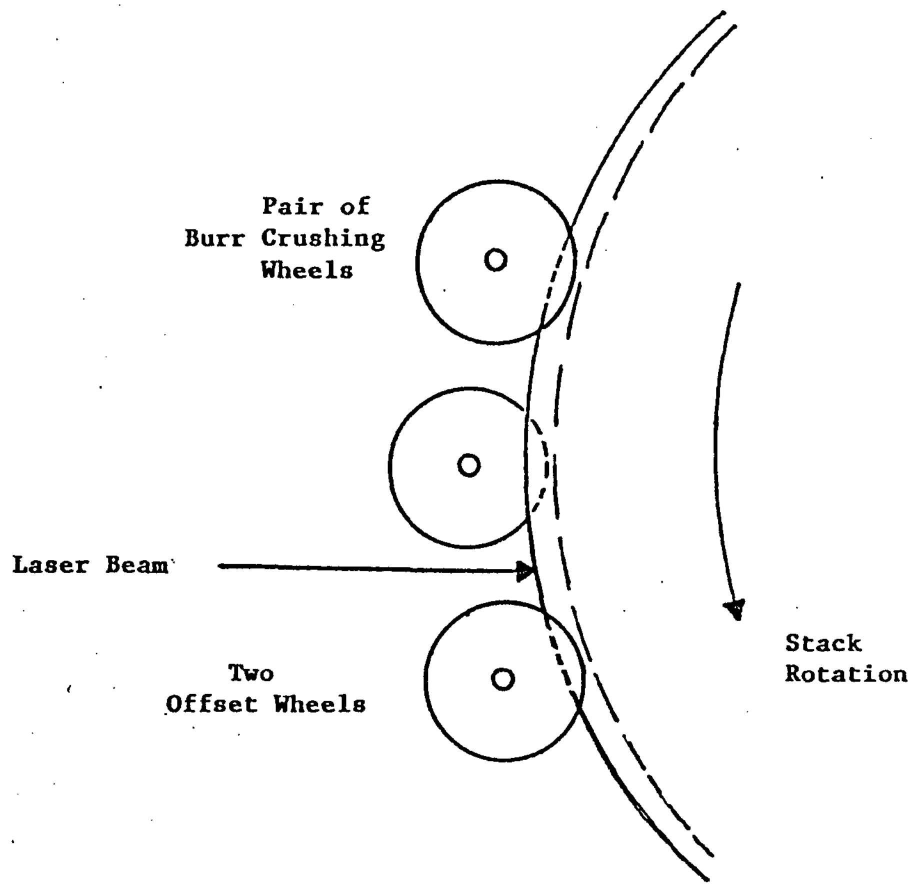
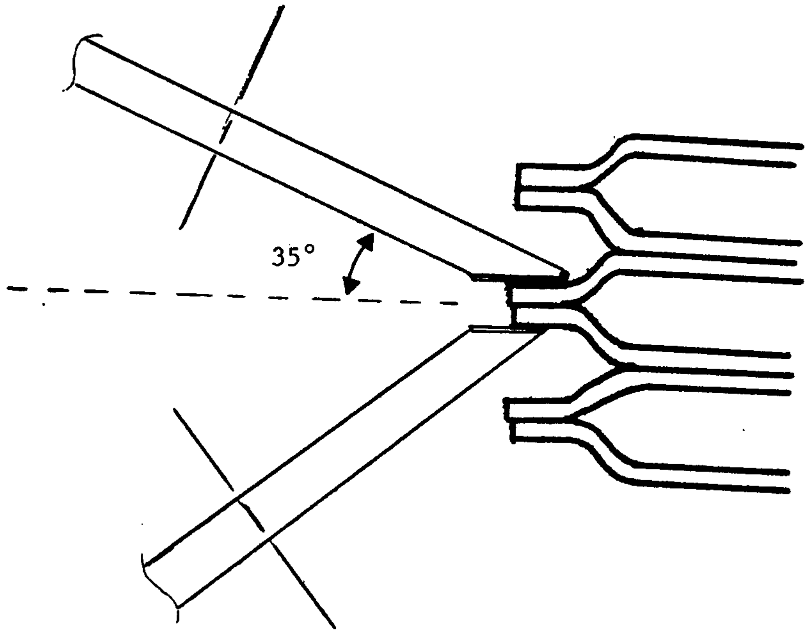
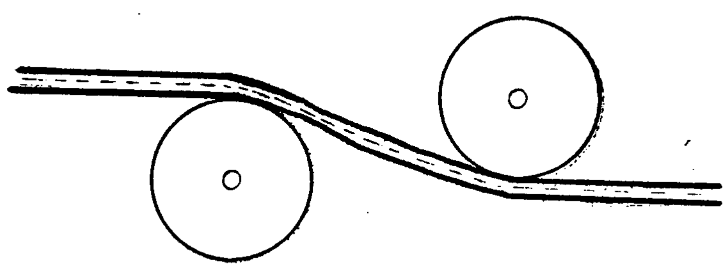


Figure 5-39. Welding Head Design "D"



a) Burr Crushing Wheels



b) Offset Wheels

Figure 5-40. Schematic of Burr Crushing and Offset Wheels deformation in the joint. This occurs in the 1.125-inch section of the joint located between the tangent points of each offset wheel. Ideally, this wheel arrangement would maintain sheet contact between the plate edges while they pass through a constant plane with respect to the laser beam.

The joint tracking trials were done using a minimum travel speed of 60 inches per minute. The burr crusher wheels tracked around the joint and problems similar to those in the previous trials with the grip wheels were found. The burr crushers skipped plates, gripped adjacent plates, and could not accommodate excessive edge mismatch. These wheels did not offer any advantage to successfully welding the inner and outer diameter joint. The offset wheels tracked smoothly around the circumference of the plate. The separation between the plates was approximately 0.000 to 0.0005 inch and was acceptable for laser welding. This tool achieved the most consistent sheet contact at the laser beam impingement point.

