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LLNL/YMP WASTE CONTAINER FABRICATION AND CLOSURE PROJECT

GFY 89 TECHNICAL ACTIVITY SUMMARY

OCTOBER 1990

LLNL CONTRACT NO. 9172105

B&W CONTRACT NO. CRD 1179

INTRODUCTION

The Department of Energy's Office of Civilian Radioactive Waste Management (OCRWM) Program is studying Yucca Mountain, Nevada as a suitable site for the first U.S. high-level nuclear waste repository. Lawrence Livermore National Laboratory (LLNL) has the responsibility for designing and developing the waste package for the permanent storage of high-level nuclear waste. To develop a design for the package, LLNL has activities underway in several interrelated areas: the package environment; the container structural materials; the container design, fabrication, closure after filling, and inspection of the closure area; and the testing and analysis of the package performance under expected repository conditions. Babcock & Wilcox (B&W) was involved with the Yucca Mountain Project (YMP) as a subcontractor to LLNL. B&W's role was to recommend and demonstrate a method for fabricating the metallic waste container and a method for the final closure of the container after filling it with waste.

This report is a summary of the technical activities for the LLNL/YMP Nuclear Waste Disposal Container Fabrication and Closure Development Project (Customer Contract No. 9172105) for GFY89.

This project involved three phases. The goal of this project was to identify the optimum means of fabricating a container for disposal of high level nuclear waste, and of identifying the best means of closing the container once it had been filled with waste.

In overview, Phase 1 of this project was a paper study to identify fabrication and closure processes worthy of further laboratory evaluations for the six candidate container materials identified by LLNL. The results of Phase 1 were presented in References 1 and 2. Candidate closure processes identified in the Phase 1 report to be worthy of further evaluation were: Friction Welding (FRW), Electron Beam Welding (EBW), Plasma Arc Welding (PAW), Laser Beam Welding (LBW), and Gas Tungsten Arc Welding (GTAW). Candidate Fabrication Processes identified by the Phase 1 report are as follows:

- Pintle and Upper Head
  - Pintle Welded to Upper Head
    - Forged
    - Spun
    - Deep Drawn
    - Centrifugally Cast
    - Machined
  - Integral Pintle and Head
    - Forged
    - Centrifugally Cast
    - Machined

- Body and Lower Head
  - Integral
    - Extruded Closed End
    - Extruded Closed End and Cold Worked
    - Deep Drawn Closed End
  - Body Welded to Head

Body	Head
Roll and Welded	Forged
	Spun
	Deep Drawn
	Centrifugally Cast
	Machined
Extruded	Same as above
Deep Drawn	Same as above
Centrifugally Cast	Same as above

  - Cold Worked and Annealed Lower Unit

Body	Head
Roll & Welded	Forged
	Spun
	Deep Drawn
	Centrifugally Cast
	Machined
Extruded	Same as above
Deep Drawn	Same as above
Centrifugally Cast	Same as above

Phase 2 of this effort involved laboratory studies to determine the optimum fabrication and closure processes. Because of budget limitations, LLNL narrowed the materials for evaluation in Phase 2 from the original six to four: Alloy 825, CDA 715, CDA 102 (or CDA 122) and CDA 952. It was decided that AISI 304L and 316L stainless steels were well characterized materials, and that, if these materials were eventually selected for container fabrication, the results of the Alloy 825 studies could be applied to the stainless steels (all are austenitic alloys). Phase 2 studies focussed on evaluation of candidate material in conjunction with fabrication and closure processes identified by LLNL. Data obtained in these evaluations would have assisted in the selection of a candidate material and process combination for further prototype manufacture and testing. Phase 3 would have involved development of means for implementing the selections in Phase 2.

Activities covered in this report were part of Phase 2. As can be seen from the list of significant activities below, Phase 2 testing began in earnest with the "release to work" on May 31, 1989. This effort ended approximately four months later when the project was terminated prior to the completion of Phase 2 due to DOE funding restrictions.

Significant events during GFY89:

Oct. 1988 - Sept. 1989	Vendor QA audits on-going.
November 1988	Calculation of required specimen length.
February 10, 1989	NQA-1 with modifications imposed (QARS-001A Rev. 0).
March 28,29, 1989	Surveillance, B&W Prequalification Survey.
April 13, 1989	Conditional approval of QA Program.
April 18, 1989	Approval of QA Plan.
May 4,5,19, 1989	LLNL readiness review.
May 31, 1989	B&W released to work.
July 1989	PAW and EBW trials initiated.
September 1989	Friction weld trials.
September 29, 1989	Informed by LLNL that project terminated.

Quality Assurance Aspects

The Quality Assurance aspects of this project played an important role in activities during GFY89. Of special significance is the fact that the QA Specification imposed on this project was revised in February 1989 requiring B&W to revise the project QA Plan to include a much more detailed QA program than previously employed. This QA Plan revision was completed and approved, then LLNL held a readiness review. When this was successfully completed, B&W was released to work. This occurred on May 31, 1989.

The QA aspects of the project affected our work in GFY89 in the following way. First, any work done prior to the imposition of the new QA Specification (February 10, 1989) was done under the old QA Plan (B&W QA Plan Rev. 1). Once the QA specification was imposed, no technical work was authorized until the new QA Plan was in place and we were formally released to work by LLNL (May 31, 1989). In the period from the formal release to work until the project was terminated, technical activities were governed by the new QA Plan (B&W QA Plan Rev. 2).

It should be noted that under both QA Plans a class of testing termed "scoping tests" was permitted. This class of testing permits preliminary tests to be performed for information purposes only, information gathered in these tests cannot be considered "data".

With this in mind, this report covers three types of activities: 1) work done under the original QA Plan, 2) work done under the revised QA Plan, and 3) work done as scoping tests.

Effect of Project Termination

It is important to understand that project termination occurred abruptly, without forewarning. This had the effect that the work that was on-going was stopped abruptly, leaving many loose ends, particularly from a QA standpoint. The stop did not permit the on-going work to be brought to a logical technical break. So, work under the new QA Plan is only partially completed from a Quality Assurance and technical perspective. Surveillance review by LLNL in July 1990 confirmed that B&W Alliance Research Center (ARC) was acting in accordance with the QA Plan at the time the project was terminated.

Technical Activities

With the above in mind, the following technical activities are covered in this summary report. Each activity is addressed as a separate appendix, each of which is intended to be a stand-alone section by an individual author responsible for the activity.

Appendix	Author	Activity	QA Level
"A"	Domian	Fabrication Activities - plans for fabrication of mock-ups - cost estimate for containers and internals - microstructural effects of cold rolling on welds	Scoping, Old QA Plan
"B"	Robitz	Friction Welding Development	New QA Plan with minimal scoping
"C"	Conrardy	Plasma Arc Welding Development	New QA Plan with scoping
"D"	Conrardy	Electron Beam Welding Development	New QA Plan with scoping
"E"	Schultz	Specimen Length Calculation	Old QA Plan

With the exception of Appendix E, all of the above appendices were specifically prepared for this report. Appendix E contains a letter summarizing work done to determine the size of specimen required so that specimen end-effects do not interfere with the residual stress distribution about a cylindrical weld. A letter documenting review of these calculations is also included in this appendix. This effort would have been used to determine specimen sizes had we been required to compare the residual stress field produced by one process with that of another. Our goal was to economize on specimen length while maintaining technical validity.

The reader is encouraged at this point to review the contents of the appendices.

CONCLUSIONS

Conclusions are not appropriate in a report of this type, however, the results of the completed work were promising. This was particularly true for the closure activities, in which a significant start at process evaluation was made. In general, the results so far indicate that the fabrication and closure activities, if taken to completion, would have led to identification of optimum fabrication and closure techniques.

Submitted By: H. A. Domian

Submitted By: E. S. Robitz

Approved By: D. F. LaCount

bz
Attach.

ACKNOWLEDGMENTS

In a project of this magnitude, numerous individuals and organizations must combine and coordinate their efforts if the project is to be a success. This was the case for the waste container development effort. While many individuals played a significant role in the successes of these projects, the Project Leaders would like to specifically acknowledge the following:

- The contributions of Chris Conrardy in taking the lead in the technical development of the Plasma Arc and Electron Beam welding processes. We would also like to acknowledge the contributions of Pat Ryan and Dan Gibson in support of these tasks.

- The thorough and professional effort of Steve Manring in his role as both Material Controller and Document Custodian for these projects.

- The invaluable assistance and recommendations, and extraordinary effort of the B&W ARC Quality Assurance Department, particularly that of: Jesse Gasper, Robin Gill and Ken Everett.

- The efforts and understanding of our primary vendors: Youngstown Welding and Engineering Co. (Weldco), and Manufacturing Technology Incorporated (MTI).

There are many others we would like to acknowledge but space does not permit, however, it must be emphasized that these projects truly represented a team effort.

REFERENCES

[1] H.A. Domian, et al., Fabrication Development for High-Level Nuclear Waste Containers for the Tuff Repository, Phase I Final Report, UCRL 15965, Lawrence Livermore National Laboratory, Livermore, CA, 1989.

[2] E.S. Robitz, et al., Closure Development for High-Level Nuclear Waste Containers for the Tuff Repository, Phase I Final Report, UCRL 15964, Lawrence Livermore National Laboratory, Livermore, CA, 1989.

APPENDIX A

Fabrication

Author: H. A. Domian

APPENDIX A

FABRICATION

Author: H. A. Domian

1.0 BACKGROUND

This project consisted of three principal activities:

- Plans for fabrication of the following container mock-ups:
  - Roll & Welded
    - CDA 715 (C71500)
    - IN 825 (N08825)
    - CDA 122 (C12200)

These alloys were selected as being representative of copper, a copper alloy and an austenitic alloy and would demonstrate the viability of the roll and welding process on these and similar alloys.

- Roll & Welded plus Spin Form
  - CDA 715 (C71500)
  - IN 825 (N08825)
  - CDA 122 (C12200)

Spin forming could provide an improved microstructure and homogeneity of the welds that could be more competitive in cost when compared to seamless fabrication such as hot extrusion plus spin forming.

- Hot Extrusion plus Spin Form
  - IN 825 (N08825)

This alloy was selected as being probably the most difficult to fabricate with this processing and if successful could demonstrate this fabrication process as being viable for the other alloys.

- Centrifugally Cast plus Spin Form
  CDA 952 (C95200)

This alloy, which is the cast version of CDA613, is the most likely candidate that would be made by centrifugal casting of the container body. The addition of spin forming after casting was expected to enhance the microstructural properties and ultrasonic inspection capabilities over that achieved by casting alone. The cost of this processing is expected to be lower than roll and welding plus spin forming.

- Cost estimate of production units of YMPO containers and internals from the following alloys:
  CDA 715 (C71500)
  IN 825 (N08825)
- Determine microstructural effects of cold rolling Gas Tungsten Arc (GTA) welds made with the following alloys:
  CDA 715 (C71500)
  CDA 952 (C95200)
  IN 825 (N08825)

The activity for making the mock-ups involved preparing drawings and discussions with prospective vendors in preparation of soliciting quotations for making the container mock-ups.

The cost estimate study for fabricating containers was completed and the results provided to LLNL in letters.(1,2,3) (These supplier estimates are provided in the Section 3.2 of this Appendix.)

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1) H.A. Domian to E. Russell, "YMP-HLNW Container Production Cost Estimates by Youngstown Welding and Engineering Co., Sept. 19, 1989.

2) H.A. Domian to E. Russell, "YMP-HLNW Container Production Cost Estimates by Joseph Oat Corporation", Sept. 22, 1989.

3) H.A. Domian to E. Russell, "YMP-HLNW Container Production Cost Estimates by B&W CNFP", Sept. 27, 1989.

The only experimental work involved scoping trials to determine the microstructural effects of cold rolling on GTA welds to provide guidance on the spin forming of container mock-ups containing welds. This work is described below.

Potentially lower cost YMP waste containers comparable in quality to seamless fabrication could be achieved if spin forming of roll and welded bodies with attached heads could be produced that would have homogeneous microstructures across the region where the welds formerly existed. Since there was no experience with spin forming the candidate alloy weldments, some scoping work using welded plates and a simulation of the spin forming process was performed to provide some guidance for the spin forming work.

1.1 Spin Forming

This process involves the reduction of cylinder thickness by using radiused rolls working the piece on the O.D. against the mandrel. The amount of wall reduction that can be accomplished in one pass is relatively small and more than one pass is usually required with annealing between the passes. This results in repetitive cold work and annealing cycles that produce recrystallization. With a weldment, the cast microstructure is transformed to a wrought structure and the heat affected zone is obliterated, provided the amount of cold reduction and annealing are sufficient.

1.2 Advantages and Disadvantages of Spin Forming of Rolled and Welded Containers

Advantages - Projected lower cost as compared to seamless container made by back extrusion.

Disadvantages - Additional inspection required for the welds.

- Chemical inhomogeneity across the weld zone due to use of filler metals that not exactly match the composition of the base metal. This could be overcome by making an autogenous (no filler metal) weld.

- May produce greater variation in dimensional tolerances of the container.

COLD ROLLING OF WELDS

2.0 RATIONALE FOR TESTING

The spin forming of container bodies having longitudinal and circumferential welds would be done with repetitive operations of wall thinning by cold reductions and annealing. There was no published data found on the effects of cold reductions on welds of these alloys (CDA 715, CDA 952 and IN 825), and some preliminary work to determine the effects of cold rolling and annealing using a laboratory rolling mill and microstructural analysis following repetitive reductions and annealing could be used to determine if grain size, hardness and microstructural inhomogeneities persisted as the material was reduced in thickness.

2.1 Specimen Description

Plates, approximately 5/8" thick x 3" wide x 18" long of the three alloys (CDA 715, CDA 952 and IN 825) were welded together using the GTA process and following filler metals.

	CDA 715	CDA 952	IN 825
Filler Metal	MIL-EN67	ERCuAl-A_2	ERNiFeCr-1

The weldments were cut into two pieces with one being rolled in the direction of the weld and the other perpendicular to it. The welds were annealed prior to the first and after each cold rolling sequence. The amount of thickness reduction in 5 sequences was increased from about 17 to 36% with each sequence to produce total reduction of about 78%.

2.2 Equipment Description

A two-high reversing 14" diameter x 20" wide rolling mill and laboratory heat treating furnace were used.

2.3 Methodology

It was planned that pieces which were cut off each weldment before and after cold rolling and annealing would be examined metallographically and hardness tested to determine the grain size, hardness and microstructural effects due to increasing amounts of reduction and repeated annealing cycles. The work was terminated before that could be done.