The welding trials were done with the offset wheels only. An acceptable weld could not be produced. Various sets of parameters were tried, all yielding the same unacceptable result. The beam cut holes in the convolutions, produced an irregular weld contour and reflected uncontrollably.

Because the sheet contact appeared to be acceptable, the specific reasons for the unacceptable welds had to be determined. The hypothesis at this time was that the parameters were incorrect. The EFA51 laser was being used for these trials instead of the 525 laser used in the original feasibility study. The slightly different mode and power density could account for the problem. To confirm this theory and better understand the variables involved in edge welding, the feasibility study was repeated using the EFA51 laser.

The feasibility study was conducted using the same procedure as the original (Ref. Section 5.3 and 5.6). Because the wheel concept appeared to have a welding speed limitation of 60 inches per minute, a high power one-pass edge weld was also investigated. The pillow test specimens were loaded into the test fixture and the beam impinged the joint from a horizontal direction. The minimum welding speed was 60 inches per minute.

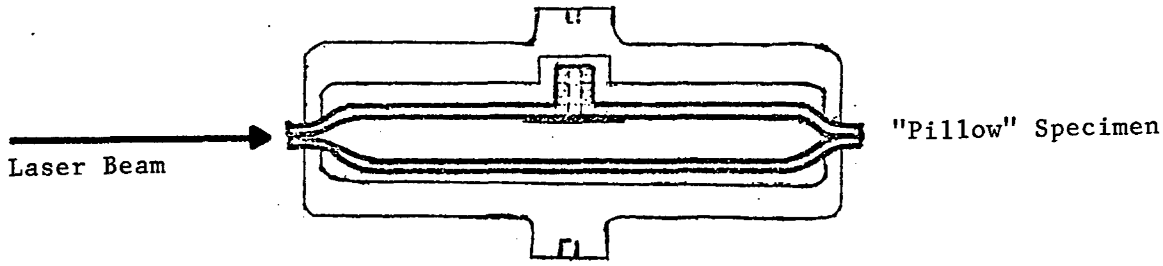
An acceptable weld was produced using the original parameters. The match-thickness head-shaped weld had a penetration of 0.019 inch, meeting the two (2) times the material thickness or 0.016 inch requirements. An acceptable weld was also produced using non-deflected, single-pass technique. This weld was produced using the following parameters; 800 watts, 2 ms pulse length, 250 Hz and the beam was defocused into the work. This technique produced a weld with a penetration of approximately 0.019 inch. These parameters would be used on the full size plates with the offset wheel tooling.

Using this information, welding trials with the two offset wheels were continued on the full size recuperator plates. These parameters and all reasonable variations of the parameters were tried and an acceptable weld could not be produced. The size of the beam spot was also varied by changing the sharpness of the beam focus and no acceptable welds could be produced. The laser beam cut holes in the convolutions reflected uncontrollably to adjacent plates and overheated the waffled area of the plates approximately three inches in from the outer diameter. If the laser beam coupled into the joint, the weld produced had a saw-toothed bead contour. The results of these trials indicated that the technique developed in the feasibility could not be transferred to full size recuperator plates.

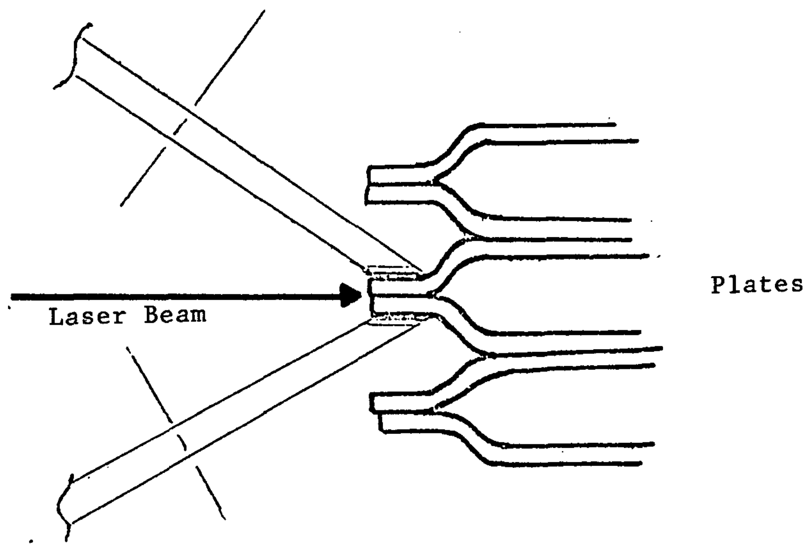
5.7.3.5. Reevaluation of the Edge Welding Technique. After extensive testing and observation on both pillow test specimens and full size recuperator plates, the problems with the welding head tooling were pinpointed. It was determined that the plate edges were not being held in a constant plane with respect to the laser beam. The plate edges wandered in and out of the laser beam spot as they passed through the tooling. Also, the inherent characteristics of the pillow specimen tooling and the welding head tooling were quite different. This comparison of the two tools provided the necessary insight to understand the edge welding technique and the reasons acceptable edge welds could not be produced on full size recuperator plates.

The pillow specimen tool or fixture applied uniform clamping pressure to the back portion of the land. The plate edges were exposed approximately 0.050 inch for laser welding, as shown in Figure 5-41. This tool rotated the plate edges in front of the laser beam. The laser beam delivery apparatus was independent from the tool and there was no relative variation between the joint and the beam spot. The joint and the tool did not move relative to each other. Therefore, once the beam was aligned with the joint, it became a constant in the welding process. Because the tool covered the convolution, it protected the convolution from the excess heat from the reflected laser beam. It also functioned like a heat sink by supporting the weld solidification process as the material melted back to the tool's wall.

The welding head tooling could not duplicate this condition on full size recuperator plates as shown in Figure 5-42. Because the tooling and laser beam delivery apparatus were both mounted on the support plate, adjustments for the variations in location of the plate edges could not be made. Because the convolutions were not protected by the tool, the excess energy overheated the plates, cut holes through the convolutions and produced a very inconsistent weld bead. Also, the separation in the joint was aggravated by the heat of the laser beam. This did not occur with the pillow specimen because the tool maintained a uniform pressure on the entire circumference of the joint. The wheel approach could not



a) "Pillow" Specimen Tool



b) Prototype Tool

Figure 5-41. "Pillow" Specimen Tool and Prototype Tool

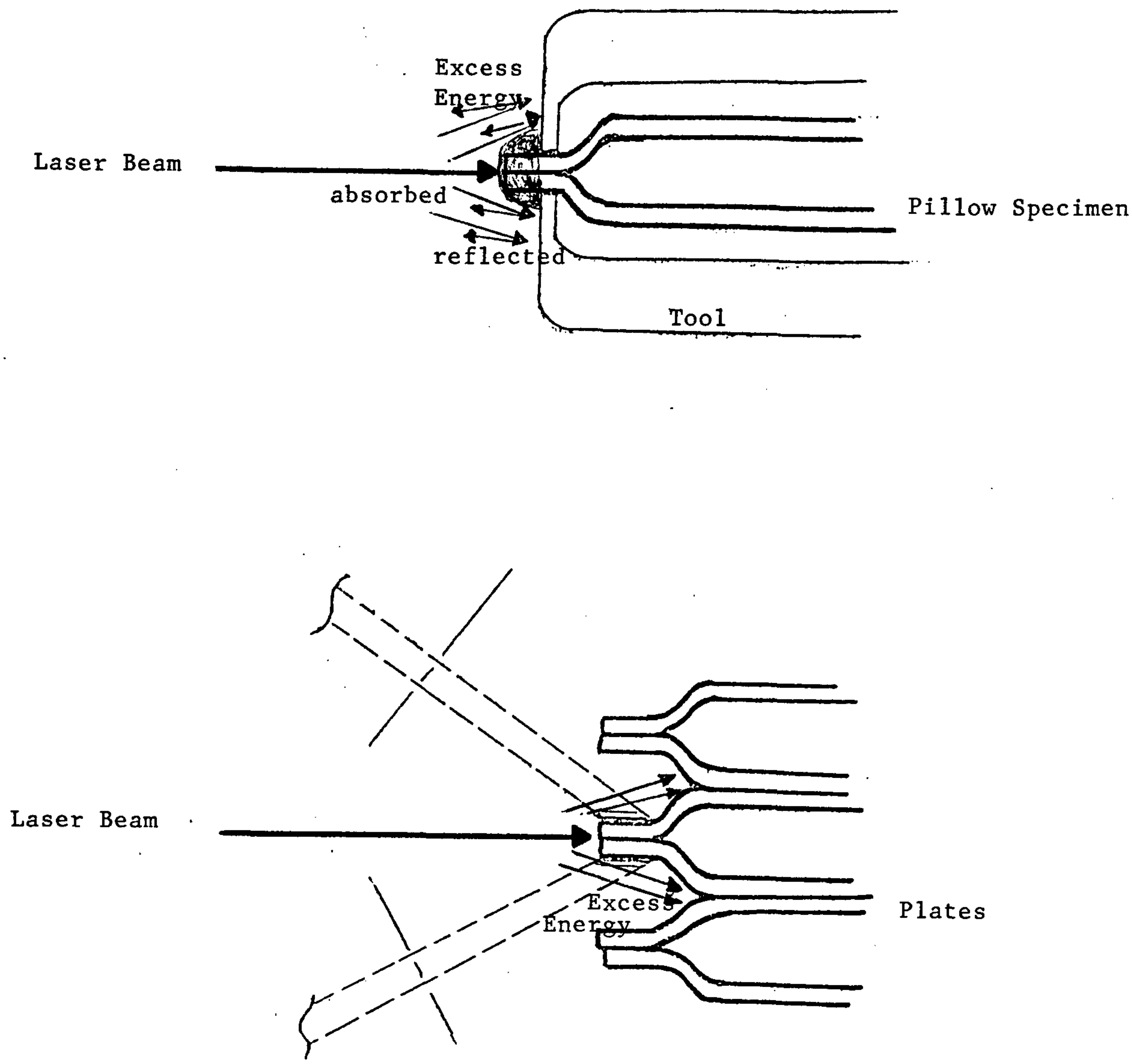


Figure 5-42. Comparison of "Pillow" Specimen Tool and Prototype Tool

be modified to correct or eliminate these problems. The design limitations imposed by the configuration of the recuperator eliminated any other tooling concepts for edge welding the recuperator.

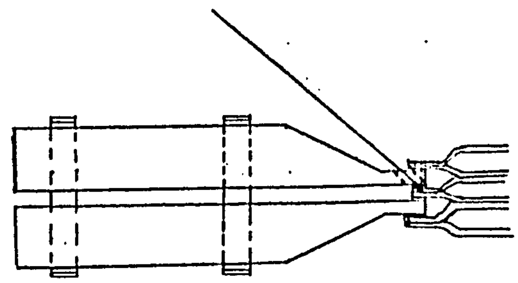
Alternative welding techniques and tool designs were discussed using the previous experimental evidence as a basis for evaluation. The lap weld technique was the alternative which had the most potential for adaptation to a production system. The lap weld would be placed in the center of the joint land. The configuration of the recuperator required the laser beam to impinge the joint at a maximum angle of 45 degrees. A steeper impingement angle would hit or be clipped by the adjacent joint. A laser beam, which impinged the joint at an angle less than 45 degrees, would lose a significant amount of coupling energy from surface reflectivity. The tool design for this lap weld should incorporate a pinch area rather than the pinch point. This should maintain wheel contact and support the joint during welding. Also, the floating z-axis should be incorporated into the tool design for more consistent joint tracking.