3.0 RESULTS

3.1 Cold Rolling of Welds - Results

The samples were produced as planned but were not examined. Tables A-1 through A-5 give some details on welding, chemical composition, planned reductions, annealing temperatures, and reductions achieved. Samples after the last annealing treatment, identified as follows, were provided to LLNL:

	Sample Number	
	Rolling Direction with Respect to Weld	
Alloy	Parallel	Perpendicular
CDA 715 (C71500)	061A	061B
CDA 952 (C95200)	062A	062B
IN 825 (N08825)	046A	046B

3.2 Container Cost Estimate - Results

The cost estimates to fabricate containers produced by the three vendors are summarized below:

VENDOR #1

Container Including Lower Unit and Upper Head Price, $/Container

Size	Materials Raw	Expendable	Labor	Total
C71500 Alloy				
26S	31,395	4,969	24,146	60,510
26L	36,472	5,700	27,482	69,654
28L	40,564	6,231	30,383	77,178
N08825 Alloy				
26S	31,022	4,921	25,819	61,762
26L	35,980	5,610	29,591	71,181
28L	40,368	6,141	31,583	78,092

Internals, $/Assembly

Size	Materials Raw	Expendable	Labor	Total
S30403 (TP 304LSS) Alloy				
Cons. 6 PWR	390	253	964	1,607
3 PWR	538	259	1,173	1,970
3 PWR + 4 BWR	884	281	1,278	2,443
10 BWR	1,080	253	1,172	2,505
4 PWR	649	274	1,016	1,939

VENDOR #2

Container Including Lower Unit and Upper Head Price, $/Container

Size	Materials Raw	Expendable	Labor	Total
	C71500 Alloy			
26S	25,775	10,013	9,025	44,813
26L	30,583	12,293	10,125	53,001
28L	33,757	13,326	11,375	58,458
	N08825 Alloy			
26S	37,707	11,487	9,825	59,019
26L	42,520	14,141	11,075	67,736
28L	47,877	15,389	12,425	75,691

Internals, $/Assembly

S30403 (TP 304LSS) Alloy

Size	Materials Raw	Expendable	Labor	Total
Cons. 6 PWR	1,307	1,381	2,400	5,088
3 PWR	817	951	1,900	3,668
3 PWR + 4 BWR	1,794	175	3,280	5,249
10 BWR	1,880	1,958	3,175	7,013
4 PWR	982	1,029	2,150	4,161

VENDOR #3

Container Including Lower Unit and Upper Head Price, $/Container

Size	Materials Raw	Expendable	Labor	Total
C71500 Alloy				
26S	27,432	14,306	6,417	48,155
26L	31,582	16,814	6,507	54,903
28L	33,896	17,624	6,681	58,201
N08825 Alloy				
26S	32,962	15,112	6,419	54,493
26L	39,882	17,877	6,420	64,179
28L	42,461	18,799	6,507	67,767
Internals, $/Assembly				
S30403 (TP 304LSS) Alloy				
Cons. 6 PWR	3,590	200	1,414	5,204
3 PWR	898	150	629	1,677
3 PWR + 4 BWR	1,792	200	1,542	3,534
10 BWR	3,887	200	1,411	5,498
4 PWR	1,197	200	673	2,070

4.0 SUMMARY

The only major activity that was completed was the cost estimate of production units of YMPO containers. The scoping trials of cold rolling and annealing of welds were partially completed and produced samples ready for examination. Planning for making of containing mock-ups was initiated and preparations were made to have vendors provide complete quotes.

TABLE A-1

Description of Weldments

Identification	061	062	046
Alloy	C71500	C95200	N08825
Plate Thickness, in. (mm)	5/8 (15.9)	5/8 (15.9)	5/8 (15.9)
Base Metal, Ht. No.	6499	86209	879R4
Filler Metal			
Type	MIL-EN67	ERCuAl-A_2	ERNiFeCr-1
Diameter, in. (mm)	.045 (1.14)	.045 (1.14)	.045 (1.14)
Ht. No.	V98504	29	HH4197F
Welding Parameters			
Current, Amps.	200-400 DC	300 DC	200-400 DC
Voltage, Volts	11-16	12.5	11-16
Travel Speed, ipm (mmps)	6-20 (2.5-8.5)	7 (3.0)	6-20 (2.5-8.5)
Wire Feed Speed, ipm (mmps)	40-120 (16.9-50.8)	48 (20.3)	40-120 (16.9-50.8)
Shield Gas	80% He/20%Ar	80% He/20%Ar	80% He/20%Ar
Flow Rate, cfh (m^3/S)	60 min (.0051 min)	100 (.0085)	60 min (.0051 min)

TABLE A-2

Chemical Composition of Materials, Wt. %

Alloy Sample	C71500 061		C95200 062		N08825 046	
	Base Metal	Filler	Base Metal	Filler	Base Metal	Filler
Ht. No.	6499	V98504	86209	29	879R4	HH4197F
C	.027	.039	--	--	.020	.019
Mn	.71	.76	--	--	.49	.36
P	.008	.006	--	--	--	.016
S	.008	.004	--	--	.002	.001
Si	--	.02	--	.011	.21	.21
Ni	29.70	30.96	--	--	41.38	42.96
Cr	--	--	--	--	20.10	20.71
Fe	.67	.60	3.35	1.27	31.33	30.54
Cu	68.65	67.10	86.94	Bal.	2.05	1.54
Al	--	.025	9.09	9.21	.135	.060
Ti	--	.350	--	--	.96	.72
Mo	--	--	--	--	3.10	2.52
Pb	.005	.004	--	.003	--	--
Zn	.040	--	--	.008	--	--
Co	.037	.018	--	--	.100	.240
Mg	--	.043	--	--	--	--
Others	--	--	.62	--	--	--

TABLE A-3

Planned Reductions in Thickness Between Anneals

	Reduction, %	
Sequence	**Per Sequence**	**Cumulative Total**
1	15	15
2	20	32
3	25	44
4	30	64
5	35	77

TABLE A-4

Alloy	**Annealing Temperature, °F (°C)**
C71500	1200-1250 (649-677)
C95200	1125-1175 (607-635)
N08825	1700-1750 (927-955)

TABLE A-5

Summary of Reductions Achieved

Specimen Number	Reduction, % For Sequence	Reduction, % Cumulative	Thickness in. (mm)	Rolling Direction* L	Rolling Direction* T	Specimen Taken Before Anneal	Specimen Taken After Anneal
Alloy C71500							
061M	0	0	.657 (16.7)	-	-	X	-
A1	0	0	.657 (16.7)	-	-	-	X
A2	19.8	19.8	.527 (13.4)	X	-	X	-
A3	19.8	19.8	.527 (13.4)	X	-	-	X
A4	19.4	35.3	.425 (10.8)	X	-	X	-
A5	19.4	35.3	.425 (10.8)	X	-	-	X
A6	23.3	50.4	.326 (8.3)	X	-	X	-
A7	23.3	50.4	.326 (8.3)	X	-	-	X
A8	29.8	65.1	.229 (5.8)	X	-	X	-
A9	29.8	65.1	.229 (5.8)	X	-	-	X
A10	38.0	78.4	.142 (3.6)	X	-	X	-
A11	38.0	78.4	.142 (3.6)	X	-	-	X
B2	19.9	19.9	.526 (13.4)	-	X	X	-
B3	19.9	19.9	.526 (13.4)	-	X	-	X
B4	18.8	35.0	.427 (10.8)	-	X	X	-
B5	18.8	35.0	.427 (10.8)	-	X	-	X
B6	23.9	50.5	.325 (8.3)	-	X	X	-
B7	23.9	50.5	.325 (8.3)	-	X	-	X
B8	30.8	65.8	.225 (5.7)	-	X	X	-
B9	30.8	65.8	.225 (5.7)	-	X	-	X
B10	36.4	78.2	.143 (3.6)	-	X	X	-
B11	36.4	78.2	.143 (3.6)	-	X	-	X

* Rolling direction parallel to welding direction - L
Rolling direction transverse to welding direction - T

TABLE A-5 (Cont'd)

Summary of Reductions Achieved

Specimen Number	Reduction, % For Sequence	Reduction, % Cumulative	Thickness in. (mm)	Rolling Direction* L	Rolling Direction* T	Specimen Taken Before Anneal	Specimen Taken After Anneal
			Alloy C95200				
062M	0	0	.635 (16.1)	-	-	X	-
A1	0	0	.635 (16.1)	-	-	-	X
A2	16.9	16.9	.528 (13.4)	X	-	X	-
A3	16.9	16.9	.528 (13.4)	X	-	-	X
A4	19.7	33.2	.424 (10.8)	X	-	X	-
A5	19.7	33.2	.424 (10.8)	X	-	-	X
A6	25.2	50.1	.317 (8.1)	X	-	X	-
A7	25.2	50.1	.317 (8.1)	X	-	-	X
A8	30.6	65.4	.220 (5.6)	X	-	X	-
A9	30.6	65.4	.220 (5.6)	X	-	-	X
A10	35.9	77.8	.141 (3.6)	X	-	X	-
A11	35.9	77.8	.141 (3.6)	X	-	-	X
B2	17.3	17.3	.525 (13.3)	-	X	X	-
B3	17.3	17.3	.525 (13.3)	-	X	-	X
B4	19.4	33.4	.423 (10.7)	-	X	X	-
B5	19.4	33.4	.423 (10.7)	-	X	-	X
B6	27.2	51.5	.308 (7.8)	-	X	X	-
B7	27.2	51.5	.308 (7.8)	-	X	-	X
B8	28.6	65.4	.220 (5.6)	-	X	X	-
B9	28.6	65.4	.220 (5.6)	-	X	-	X
B10	36.4	77.9	.140 (3.6)	-	X	X	-
B11	36.4	77.9	.140 (3.6)	-	X	-	X

* Rolling direction parallel to welding direction - L
Rolling direction transverse to welding direction - T

TABLE A-5 (Cont'd)

Summary of Reductions Achieved

Specimen Number	Reduction, % For Sequence	Reduction, % Cumulative	Thickness in. (mm)	Rolling Direction* L	Rolling Direction* T	Specimen Taken Before Anneal	Specimen Taken After Anneal
			Alloy N08825				
046M	0	0	.654 (16.6)	-	-	X	-
A1	0	0	.654 (16.6)	-	-	-	X
A2	20.6	20.6	.519 (13.2)	X	-	X	-
A3	20.6	20.6	.519 (13.2)	X	-	-	X
A4	21.6	37.8	.407 (10.3)	X	-	X	-
A5	21.6	37.8	.407 (10.3)	X	-	-	X
A6	24.1	52.8	.309 (7.8)	X	-	X	-
A7	24.1	52.8	.309 (7.8)	X	-	-	X
A8	31.7	67.7	.211 (5.4)	X	-	X	-
A9	31.7	67.7	.211 (5.4)	X	-	-	X
A10	33.7	78.6	.140 (3.6)	X	-	X	-
A11	33.7	78.6	.140 (3.6)	X	-	-	X
B2	20.6	20.6	.519 (13.2)	-	X	X	-
B3	20.6	20.6	.519 (13.2)	-	X	-	X
B4	22.4	38.4	.403 (10.2)	-	X	X	-
B5	22.4	38.4	.403 (10.2)	-	X	-	X
B6	24.8	53.7	.303 (7.7)	-	X	X	-
B7	24.8	53.7	.303 (7.7)	-	X	-	X
B8	30.4	67.7	.211 (5.4)	-	X	X	-
B9	30.4	67.7	.211 (5.4)	-	X	-	X
B10	34.6	78.9	.138 (3.5)	-	X	X	-
B11	34.6	78.9	.138 (3.5)	-	X	-	X

* Rolling direction parallel to welding direction - L

Rolling direction transverse to welding direction - T

APPENDIX B

Friction Welding Development

Author: E. S. Robitz

APPENDIX B

FRICTION WELDING DEVELOPMENT

Author: E. S. Robitz

1.0 BACKGROUND

In this section we discuss the background information needed to understand the rationale for the testing approach taken for evaluation of friction welding.

We discuss how a bond is formed in friction welding. The fact that melting of the material is not required for joining distinguishes the friction welding process from all of the other processes under investigation. This characteristic gives rise to many of the advantages of this process from a materials performance point of view.

We discuss the sequence of events in friction welding and identify important welding parameters. The fact that there are only a few important parameters makes this process attractive from a process control point of view.

We discuss the influence of materials selection on the process. For this investigation: Incoloy 825 (a nickel-iron-chromium alloy developed for aggressively corrosive environments), CDA 715 (70Cu-30Ni), and CDA 952 (a cast aluminum bronze) were chosen by LLNL for investigation.

We summarize by listing some of the advantages and disadvantages of friction welding.

1.1 Pressure Welding

Friction welding is a representative of a class of welding processes known as "pressure welding". In pressure welding, applied pressure is used to force the parts to be joined into intimate contact. Under certain conditions, this intimate contact gives rise to the formation of a welded joint. One of the necessary conditions for successful pressure welding is high plasticity in the vicinity of the joint for the parts to be welded. Highly plastic metals, such as lead, can be pressure welded at room temperature. Other metals require elevated temperatures before they become sufficiently plastic for welding. Temperatures approaching about two-thirds of the melting temperature are required for pressure welding of most engineering alloys. Friction is one means employed to supply the energy necessary to achieve the high temperatures (high plasticity) needed in the surfaces of parts to be welded.

1.2 Friction Welding Process Overview

While friction welding can be implemented in a number of different ways, it usually involves the following sequence:

1) One of the parts to be joined is held stationary.

2) The other part to be joined is rotated. The rate of rotation is governed by the amount of energy needed to make a given weld, which in turn is dependent on the materials to be joined. It is also related to the surface area of the joint, and the geometry of the parts being joined.

3) When the proper rate of rotation is achieved, the two parts are brought together so that they touch. The relative motion between the rotating and stationary parts results in friction which generates the heat needed in the surface of the part for welding.

   Note: At this point the distinction should be made between two common process variations for friction welding: continuous drive and inertia friction welding. In continuous drive friction welding, the motor stays engaged to the rotating part through-out the welding process, thus it has direct control over the energy of welding. In inertia friction welding, the rotating part is disengaged from the motor through a clutching mechanism, typically just prior to bringing the parts into contact. The inertia of the rotating part (and of the associated chuck and flywheel) provide the energy needed for welding.