If adapted, the lap weld concept had many advantages. It is the same type of weld used to join the elliptical and triangular holes. The lap weld is a full penetration weld, which can be visually inspected. The same laser (S-48) used to weld the plate pair holes, can be used for the inner and outer diameter joints. This would simplify the task of training operators and maintenance personnel. Also, the spare parts inventory for the laser systems would be reduced.

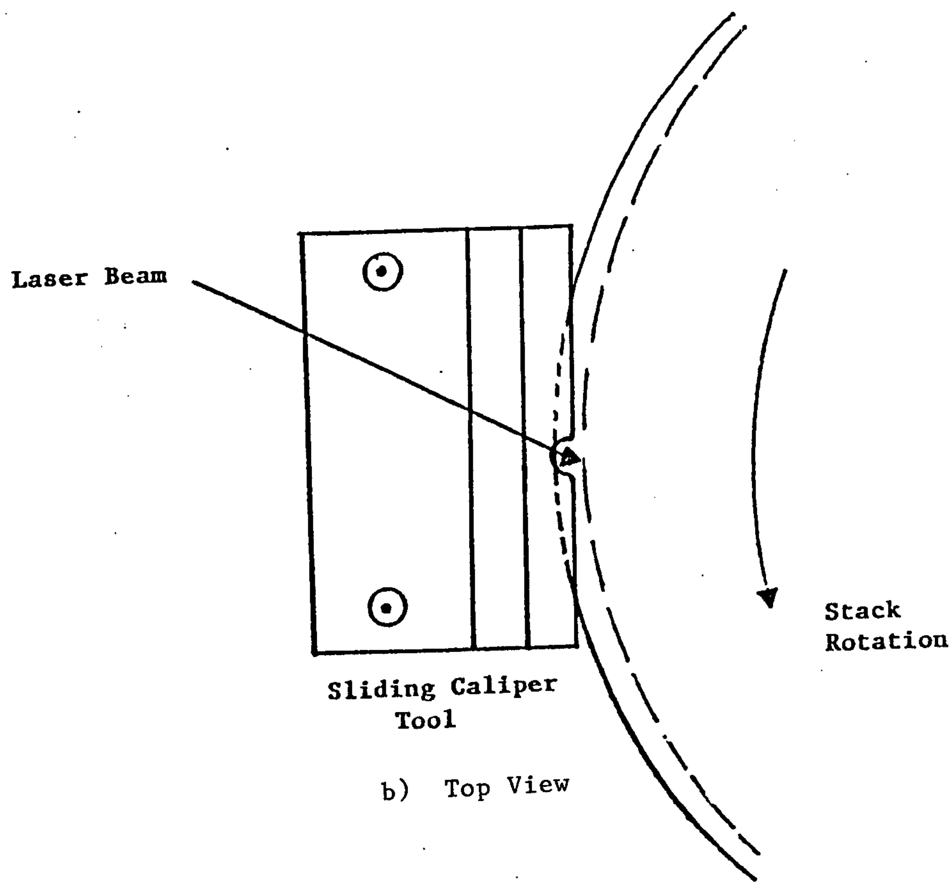
5.7.3.5. Welding Head Design "E." The sliding caliper tool, as shown in Figure 5-43, was designed to meet the requirements of the lap weld approach. The fingers of the caliper tool were inserted in the space between the joints to achieve the sheet contact necessary for laser welding. The fingers of the caliper tool were 0.075 inch thick. The tool was made from mild steel held together by partially threaded bolts and expansion springs. The pressure exerted on the joint by the caliper fingers was regulated by adjusting the force of the expansion springs. The top half of the tool had a 0.100 inch by 0.125 inch cut out in the fingers to expose the joint for the laser beam impingement. This was possible because the diameter of a focused beam was approximately 0.007 inch. The shielding gas was delivered to both sides of the joint through a channel inside the tool.

The joint tracking trials were done at a minimum linear speed of 60 inches per minute. The tool tracked the entire joint without problems. Even at 100 inches per minute, the tool did not bind on burrs or jump off the land. After several times around the circumference, the abrasion wear on the mild steel tool was minimal.

The EFA 51 laser was used for the welding trials because it was readily available. This laser would adequately demonstrate the feasibility of the lap welding concept. If this work produced acceptable welds, the trials would be repeated using an S-48 laser, which is currently used in



a) Side View



b) Top View

Figure 5-43. Welding Head Design "E"

the hole welding systems. The first trials were done using parameters which produced a full penetration weld. The selected parameters were 150 watts, 1.5 millisecond pulse length, 70 Hertz frequency at 30 inches per minute. The test pack of five inner and five outer diameter joints were welded using these parameters. The tool operated smoothly and maintained the sheet contact necessary for effective laser beam coupling. The wear on the tool was minimal and the black chromium oxide did not adversely affect the tool's tracking capability.

The microsections of the weld shown in Figure 5-44, were similar to the plate pair welds. However, the weld was not consistent around the entire joint. Intermittent defects such as stitching, pin holes and burn through were found during the visual inspection. Although the sliding caliper tool showed potential as a production suitable design, the welding speed of 30 inches per minute had to be improved.

The sliding caliper tool caliper would be modified to enhance its production suitability, particularly the welding speed. The parameters would be optimized on the S-48 laser. The evaluation of the welding head would be done according to the criteria outlined in the project plan.

5.7.3.7. Welding Head Design "F." The design of the new sliding caliper tool, shown in Figure 5-45, was based on the results of the trials conducted with the first sliding caliper welding head. The improved tool consisted of the main body and the removable inserts. The inserts were fabricated from oil quenched hardenable steel for abrasion resistance. Two different pairs of inserts were designed to match the curvature of the inner and outer diameter, respectively. The edges of the inserts were rounded for smooth tracking over burrs and dents in the plate edges. The top insert, shown in Figure 5-46, had a 0.125 inch by 0.250 inch cut out to expose the joint for laser welding. A relief groove was cut into the interior of the insert to avoid interference with the weld bead. The inserts were attached to the main body by bolts countersunk in the interior surface.

The main body of the tool was fabricated in two halves. It was made from mild steel, which was inexpensive and readily available. The two halves of the tool were held together by two partially threaded bolts and expansion springs.

The pressure exerted on the joint by the inserts was controlled by adjusting the force on the expansion springs. The shielding gas was delivered to the weld through a channel in the upper half and another in the lower half of the tool.

The main body of the tool was also water cooled in a manner similar to laser turning mirrors and lenses. This was done to prevent overheating and possible distortion in the thinner sections. The tool was mounted on the support plate to maintain the location of the inserts. The

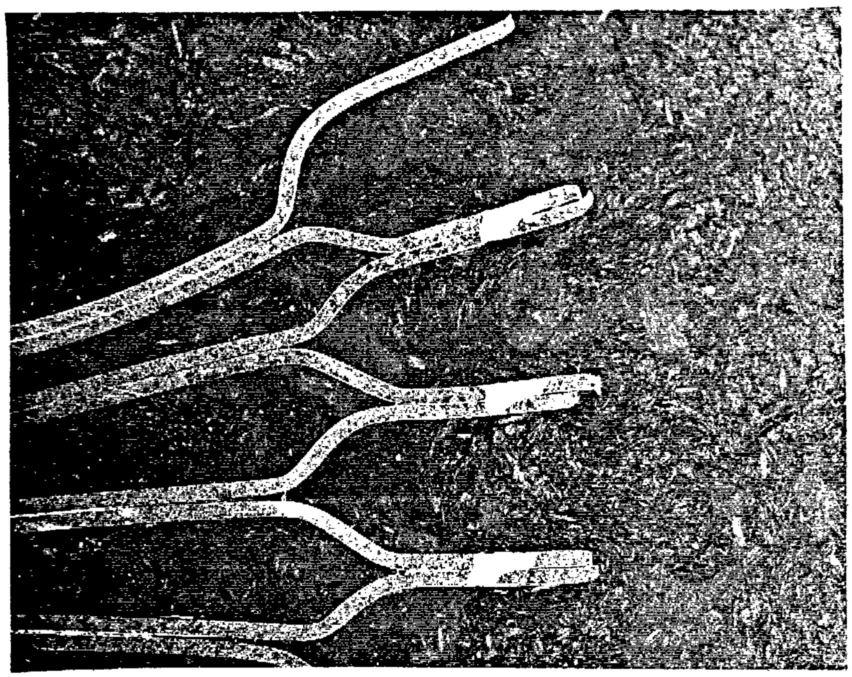
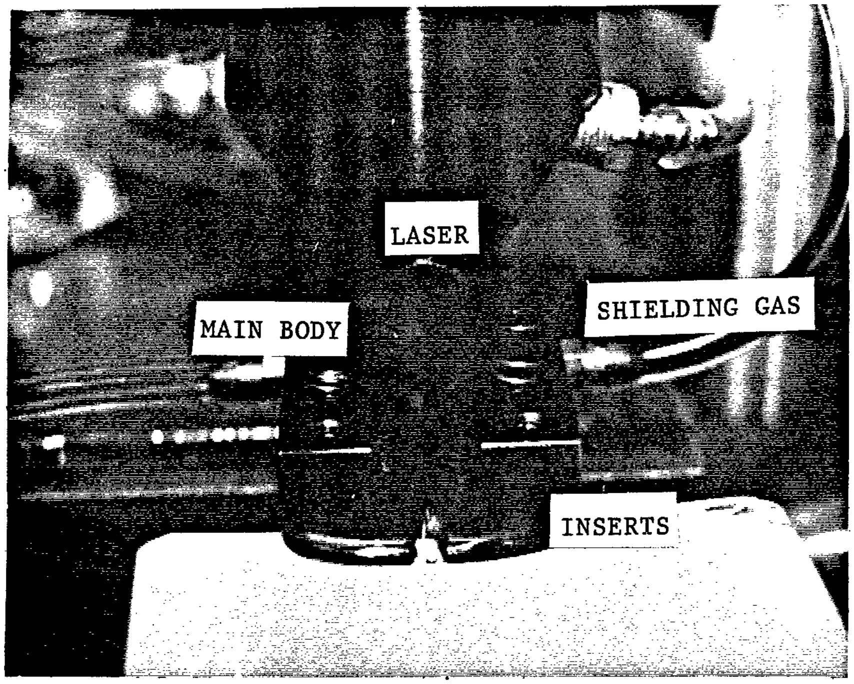