4) Once sufficient heat has been generated, the two parts are forced together under a thrust load applied normal to the weld. This causes material to flow into the joint, bond together; then under the influence of continued loading, the material flows out of the joint forming a rim of material known as the "flash". The formation of this flash is very important in ensuring the soundness of the friction welded joint. Formation of an adequate flash assures that (perhaps oxidized or contaminated) material originally on the joint surface has been carried out of the joint. It is also a clear verification that the process worked as it should.

Once the parts to be joined have been installed into the friction welding machine, the weld can be completed in a matter of a few minutes. Most of this time is consumed in preparing the equipment and bringing the part up to speed. The actual welding sequence takes only a few seconds. Figure B-1 depicts a typical sequence of events as a function of time for an inertia friction weld.

1.3 Relevant Friction Welding Parameters

For the case at hand, the inertia friction welding process was used to prepare weld specimens for evaluation. The following welding parameters are relevant for this process:

1) Rate of rotation (rpm)

2) Rotational moment of inertia (termed WK^2 with units of $lb\text{-}ft^2$) - taking into account the contributions of all rotating components such as the flywheel etc. Note that flywheels are massive rings which are added or removed from the spindle to control the moment of inertia.

3) Dwell time (sec.) - length of time the thrust load is maintained after rotation stops. This permits the weld to cool with applied compressive stress on the weld joint.

4) Thrust load (lbs)

5) Displacement (in.) - This is the total change in length of the two parts being joined due to formation of the weld. This parameter allows for control over the formation of an adequate flash. The parameter is not directly controlled, rather it is the result of adequate weld parameters (i.e. WK^2, thrust load, and rate of rotation). Displacement might more properly be considered a resultant "target" value rather than a true welding parameter.

It should be noted that the state of the art of friction welding is such that the accuracy required for control of some of these welding parameters is not high. For instance, successful welds can be made over a range of displacements varying over +/- 50% about a mean. This of course has implications concerning the accuracy required for the welding parameters which give rise to displacement.

1.4 Material Considerations

The properties of the materials being joined have a strong bearing upon whether the friction welding process can be made production-worthy for a given application. For instance, early on in our investigation (prior to the period covered by this report) scoping trials were performed to determine whether pure copper could be practically joined to itself using the friction welding process. In these tests 4" diameter copper bar stock was machined to have a 1" wall, then an attempt was made to friction weld these parts together. The result of these tests was that successful welds were made, but that the torque generated in the welding equipment was sufficiently high that the friction welding equipment would not have survived the making full-scale container welds. Thus the friction welding process was eliminated as a possibility for closure of pure copper containers.

The properties of the materials being joined also have a strong influence on the welding parameters required to perform a weld. Typically a friction welder will have a history of previous successful welds for a given (or similar) material which would give him guidance for selection of the initial welding parameters for welding procedure development. This was the case for welds made for Alloy 825, CDA 715, and CDA 952. Lacking a previous history for a material, the friction welder will start with attempts to manufacture small scale welds, as was the case for the pure copper welds above. Success or failure of these initial welds would allow the welder to decide whether and how to proceed.

1.5 Advantages and Disadvantages of Friction Welding

The advantages and disadvantages listed below are based upon the process characteristics discussed above. Most were previously discussed in the Phase 1 report for this effort, however the list has been updated based on information received in the course of this effort.

Advantages:

- No fusion zone is generated - thus a transition from wrought to cast structure is generally avoided.
- A small heat affected zone (HAZ) is generated. This results from the fact that the interface to be welded reaches a temperature of about 2/3 the melting temperature, and the weld occurs very quickly.
- Low distortion and residual stresses are likely. This results from the uniform geometry of the weld and the fact that high shrinkage stresses associated with fusion welding are not anticipated.
- Easy and infrequent maintenance are likely. This results from the simplicity of the process and the robustness of the equipment.

- High production rates are expected. Because the welding process is necessarily fast (most of the time needed is in setting-up), this process is expected to be faster and more reliable than any of the fusion welding processes.

- Easy monitoring of the process is expected. This results from the fact that the process has few variables to monitor and the accuracy required to assure a good weld is not great.

Disadvantages:

- An internal and external "flash" is formed. The external flash must be removed for inspection and material performance considerations. This results in additional processing and the need to dispose of waste metal and perhaps cutting fluid.

- Equipment failure scenarios need to be carefully considered. The effects of these need to be minimized. Failure of this massive equipment in process could cause damage within the hot cell facility. Such occurrences would need to be carefully avoided or controlled.

- Repair welding would not be possible using this process -except for the cases where a full re-weld is possible. This potentiality gives rise to the need for establishing a second (likely fusion) weld process for repair - or the policy of disposal of containers from any failed attempts. In any case it is judged that failure of the welding process would be a low probability event.

- A flanged container design may be necessary. This derives from the fact that the container may be a thin-walled cylinder. Because of this there is concern that the container might collapse under the applied thrust loads, or deform in a spiral manner as the weld is being made. The probability of these occurrences is increased as the gripping points become further from the weld. Initial thoughts are that the flanges would be needed within a couple inches of the weld to minimize this potential problem.

- Close dimensional tolerances are required for containers and tooling. The slippage of a part within its tooling can lead to welding of the part to the tooling. It might also lead to damaging of the part and/or the tooling in other ways. Tight tolerances are also required to assure that the head and body of the container mate when they are brought together for welding.

- The friction welding equipment needed for this effort would be a unique, first-of-a-kind item. The welding equipment needed for this effort would be the largest in the world. Technically it is anticipated that this presents only scaling problems, however because of its uniqueness the initial cost per unit is expected to be high. (The last unofficial estimate exceeded $10M.)

Controversial:

- Inspectibility is in question. Whether or not a friction weld is inspectable is open to debate. Some investigators have reported good success, however most friction welding users do not rely on surface or volumetric inspection to verify the adequacy of a weld. Rather, what is more typical is that the process itself is qualified and if it can be demonstrated to have been performed within the tolerance bands of the critical parameters, then the part is deemed acceptable. One added assurance is that it is the friction welder's experience that either he has a good weld or he does not. There are few minor defects. We would anticipate from this that after friction welding, if we could lift a container by its pintle then we could be assured of a good weld. In any case this subject is worthy of further evaluation.

2.0 TESTING APPROACH

With the above in mind the following testing approach was developed for evaluation and optimization of the friction welding process for container closure.

2.1 Specimens

There were three materials being evaluated for this process: Alloy 825, CDA 715, and CDA 952. Ideally the procedure evaluation and development specimens would be carried out using full-scale welds (in terms of diameter and wall thickness, not length). The largest welds MTI was capable of welding were roughly 18" in diameter (as opposed to the roughly 26" diameter anticipated for the actual containers). MTI, the friction welder, is considered to be sole source in the U.S. at this time because of the size of the equipment needed for the container closure weld. After discussions, LLNL instructed us to test 18" diameter Alloy 825 and the CDA 715 specimens. These materials were judged by LLNL to have a higher probability of being used in container fabrication.

We were also instructed to perform friction welding trials for the CDA 952 using 4" diameter specimens, in a manner similar to that used earlier to evaluate the friction welding of pure copper.

Figure B-2 shows a drawing of the 18" diameter friction welding specimens. Note that a pair of cylinders are joined to make a weld specimen. The rotating member of the pair is 6" long with 18" diameter and a 5/8" wall. The 6" length was selected because it could fit easily into the rotating chuck. The stationary member of the pair is 9" long with a 17.8" diameter and a 3/8" wall. The length of the stationary specimen was chosen simply to provide material for subsequent testing. The differences in diameter and wall thickness were chosen so that the parts would mate on approximately a common centerline for the wall when the weld is made, see Figure B-3. The thinner wall represents the actual anticipated wall thickness for a container. The thicker wall cylinder represents the closure head.

Figure B-2 shows that the ends of the cylinders to be joined are slotted. This provides a positive interface with the chuck of the welding machine. MTI indicated that the 18" diameter was the limit to which we could go before we would need to have a flanged cylinder design. Figure B-4 shows a potential flanged cylinder design. Per LLNL instruction, flanged cylinders were not tested early on because of the added expense of the flanges and tooling.

The 18" diameter cylinders were manufactured by the roll and welding process. In this process flat plate is formed into a cylinder, then a long seam is welded to complete the cylinder. Because of material inhomogeneity in the fusion weld that would not be present with a seamless body or closure head, it was anticipated the fusion weld interface portion of the friction weld would not be evaluated in testing.

The CDA 952 specimens were machined from cast bar stock. Figure B-5 shows the specimen design. Note that slots were not required for these smaller specimens, because the friction welding machine used a hydraulic grip to secure these specimens within the chucks of the machine.

2.2 Equipment

For the 18" diameter specimens:

MTI, Model 400SBX Inertia Friction Welder

Equipment Capabilities:

Total moment of Inertia, WK^2: --- 125,000 max.
Weld RPM: --- 500 max.
Thrust load (lbs): --- 850,000 max and 85,000 min.

For the 4" diameter specimens:

MTI, Model 250B Inertia Friction Welder

Equipment Capabilities:

Total moment of Inertia WK^2: ---	2,776 max.
Weld RPM: ---	4,000 max.
Thrust load (lbs): ---	200,000 max. and 10,000 min.

Special collet liners had to be manufactured to mate the slotted 18" diameter specimens with the collets of the welder.

2.3 Testing Sequence

The sequence for testing and evaluation of the friction welding process is depicted in Figure B-6. The purpose of this sequence was to provide a logical approach to the selection of a preferred welding process for closure welding. Note from the flowchart in this figure that we were able to complete only the initial part of the testing prior to termination of the project.

The initial tests in the sequence involved iterative slotted cylinder weld specimen manufacture, followed by weld evaluation. The results of the evaluation would be used to indicate welding parameters for manufacture of the next weld specimen. Since it was not practical to weld and evaluate specimens on an individual basis, a group of specimens were intended to be welded in each welding session. Welds would be evaluated during a session visually, and with metallographic and bend scoping tests as needed. After a weld session was completed, specimens were to be brought back to the ARC lab and subjected to a more thorough evaluation (using tests such as metallography, tensile, and bend testing). The results of these laboratory tests would indicate the course for welding parameter variation for the next session. Through this iterative testing it was intended that a set of optimum welding parameters be generated for each of the materials of concern. These would be employed to provide guidance for further confirmation testing using specimens whose design more closely matches that of an actual container.

The first friction welding session of the project was completed about one week prior to termination of the project, therefore the first set of welds has not been subjected to laboratory testing.

3.0 DESCRIPTION OF TESTING TO DATE

The goal of the first friction welding session at MTI was to perform initial welding parameter development for 18" diameter slotted Alloy 825 and CDA 715 cylinders, and to perform a preliminary evaluation of friction welding of CDA 952 using 4" diameter specimens (recall the flow chart in Figure B-6). This work was performed at MTI during the period of September 18 through 22, 1989.

18" Diameter Cylinder Tests

Originally, twelve pairs of slotted 18" diameter cylinders were manufactured from Alloy 825 and CDA 715. Five of these pairs were consumed in the initial testing session. Seven remain untested for each material. Technical Procedure ARC-TP-832 provides the technical and procedural guidelines for friction welding procedure development for the 18" diameter specimens.

The welding process for the 18" diameter specimens is described in detail in Figures B-7 through B-20. These figures are provided to illustrate how the friction welding testing progressed. The technical procedure should be referred to if more detail is required.

Figure B-7 shows the packaging of the specimens and their condition on receipt at MTI.

Figures B-8 and B-9 show the receipt inspection and identification activities. These activities are fully documented by route sheets for each specimen.

Figure B-10 shows one of the slotted rings used as a collet liner to mate with the 18" diameter specimens and protect the tooling of the welder.

Figure B-11A shows the Model 400SBX inertia friction welder used for the 18" diameter specimen tests. Figure B-11B shows flywheels that are added or taken off of the spindle of the welder to control the rotational moment of inertia.

Figure B-12 shows the mounting of the rotating specimen within the collet of the spindle. Tight specimen tolerances were required to mate the specimens with the collet liner and the keys of the tooling within the tailstock. Slippage could result in welding of a specimen to the collet liner, destroying the liner and making the specimen unusable.

Figure B-13A shows the collet on the tailstock ready to receive the stationary specimen. This collet also has keys and a collet liner that must be mated with the specimen. The collet in this case is somewhat deeper. This results in requiring a deeper, more flexible (and more easily damaged) collet liner than that shown in Figure B-10. Figure B-13B shows the acetone wipe of the surface to be welded once the stationary specimen is in place.

Once they are in place, the stationary specimen is forced against the rotating specimen to seat both. Figure B-14A shows this activity. Note that the region to be welded is located within an alignment bearing which acts as a retaining ring. Figure B-14B shows a weld in progress.

Immediately after the weld has been completed, a brief dwell time is imposed, then the tailstock is backed away from the headstock to reveal the welded specimen. This is depicted in Figure B-15. Figure B-16 shows further detail of the specimen within the collet of the tailstock.

After the welded specimen has been removed from the welder, strip charts and data were removed from the recording device, see Figure B-17. These charts and data were recorded in the laboratory notebook provided for each material type.

Figure B-18A shows the flash generated in a visually acceptable friction weld. As was pointed out in Table B-1, one of the Alloy 825 specimens was sectioned for metallography and bending test scoping trials. Figure B-18B shows a section taken for scoping trials which shows typical flash at both the internal and external surfaces. The specimen pictured in Figure B-18B would be representative of the piece used in the scoping bend test. It is also marked to show how it would be sectioned for scoping metallographic evaluation. Figure B-19 shows scoping bend and metallographic evaluations in progress.

With the exception of the scoping tests, the sequence above was followed for each of the 18" diameter specimens tested.

The testing progressed in a sequential manner for any given material, with the results of previous tests used to indicate parameters for subsequent tests. Once good welds were achieved (based on visual inspection and scoping tests), additional tests were performed in which parameters were increased or decreased slightly in an attempt to determine the effects of parameter variation. The testing session was completed to the point where it was necessary to section and test the welds before additional testing. A total of ten 18" diameter welds were made.

Tables B-1 and B-2 provide the parameters used for the preliminary friction welding trials for the 18" diameter specimens. In addition to providing the weld test parameters, Tables B-1 and B-2 also provide the basis for parameter selection and any observations for each 18" diameter cylinder weld test.

4" Diameter Cylinder Tests

Twelve pairs of the 4" diameter CDA 952 specimens were initially manufactured. Six were consumed in testing. Six remain for future testing.