Figure 5-44. Cross Section of Lap Weld



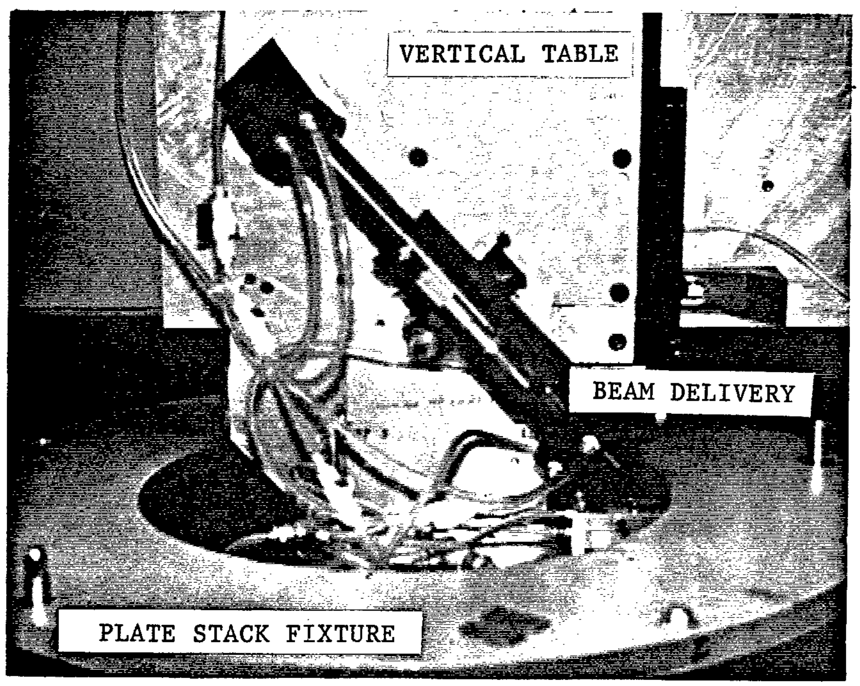
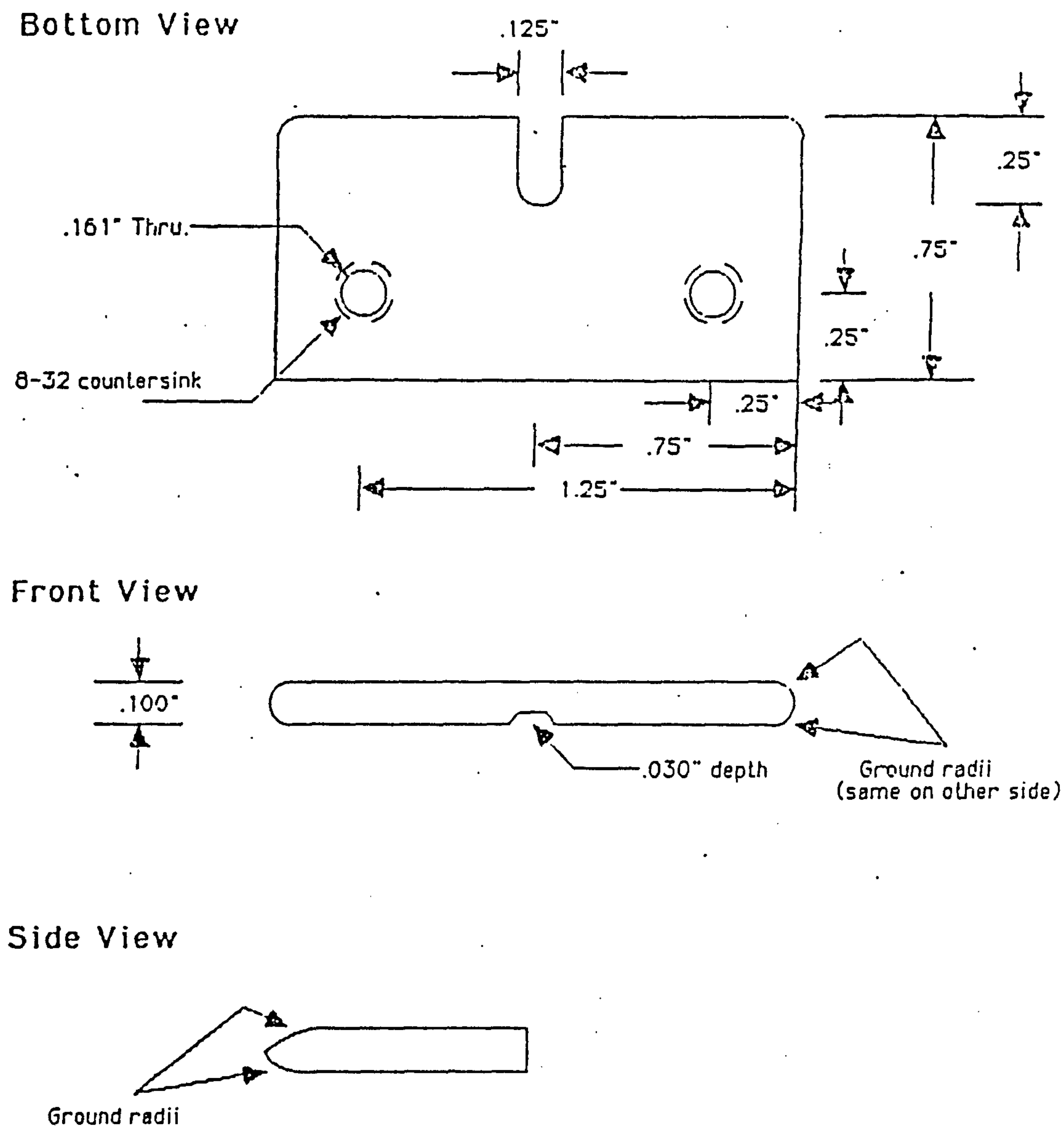
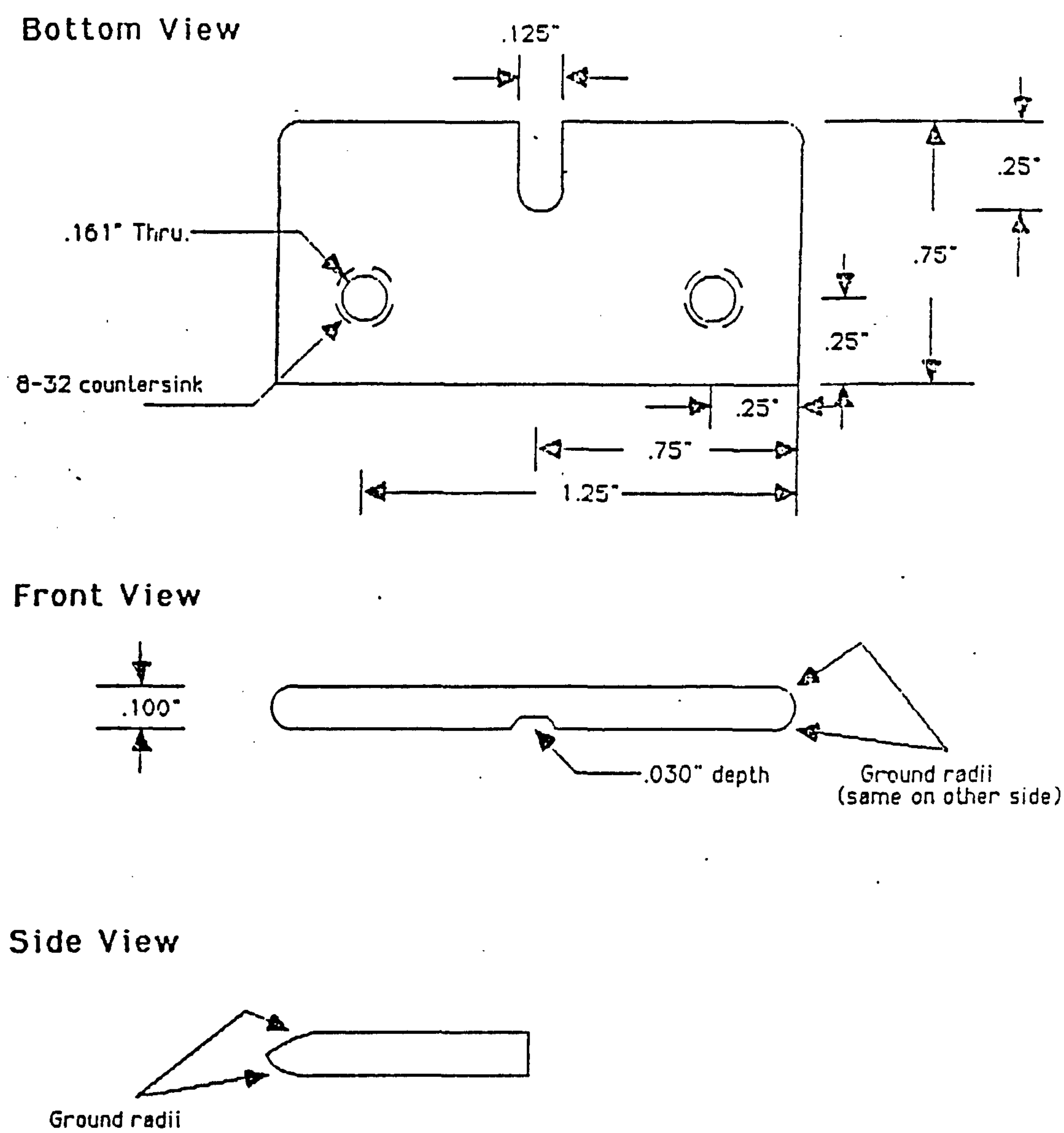