The testing sequence for the 4" diameter specimens was much the same as for the 18" diameter specimens. Technical Procedure ARC-TP-884 provides the technical and procedural guidelines for this testing. Figures B-21 through B-25 provide a brief overview of this testing.

Figures B-21 and B-22 show the Model 250B inertia friction welder used for the weld trials involving the 4" diameter specimens. With the exception of the chucking mechanism, the features of this welder are much the same as those of the welder used for the 18" diameter specimens. Only the scale is different.

Figure B-23 shows both the rotating and stationary specimens mounted in their respective chucks. Figure B-24A shows them being brought into position for the seating process. Figure B-24B shows the actual weld being made. The weld is visible in this figure because of the lack of a retaining ring around the weld. The weld glows "cherry red" immediately prior to completion of the process.

As with the 18" diameter specimens, testing of the 4" diameter specimens progressed in a sequential manner, with results of previous tests used to indicate parameters for subsequent tests. Table B-3 provides the parameters used for these welding trials. Note that in the opinion of the welder, the first welding trial yielded good welding parameters. Two additional specimens were made to these parameters, then three tests were performed in which the parameters were varied to determine the effects of these variations.

Scoping bend and metallography tests were also performed to evaluate the quality of the welds being made. Figure B-25 shows one specimen sectioned for these purposes.

General Comments

A general observation that might be made is that, in terms of having the rotating part bond to the stationary part, successful welds were made in every trial. This success was experienced in spite of wide variations in welding parameters. This strongly suggests that if having a sound weld were the only issue, closure would prove to be feasible for all of the materials evaluated using the friction welding process.

Little or no specimen ovaling, buckling, or spiral distortion was experienced due to welding. Figure B-26 depicts minor diametral distortion found in all of the 18" diameter specimens to varying degrees. This distortion was due in part to the collet liner being slightly undersized with respect to the specimens. This distortion resulted even though the collet liner was designed to be flexible. The minor distortion of the specimens should have no effect on the outcome of future testing, however, the collet liner itself has sustained significant damage due to testing so far.

Scoping metallography and bend tests were performed for Alloy 825 and CDA 952. No defects were found in the metallographic specimens. The Alloy 825 weld was bent through 180° without evidence of cracking. The CDA 952 specimen cracked into two pieces in a brittle manner when bent slightly. This cracking was away from the weld. While it hasn't been confirmed, it appeared that the cracking was due solely to the brittle nature of this cast material.

The preliminary results of this testing indicate that friction welding of Alloy 825 and CDA 715 cylinders will likely prove feasible. This work has demonstrated that friction welding of CDA 952 is possible, but the scoping bend test called into question the inherent ductility of this material. Table B-4 provides the preliminary optimum welding parameters developed for each of the materials in this testing. Additional work would be necessary to further refine the optimum welding parameters and verify the feasibility of using the friction welding process to close containers made from these materials.

4.0 PRELIMINARY RESULTS

Based on the results of the testing to date, the following preliminary results and comments are offered:

1. It appears that successful welds were made for all three materials evaluated.

2. If these welds are confirmed to be successful, it is projected that friction welding of full-size Alloy 825 and CDA 715 containers will prove feasible.

3. The use of CDA 952 for full-scale containers is currently in question because of the brittle nature of this material in scoping tests. This would need to be further investigated. It should be noted, however, that successful welds were made and the scoping bend tests failed in a region away from the weld.

4. Preliminary optimum friction welding parameters were developed for all three materials. These have yet to be confirmed.

TABLE B-1

Friction Welding Trial Record - Alloy 825

Test Sequence	Specimen Identification	Total WK^2 ($lb-ft^2$)	Weld RPM	Thrust Load (lbs)	Displacement* (in)	Dwell Time (Sec)	Parameter Selection Criteria	Observations
1	WS-825-01	74,695	310	519,548	0.130 0.124	20	• Parameters based on standard calculation for stainless steel of equal dimensions.	• Visual-flash curl less than optimum, more energy needed. • Clamping ring reduced diameter of rotating specimen resulting in deformation (see Figure __).
2	WS-825-02	74,695	345	519,548	0.223	20	• Results of Test #1 indicated more energy needed. Increased rpm by about 25%, based on the fact that energy is proportional to $(RPM)^2$.	• Overall appearance of flash curl and weld area is good. • Displacement results consistent with good weld. • Scoping metallography showed no defects. • Scoping bend test showed no defects when bent through 180°.
3	WS-825-03	74,695	345	519,548	0.219 0.218	20	• Duplicate of Test 2.	• None.
4	WS-825-04	74,695	345	519,548	0.229 0.223	20	• Duplicate of Test 2.	• None.
5	WS-825-04	74,695	360	542,639	0.328 0.332	20	• Slight modification of Test 2 to evaluate about (5%) increase in thrust load and about (10%) increase in energy.	• Weld appears adequate.

*Calculated by taking the dry-stack height of the rotating and stationary specimens and subtracting the total height after the weld has been made - measurements at two orthogonal positions.

TABLE B-2

Friction Welding Trial Record - CDA 715

Test Sequence	Specimen Identification	Total WK^2 ($lb\text{-}ft^2$)	Weld RPM	Thrust Load (lbs)	Displacement* (in)	Dwell Time (Sec)	Parameter Selection Criteria	Observations
1	WS-715-01	74,695	300	519,548	0.393 0.382	20	• Parameters based on standard calculations for nickel tubing of this geometry.	• At the end of the weld the tooling over-travel switch was tripped. This results in immediate removal of the axial load. This specimen is considered as having a "bad" weld.
2	WS-715-02	74,695	285	473,366	0.234 0.251	20	• Reduction of both energy and thrust load required based on Test 1.	• Adequate weld made.
3	WS-715-03	74,695	285	473,366	0.263 0.262	20	• Duplicate of Test 2.	• Adequate weld.
4	WS-715-04	74,695	285	473,366	0.251 0.251	20	• Duplicate of Test 2.	• Adequate weld.
5	WS-715-05	74,695	300	496,457	0.349 0.361	20	• Derived from Test Record 2. Energy increased about (10%), load increased about (5%).	• Adequate weld.

*Calculated by taking the dry-stack height of the rotating and stationary specimens and subtracting the total height after the weld has been made - measurements at two orthogonal positions.

TABLE B-3

Friction Welding Trial Record - CDA 952

Test Sequence	Specimen Identification	Total WK^2 ($lb\text{-}ft^2$)	Weld RPM	Thrust Load (lbs)	Displacement* (in)	Dwell Time (Sec)	Parameter Selection Criteria	Observations
1	WS-925-01	115.8	2450	53,750	0.124 0.128	8	• Based on standard calculations for aluminum-bronze alloys of this weld interface dimensions.	• Visually weld looks good. • Scoping metallography revealed no defects. • Scoping bend test resulted in failure outside weld zone.
2	WS-925-02	115.8	2450	53,750	0.130 0.129		• Duplicate of Test 1.	• Adequate weld.
3	WS-925-03	115.8	2450	53,750	0.124 0.122		• Duplicate of Test 1.	• Adequate weld.
4	WS-925-04	115.8	2700	60,000	0.212 0.213	10	• Modification of Test 1 - increased energy by about (21%) and increased load about (12%)	• None.
5	WS-925-05	115.8	2125	53,750	0.077 0.073		• Modification of Test 1 - increased energy by about (25%).	• None.
6	WS-925-06	115.8	2450	43,000	0.094 0.097		• Modification of Test 1 - thrust load reduced by about (20%).	• None.

*Calculated by taking the dry-stack height of the rotating and stationary specimens and subtracting the total height after the weld has been made - measurements at two orthogonal positions.

TABLE B-4

Preliminary Optimum* Welding Parameters

Material	Total WK^2 (lb-ft^2)	Weld RPM	Total Thrust Load (lbs)	Dwell Time (Sec)	Target** Displacement (in)
Alloy 825 (for 18" Dia. Specimen)	74,695	345	519,548	20	0.22 - 0.24
CDA 715 (for 18" Dia. Specimen)	74,695	285	473,366	20	0.22 - 0.27
CDA 952 (for 4" Dia. Specimen)	115.8	2450	53,750	10	0.12 - 0.13

* Would need to be confirmed by subsequent testing.

** Not truly a weld parameter, but rather a target value which in the past was consistent with a good weld.

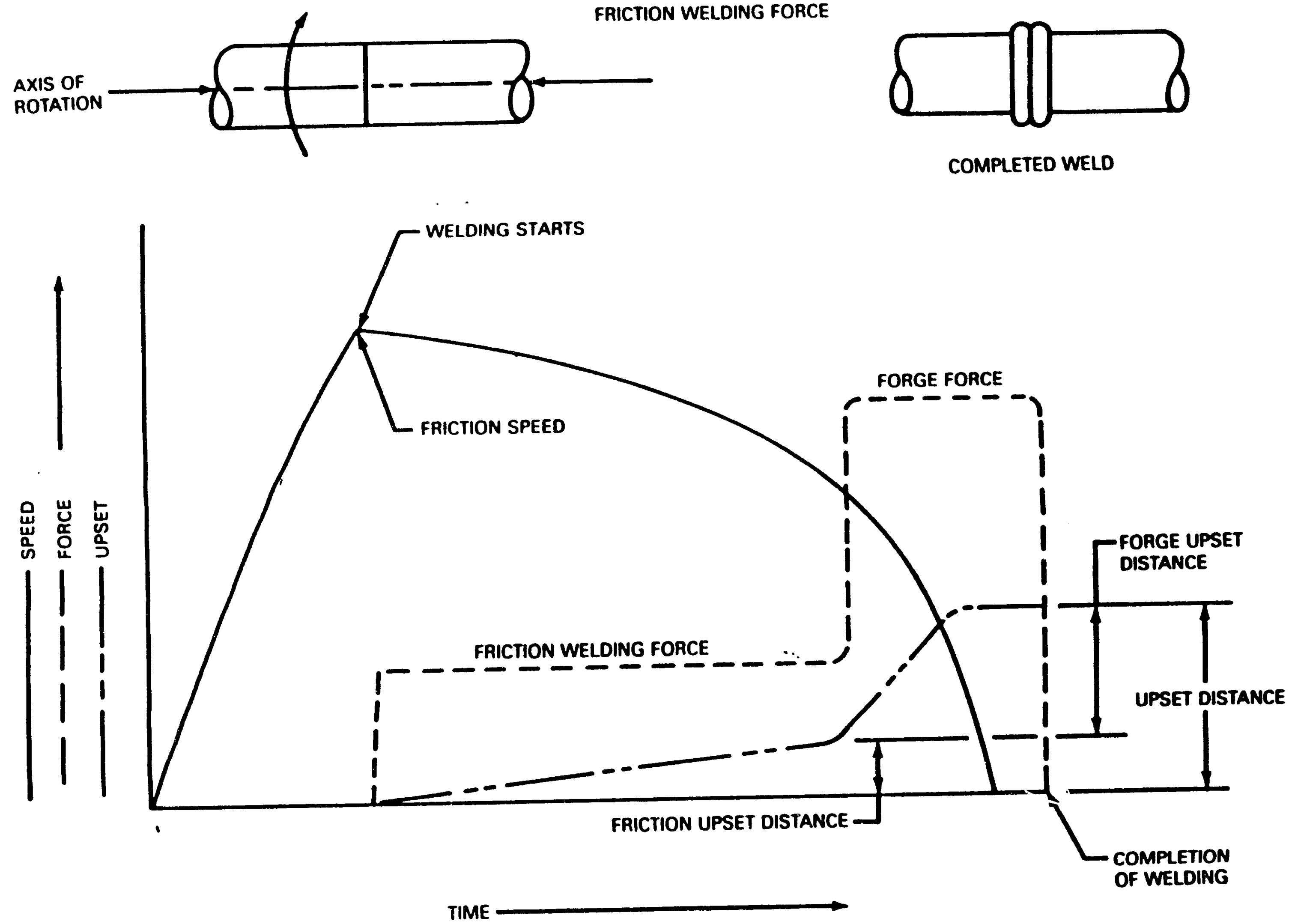
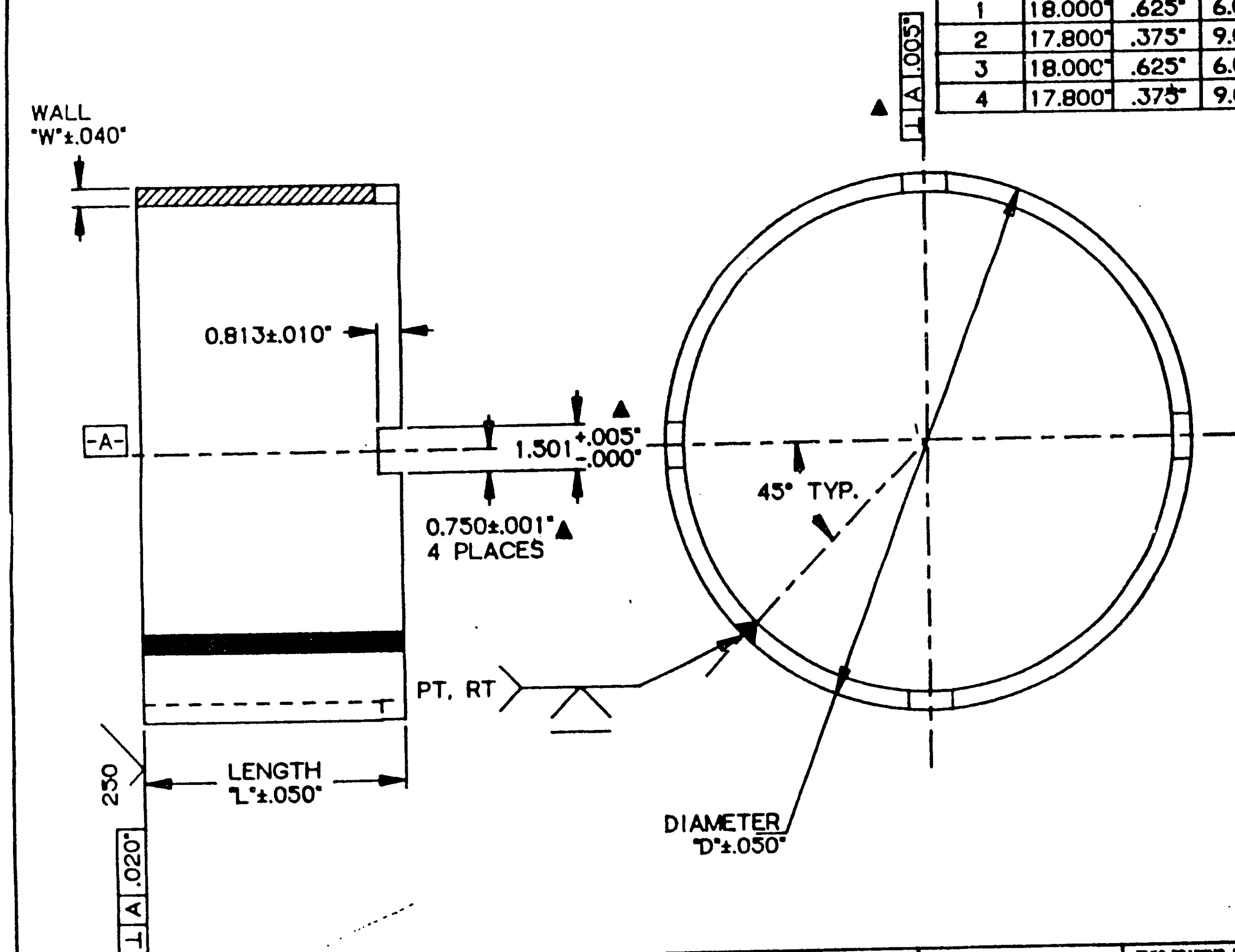


FIGURE B-1. Inertia Friction Welding Parameter Characteristics*.