Figure 5-45. Welding Head Design "F"



a) I.D. Sliding Caliper Tool Inserts

Figure 5-46. Inserts for Sliding Caliper Tool



b) O.D. Sliding Caliper Tool Inserts

Figure 5-46. Inserts for Sliding Caliper Tool (Continued) entire welding head moved on a counterbalanced weight system to adjust to the variations in the plate edges.

The welding technique used in conjunction with the caliper tool was a single-pass lap weld. This weld was the same type used to join plate pairs around the triangular and elliptical holes. An S-48 laser was selected for this application because it was common with the laser used in the hole welding machines and it had the proper power range, mode and option of continuous wave or pulsed operation. A 3.75-inch focal length lens was selected because it delivered a medium range of power density and was located far enough from the work to avoid contamination. The laser beam impinged the joint from a 45 degree angle. This was the steepest angle possible to avoid clipping of the beam by the adjacent plates. The inserts were designed to slide over the joint while covering approximately 0.090 inch of the plate edge. This located the weld approximately in the center of the 0.100-inch joint.

The lap weld was evaluated to the established quality standards for the hole welds. The weld was required to have complete penetration and to be defect-free, i.e., no pinholes, stitching, or severe undercut. The size of the weld, which was determined by cross section examination, was required to be equal to or greater than that of the hole weld. An acceptable laser weld had to be produced at a minimum welding speed of 60 inches per minute to be a cost effective alternative to resistance welding.

The trials with the new welding head were done under conditions very similar to the actual production environment. The method of fixturing the plates currently used in production was duplicated. A one-inch thick aluminum jig plate was used to cover the entire stack. The stack was compressed by bolting this top plate to the end plate, which was fixed on the rotary table. This achieved the required 0.080-inch spacing between the plates. The plates and the rotary table were located on the x-y table and were moved to either the inner or the outer diameter position for welding trials.

The tracking trials were done at speeds ranging from a minimum of 60 inches per minute to 100 inches per minute. The new tool tracked the joint very smoothly on both the inside and outside diameters. It did not jump off the joint or pick up adjacent plates. The performance of the tool did not degrade as the travel speed was increased. The floating z-axis tracked the joint variations without any detectable problems.

Because the original caliper tool welded the five plate pair stack at a speed of 30 inches per minute, this speed was selected as a starting point for trials with the new tool. The parameters used in the trials were as follows: 150 watts, 1.5 millisecond pulse length, 70 Hertz frequency, 375-inch focal length lens, and 30 inches per minute. At this speed, good welds were produced on both the inner and outer diameter joints. The welds met the penetration and metallurgical requirements. The tool functioned properly at this speed and maintained the sheet contact between the plates. However, 30 inches per minute was not a production suitable welding speed because the resistance welding machines ran at 50 inches per minute. Improvements in the welding speed were necessary to meet the production suitability criteria stated in the project plan.

Optimization of the parameters using 3.75-inch focal length lens and a travel speed of 75 inches per minute was attempted (see Table 5-2). This travel speed was 15 inches per minute faster than the minimum requirement of 60 inches per minute. The power, pulse length, and frequency were varied and the resulting welds were visually inspected. Acceptable welds could not be produced. The high power, which was required for full penetration, reflected uncontrollably. This excess power damaged the convolutions and adjacent plates. If the power was reduced, full penetration was not achieved.

The welding speed was reduced to 60 inches per minute and the trials were continued. Continuous wave mode was tried at 350, 500 and 650 watts with a 3.75-inch focal length lens. The result was a lack of coupling into the joint due to the uncontrolled reflection of the beam. The high peak power of the pulsed mode was essential to initiating the weld.