*Ref. - ANSI/AWS C6.1-89, "Recommended Practices for Friction Welding," AWS, Miami, Florida.

MATL NO.	"D"	"W"	"L"	SPEC.	ALLOY UNS NO.	FILLER METAL AWS	ANNEALING TEMP. °F
1	18.000"	.625"	6.000"	SB-171	C71500	5.7 ER Cu Ni	
2	17.800"	.375"	9.000"	SB-171	C71500	5.7 ER Cu Ni	
3	18.000"	.625"	6.000"	SB-424	N08825	5.14 ER Ni Fe Cr-1	1700-1750
4	17.800"	.375"	9.000"	SB-424	N08825	5.14 ER Ni Fe Cr-1	1700-1750



NOTES:
1. TO BE MADE ACCORDING TO LATEST VERSION OF B&W TECHNICAL PROCEDURE ARC-TP-760.
2. WELD JOINT GEOMETRY AND PROCESS, GTAW AND/OR GMAW, TO BE AT OPTION OF FABRICATOR WITH APPROVAL OF BUYER.
3. WELDS ARE TO BE GROUND FLUSH WITH THE I.D. AND O.D.
4. WELD REPAIRS ON BASE METAL NOT ASSOCIATED WITH THE WELD JOINT ARE PROHIBITED.
5. ALL WELDS ARE TO BE 100% VISUALLY INSPECTED, LIQUID PENETRANT TESTED (PT), AND RADIOGRAPHICALLY TESTED (RT).
6. STAMP IDENTIFICATION ON O.D. NEAR SLOTTED END.
   MATERIAL SPECIFICATION
   UNS. NO.
   HEAT NO.
   FABRICATOR IDENTIFICATION
   PURCHASE ORDER NO.
7. ▲= CRITICAL DIMENSION.
8. CORRESPONDING ASTM SPECIFICATION IS ACCEPTABLE.
9. N08825 MATERIAL TO BE ANNEALED AFTER WELDING, DESCALED MECHANICALLY AND INSPECTED ACCORDING TO NOTE 5.

REFERENCE ONLY

REV NO	APPD
3	[signature] 4-7-89
2	J.GASPER
1	J.GASPER

QA

REV NO	REV BY / DATE	CHKD BY / APPD BY	REVISION
2	ILF 03-22-89	RJFROST / HJDOMIAN	ELIMINATED ANNEALING REQUIREMENT PREVIOUS NOTE #6.
1	ILF 12-03-88	RJFROST / HJDOMIAN	ADDED NOTE #8 & #9. WALL TOL. ±.040 WAS ±.030". SPEC. SB-171 WAS SB-402 & 17.800" WAS 17 3/4". ADDED QA BLOCK.
3	ILF 04-07-89	[signature]	ADDED ANNEALING TREATMENT FOR N08825 MATL. NOTE #9.

REFERENCE DRAWINGS

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DRN BY LPREED — DATE 11-09-88 — CHKD BY RJFROST — APPD BY HJDOMIAN

FRICTION WELD TEST — CYLINDERS - SLOTTED

SCALE NONE — GRD NO 4544-17 — SHT NO — CONT ON — DWG NO 13326-B — REV 3

THIS IS A CAD DRAWING - DO NOT REVISE MANUALLY

FIGURE B-2. Slotted Cylinder Drawing.

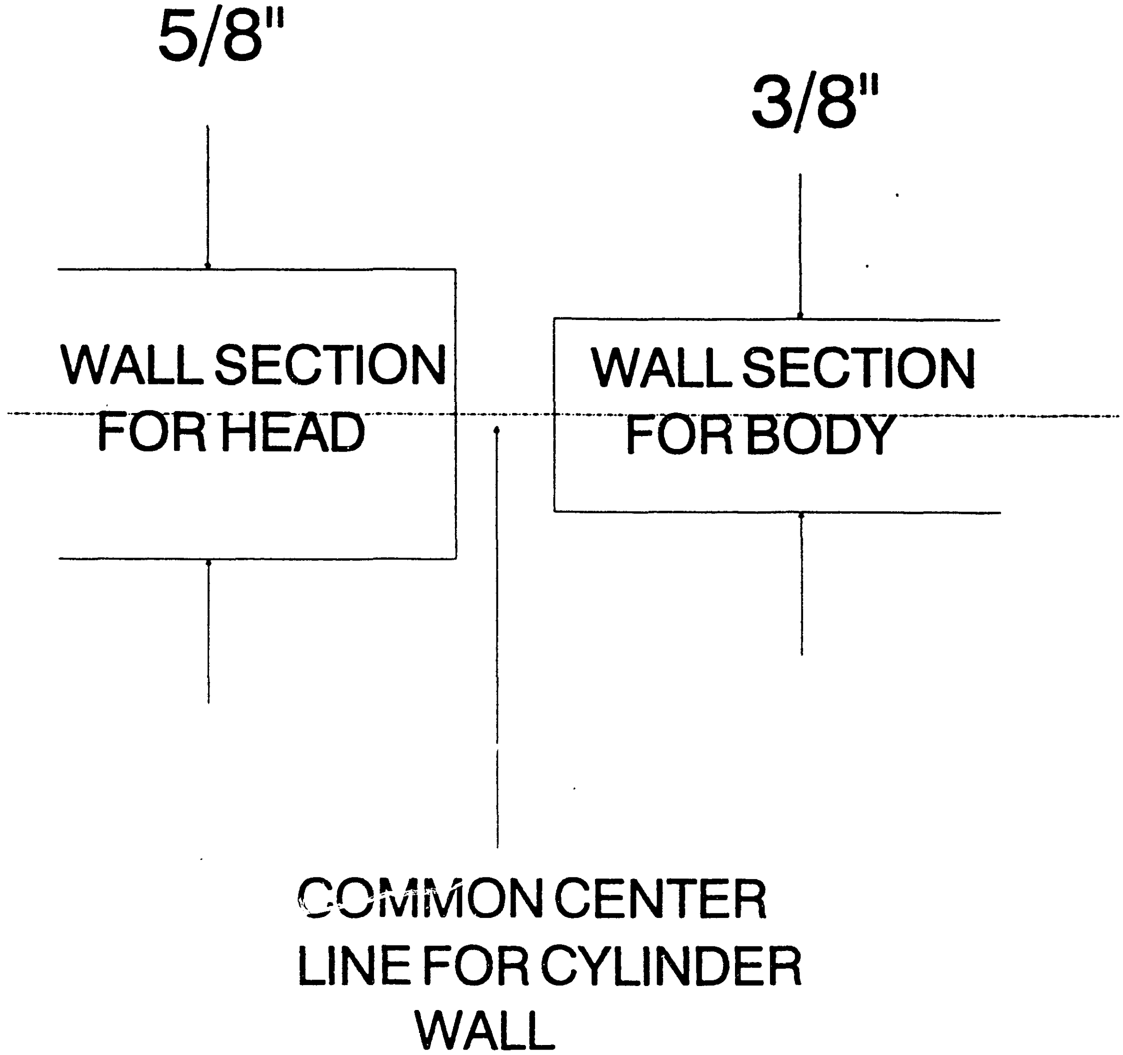


FIGURE B-3. Sketch Showing Intent of How the Body Would Mate With the Head.

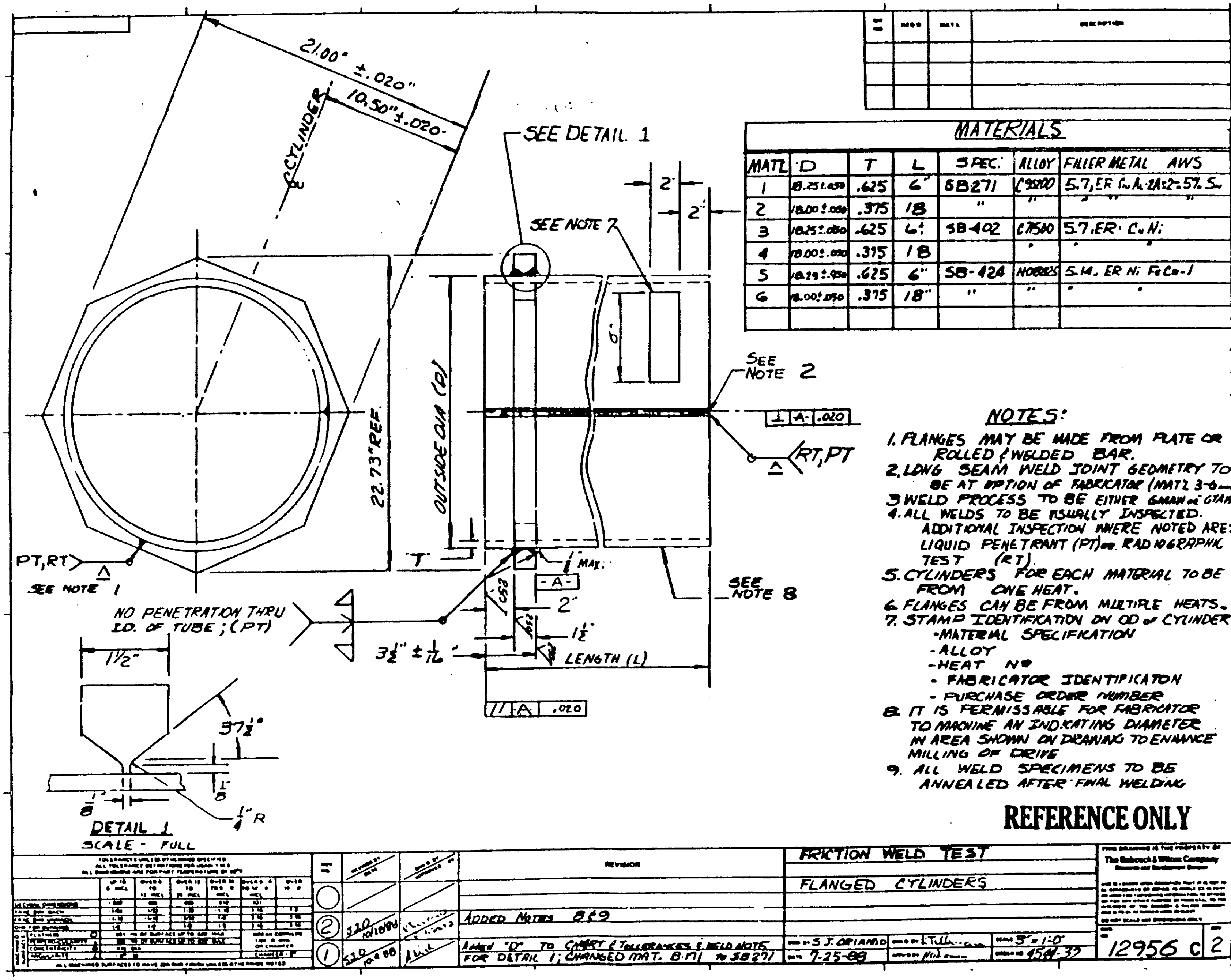


FIGURE B-4. Potential Flanged Cylinder Design.

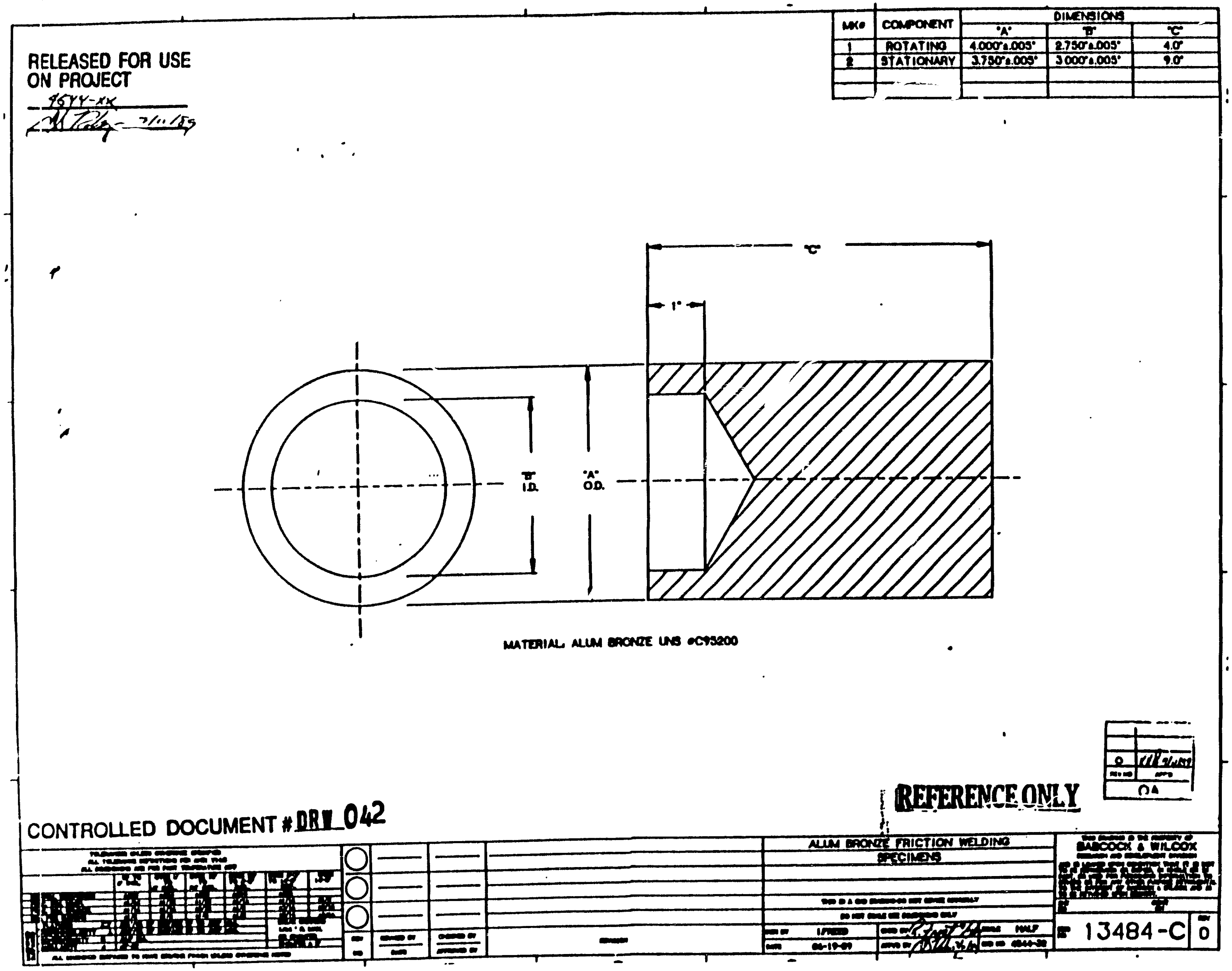


FIGURE B-5. CDA 952 Specimen Design.

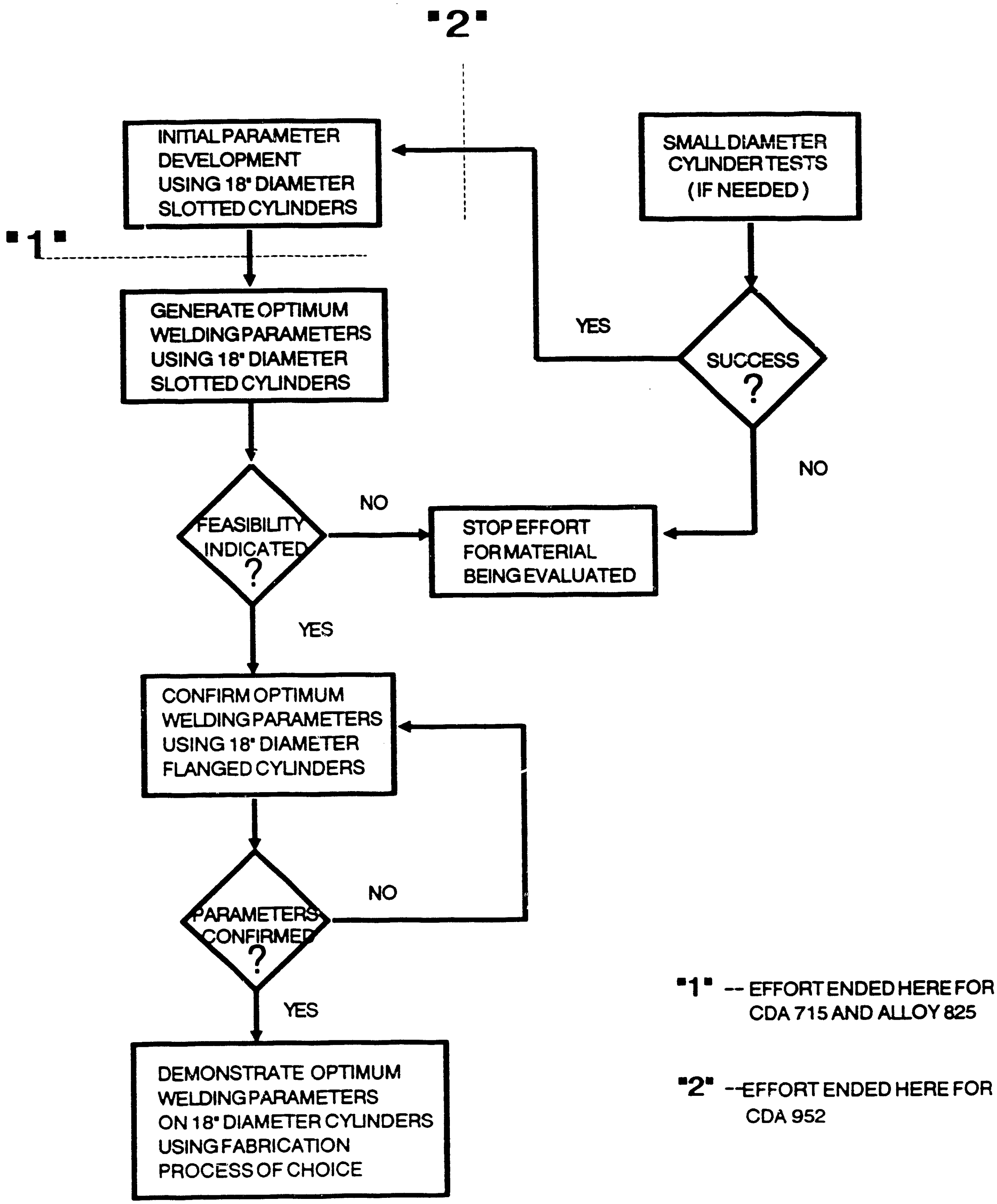


FIGURE B-6. Phase 2 - Friction Welding Test Sequence.

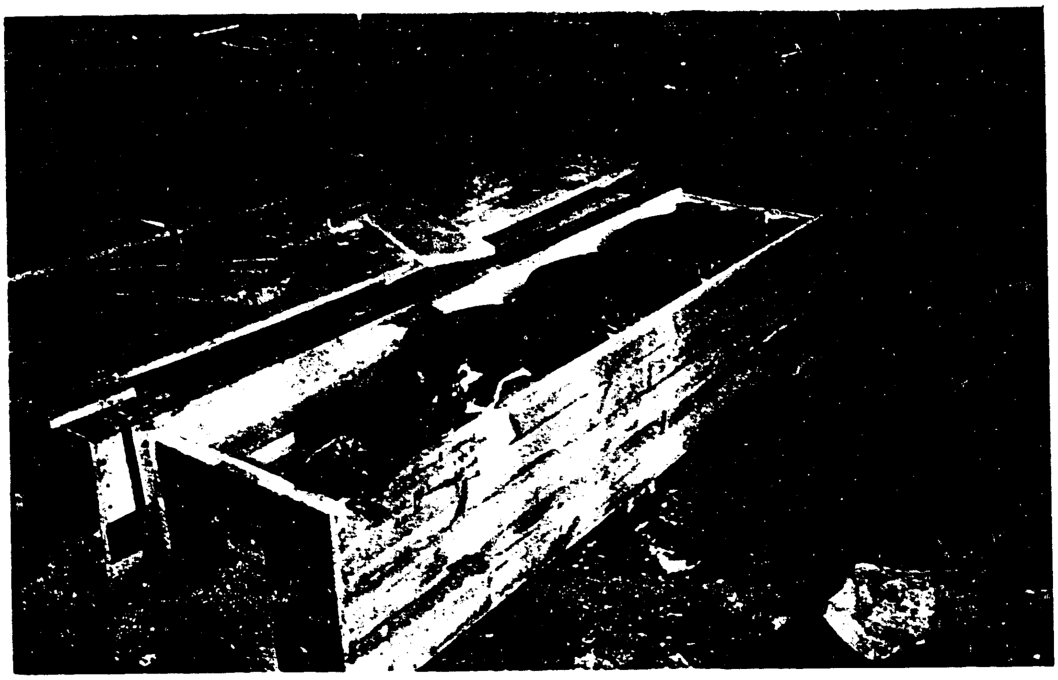


FIGURE B-7A. 18" Diameter Specimens As-Received at MTI.

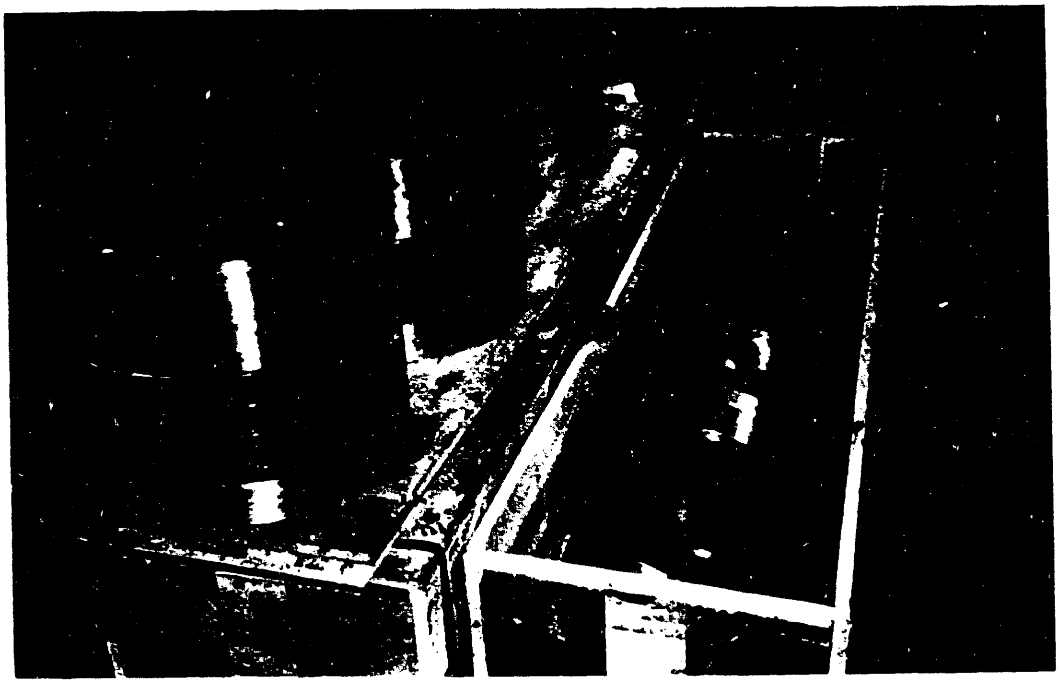


FIGURE B-7B. 18" Diameter Specimens With Protective Wrap Removed.

FIGURE B-8A. Receipt Inspection Height Measurement of 18" Diameter Rotating Specimen. Records Kept on Route Sheet in Foreground.

FIGURE B-8B. Receipt Inspection Wall Thickness Measurement of 18" Diameter Rotating Specimen.

FIGURE B-9A. Receipt Inspection Diameter Measurement on 18" Diameter Stationary Specimen.

FIGURE B-9B. Specimen Identification Marking at MTI.

FIGURE B-10A. Collet liner for Rotating Specimen.

FIGURE B-10B. Testing of Fit of Collet Liner With Rotating Specimen.

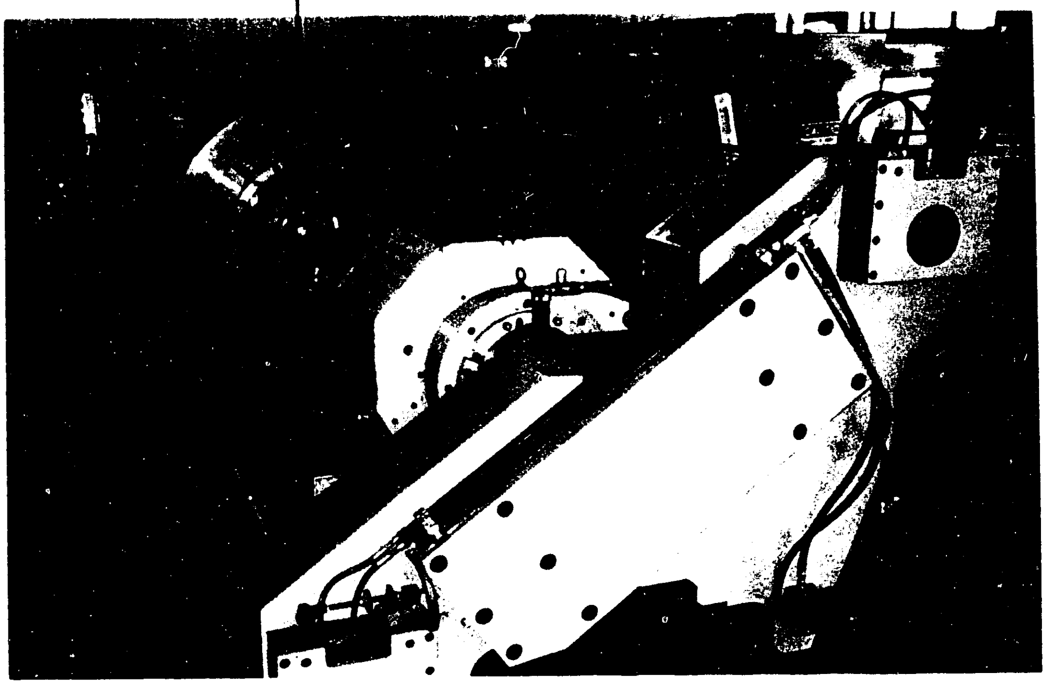


FIGURE B-11A. Model 400 SBX Inertia Friction Welder.

FIGURE B-11B. Spare Flywheels for Model 400 SBX Inertia Friction Welder.

FIGURE B-12A. Placing of Rotating Specimen Into Collet of Spindle.