The welding speed of 60 inches per minute and the pulsed mode laser were used in the next trials (see Table 5-3). The results were similar to the first set of trials at 75 inches per minute. The high power produced excessive weld spatter, severe undercut, holes and other defects. At the lower power setting below 325 watts, full penetration was not achieved. Also, a variation on the power versus pulse length was tried (see Table 5-4) and the results were similar to those observed in the previous trails using the continuous wave mode. The high power and long pulse length parameter produced uncontrolled reflection and inconsistent coupling into the joint. This indicated that the peak power achieved with the longer pulse length was not adequate for this application.

The results of these trials indicated that a high power and a short pulse, which produced a high peak pulse power, were necessary. Based on previous laser welding experience, a 5-inch focal length lens was selected for these power settings so full penetration could be achieved. The lower power density produced by this lens would reduce the weld spatter at the higher power setting. The parameter selection for the trials using a 5-inch focal length lens was based on the results of the previous trials. The parameters were based on a power setting between 300 and 325 watts and short pulse length of approximately 1.0 millisecond. The welds produced were unacceptable. The problems were the same as in the previous trials. Also, some reflection was observed. This indicated that all the output power was not being used to couple into the joint. Therefore, incomplete penetration occurred. No combination

TABLE 5-2. TEST PARAMETERS
TEST PARAMETERS

O.D. WELD PARAMETER TEST
3.75 INCH FOCAL LENGTH LENS
WELDING SPEED - 75 INCHES PER MINUTE

POWER (WATTS)	PULSE LENGTH (MILLISECOND)	FREQUENCY (HERTZ)	COMMENTS
250	1.0	200	Back - no full penetration top - smooth
300	1.0	200	Back - no full penetration top - smooth
350	1.0	200	Back - no full penetration top - some undercut; fairly smooth
350	1.0	150	Back - 90% full penetration top - undercut, spatter during weld
300	1.0	150	Back - scattered penetration top - undercut spatter during weld
250	1.0	150	Back - no full penetration top - fairly smooth

TABLE 5-3. TEST PARAMETERS

O.D. WELD PARAMETER TEST
3.75 INCH FOCAL LENGTH LENS
WELDING SPEED - 60 INCHES PER MINUTE

(A)

POWER (WATTS)	PULSE LENGTH (MILLISECOND)	FREQUENCY (HERTZ)	COMMENTS
250	1.0	150	No full penetration
300	1.0	150	Scattered penetration
300	1.5	150	No weld
350	1.5	150	No weld
300	1.0	150	No weld
350	1.0	150	Full penetration, lots of spatter
325	1.0	150	No full penetration, heat affected zone visible
300	1.5	200	No weld
(B)			
300	3.0	150	No coupling
450	3.0	150	No weld
400	2.0	150	No full penetration

TABLE 5-4. TEST PARAMETERS

O.D. WELD PARAMETER TEST
5 INCH FOCAL LENGTH LENS
WELDING SPEED - 60 INCHES PER MINUTE

POWER (WATTS)	PULSE LENGTH (MILLISECOND)	FREQUENCY (HERTZ)	COMMENTS
300	1.25	150	No penetration
325	1.25	160	Spatter, stitching
325	1.25	200	Reflection
325	1.67	150	Reflection

of parameters was found which would couple into the joint, establish the keyhole weld, and then maintain it around the joint.

A 2.5-inch focal length lens was tried because it produced a higher power density to the joint (see Table 5-5). This higher power density would initiate the weld at a lower power level and would maintain it around the joint. The tool required minor modification to the top insert. The semicircular cutout was increased to accommodate the broader focal cone of the 2.5-inch focal length lens.

Good welds were produced on the inner diameter joint using the following parameters: 250 watts, 1.75 millisecond pulse length, and 150 Hertz frequency at 60 inches per minute. Acceptable welds could not be produced on the outer diameter. This was attributed to the variations in stiffness and heat sink characteristics between the inner and outer diameter configurations. The inner diameter joint has a constant stiffness around the entire circumference and does not flex in any particular locations. The outer diameter joint showed a significant amount of vertical variation between the end of the elliptical holes and the base of the triangular holes. Numerous parameter combinations were tried on the outer diameter joint and no combination produced an acceptable weld.

Acceptable welds were not produced because no parameter combination could be developed to overcome the problems associated with the 45 degree impingement angle of the laser beam. A significant amount of the power was reflected and this reduced the amount of power available for weld initiation. In laser welding, once the weld is initiated, the reflectivity of the material is drastically reduced as the molten weld puddle forms. The high power needed to initiate the weld is too much to properly maintain a smooth, full penetration weld. The excess energy caused the severe undercut, holes and other defects found in the resulting welds.

At this time, laser technology does not exist to overcome this problem. The power density was the primary reason for the inability to develop optimum parameters. It could be changed by changing the focal length of the lens. However, it could not be varied between the initiation of the weld and the continuation of the weld around the circumference of the plate. This problem was not solvable using the present generation of laser, but, the next generation of laser with higher power density capability could provide the optimum welding parameters for this application.

TABLE 5-5. TEST PARAMETERS

O.D. WELD PARAMETER TEST
2.5 INCH FOCAL LENGTH LENS
WELDING SPEED - 60 INCHES PER MINUTE

POWER (WATTS)	PULSE LENGTH (MILLISECOND)	FREQUENCY (HERTZ)	COMMENTS
325	1.25	150	Excessive spattering
200	2.0	150	Spattering
225	1.75	150	Smooth weld, full penetration
170	2.0	150	No full penetration, some undercut
210	2.5	150	Same as above
180	2.1	150	Same as above
195	2.25	150	Same as above

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SELECTED BIBLIOGRAPHY

Coherent, Inc. Engineering Staff, Lasers, Operation, Equipment, Application and Design. New York, NY: McGraw-Hill Book Company (1980)

Miller, Jule A., From Idea to Profit. The Management of Advanced Manufacturing Technology, New York, NY: Van Nostrand Reinhold Company (1986)

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