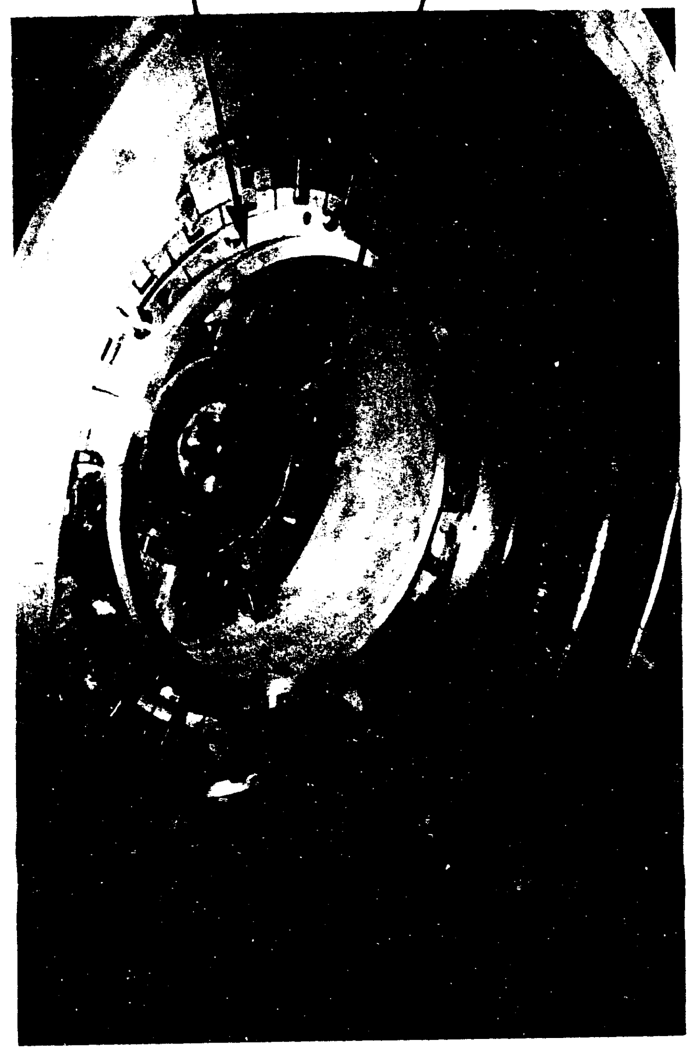


FIGURE B-12B. Rotating Specimen Properly Placed Within Collet.

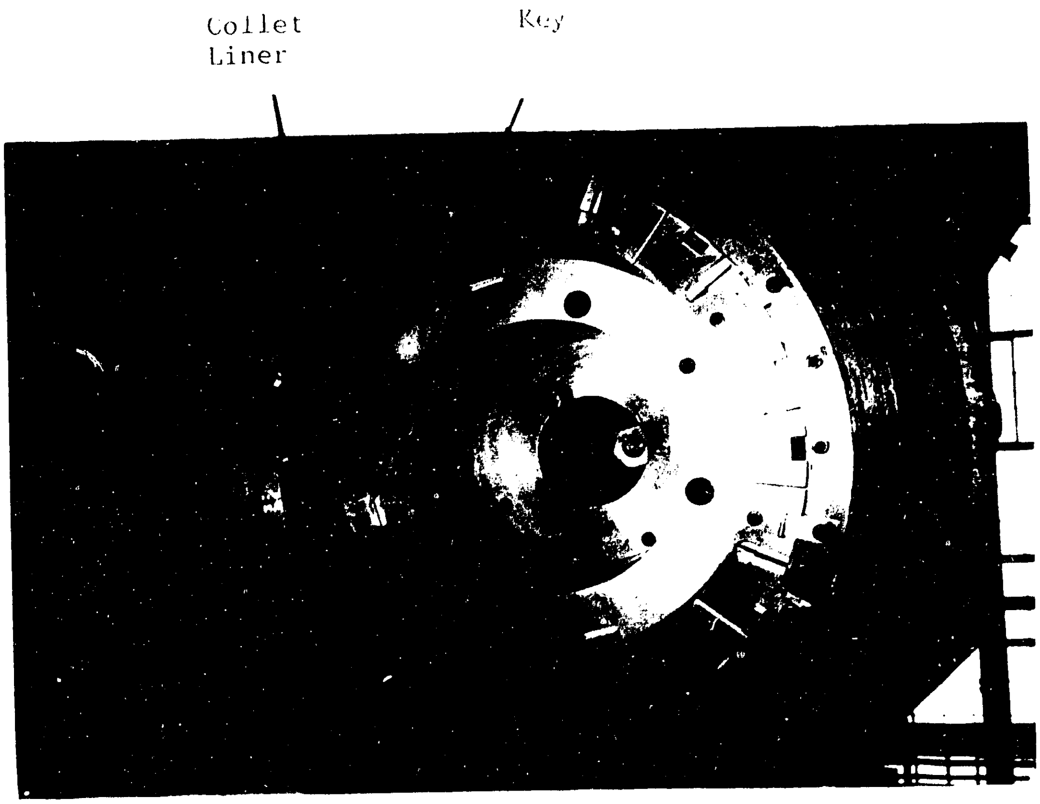


FIGURE B-13A. Collet to Hold Stationary Specimen.

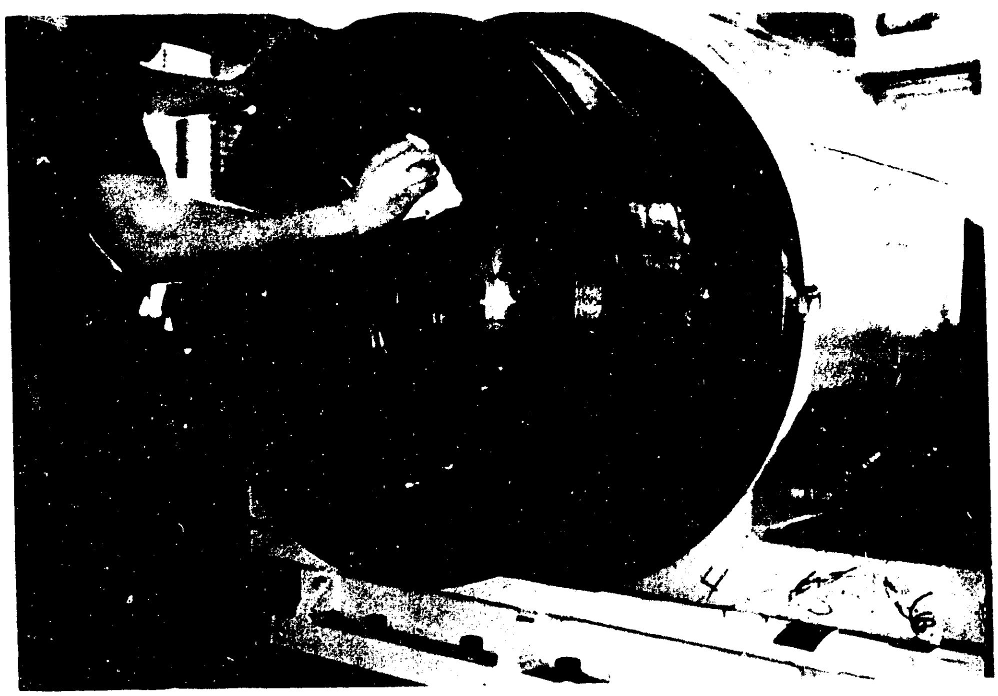


FIGURE B-13B. Stationary Specimen in Place Within Collet. Acetone Wipe Being Administered.

Specimen Within
Retaining Ring/Bearing

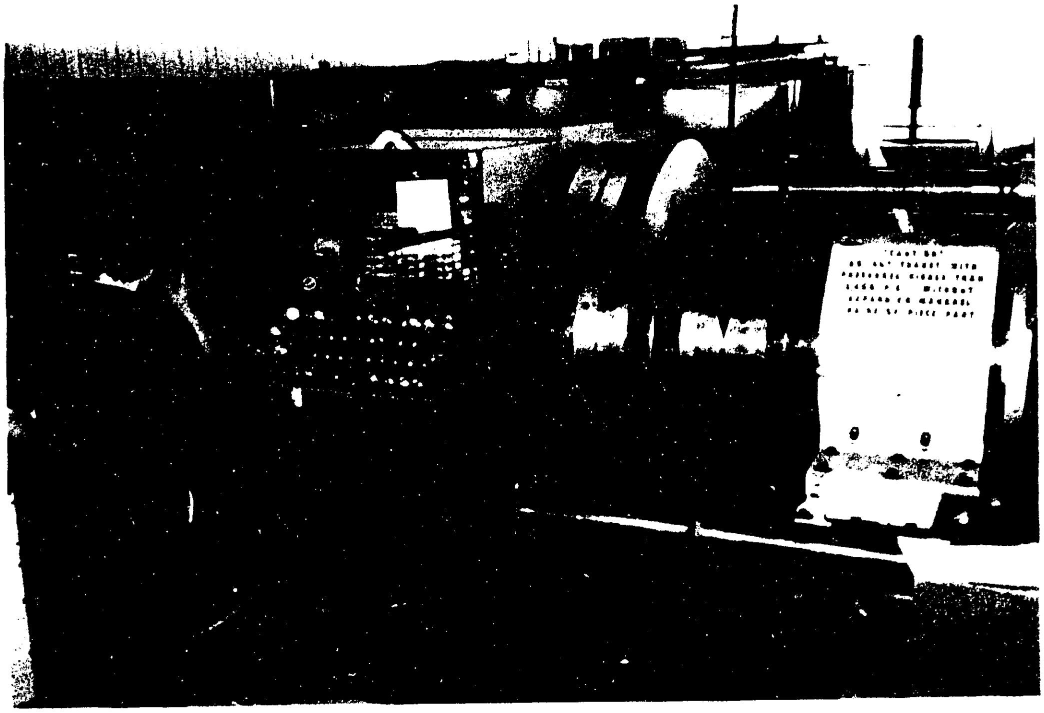


FIGURE B-14A. Seating of Specimens and Alignment Prior to Welding.

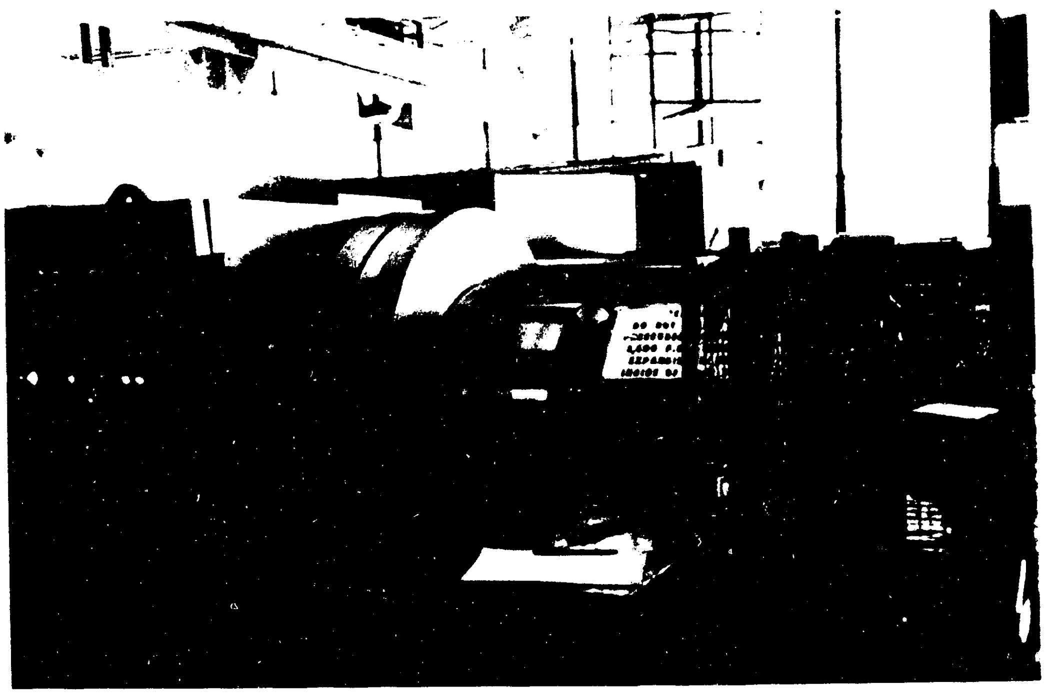


FIGURE B-14B. Welding in Progress.

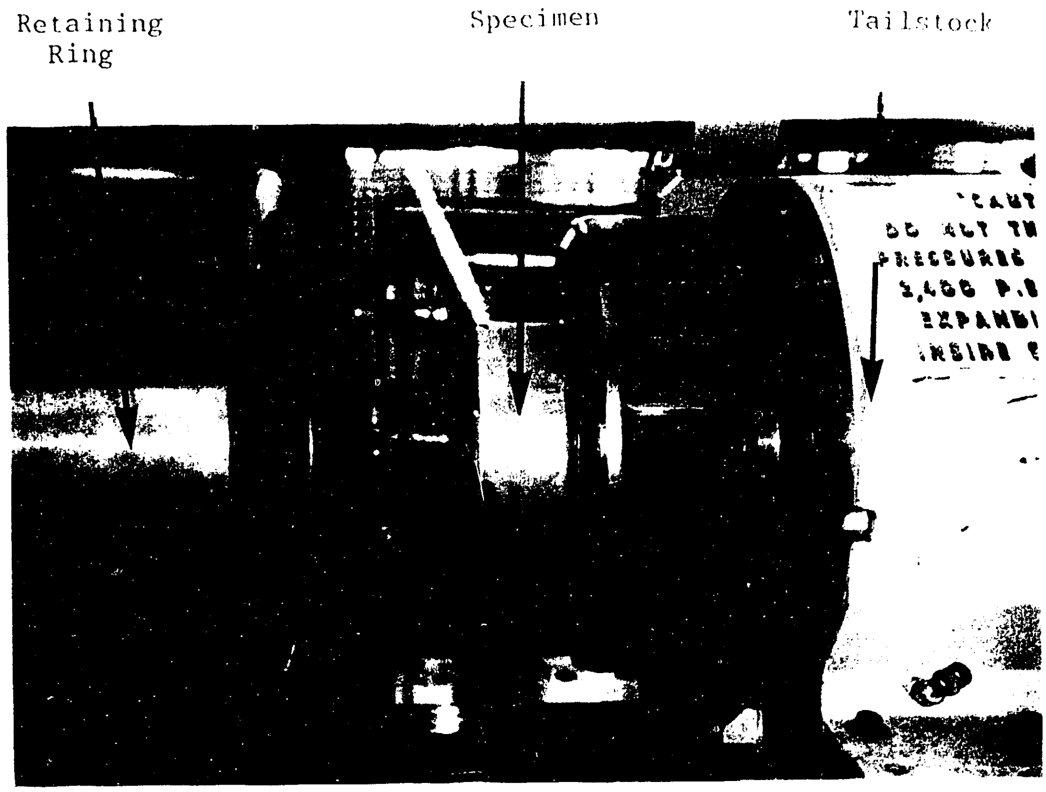


FIGURE B-15A. Retraction of Tailstock With Specimen Lodged in Stationary Collet.

FIGURE B-15B. Welded Specimen Within Stationary Collet.

FIGURE B-16A. Welded Specimen Within Collet.

FIGURE B-16B. Welded Specimen Partially Removed From Collet.

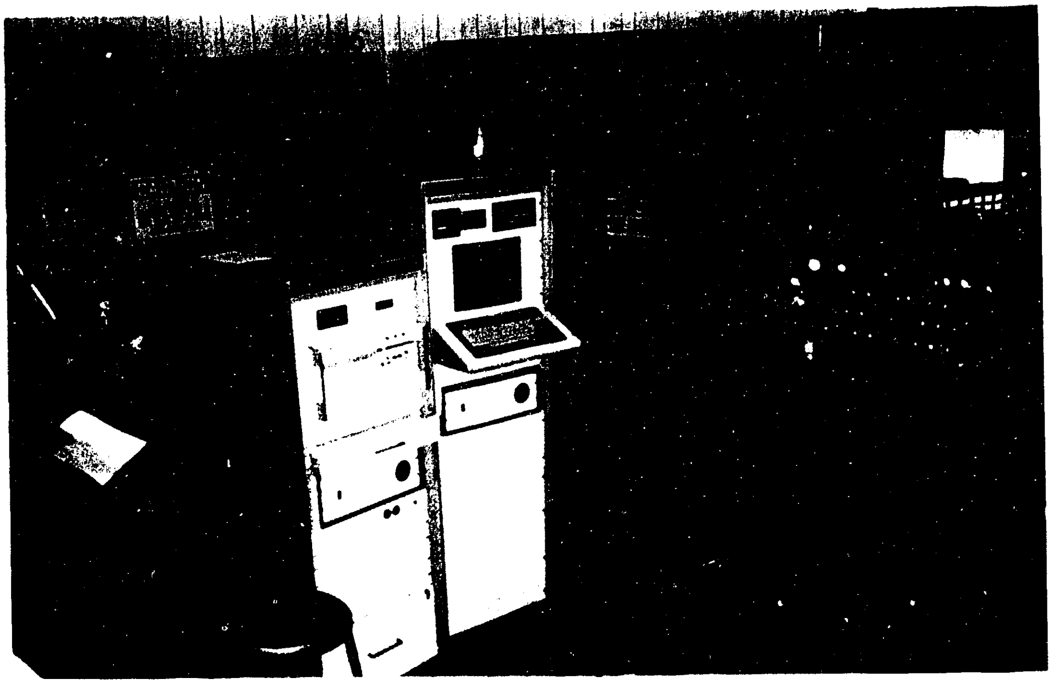


FIGURE B-17A. Recording Devices for Model 400 SBX Inertia Friction Welder.

FIGURE B-17B. Marking of Strip Chart After. Note Completed Weld in Foreground.

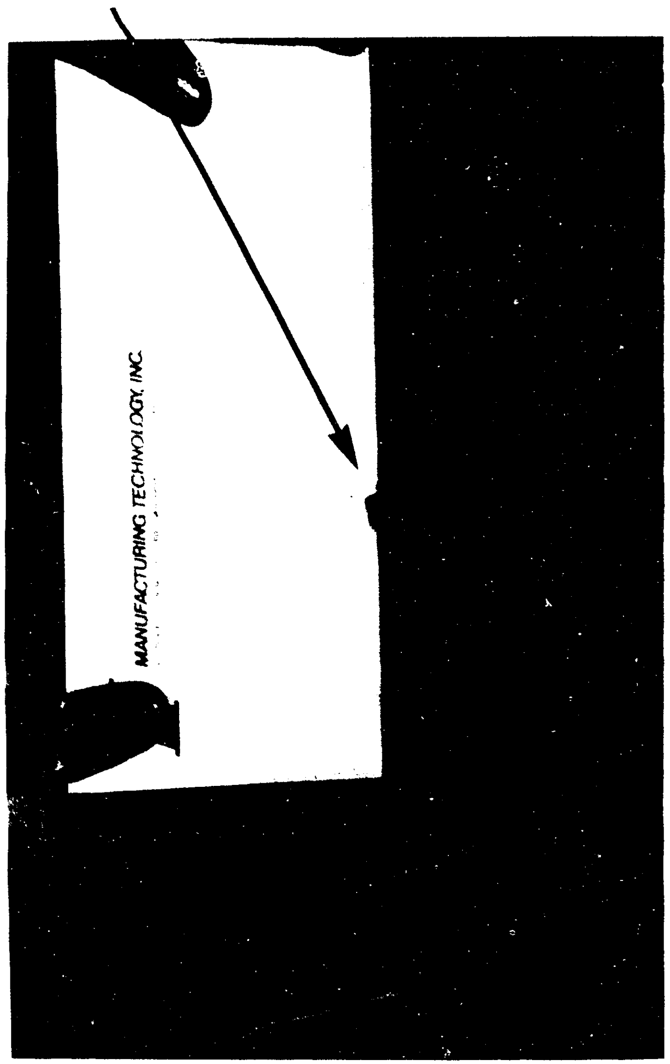


FIGURE B-18A. Flash Developed at O.D. of 18" Diameter Specimen.

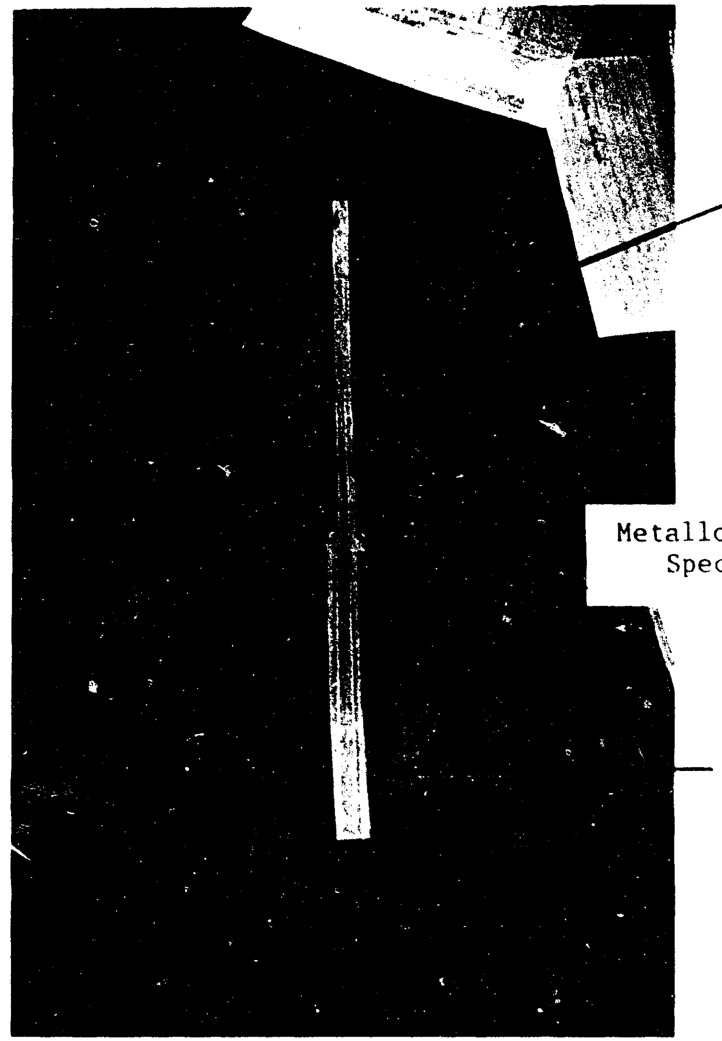


FIGURE B-18B. Section of 18" Diameter Alloy 825 Specimen for "Scoping" Trials. A Full-Length Specimen Such as This was Bend-Tested. The Markings on This Particular Specimen Show Where it was Further Sectioned for Metallography.

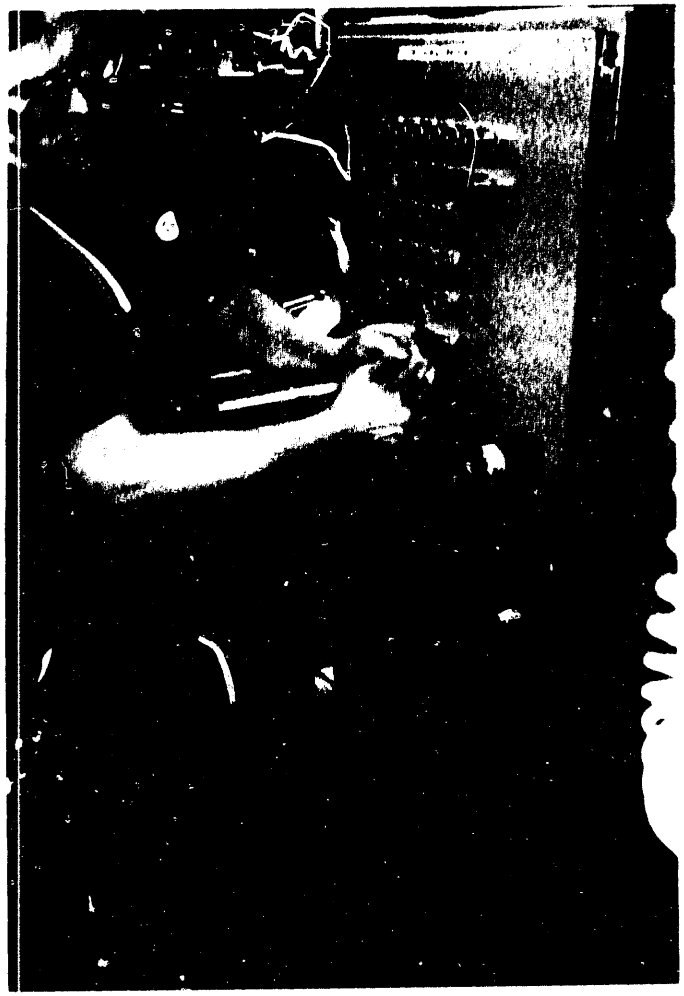


FIGURE B-19A. Scoping Bend Test.

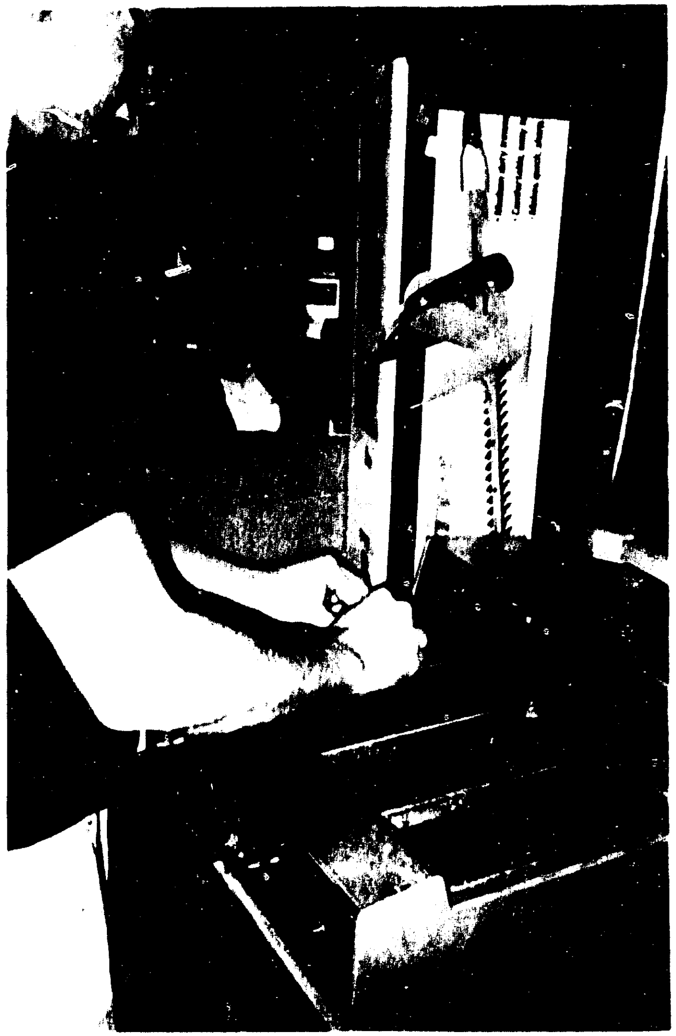


FIGURE B-19B. Scoping Metallography.

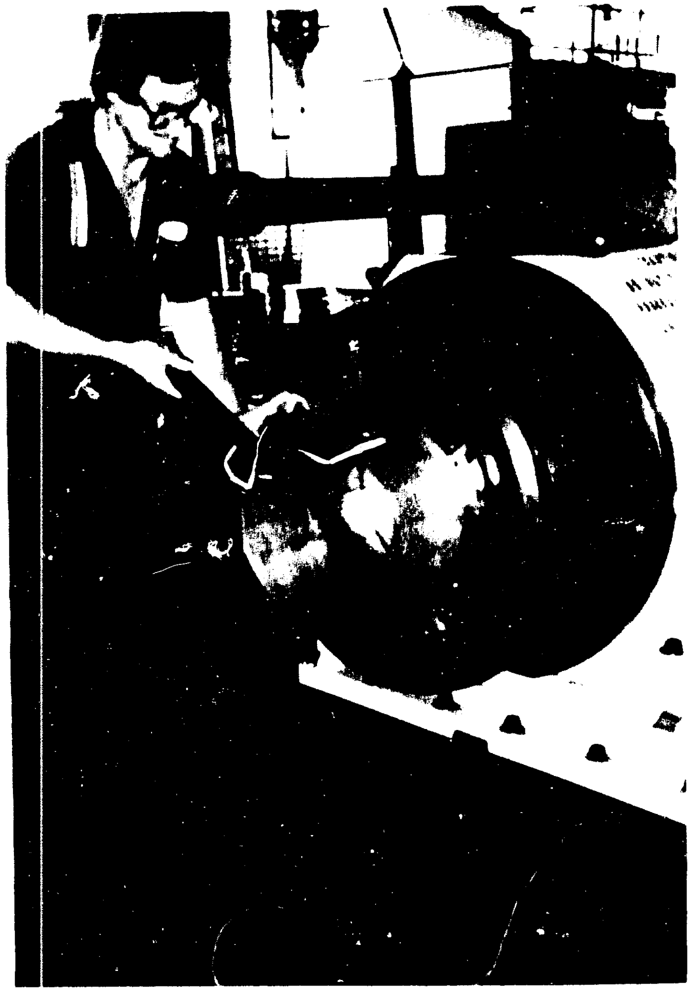


FIGURE B-20A. As Testing Went on, Difficulties Were Experienced in Inserting Stationary Specimen Within the Stationary Collet Liner.

FIGURE B-20B. Similar Difficulties Were Experienced in Mating the Rotating Specimen Within the Rotating Collet Liner.

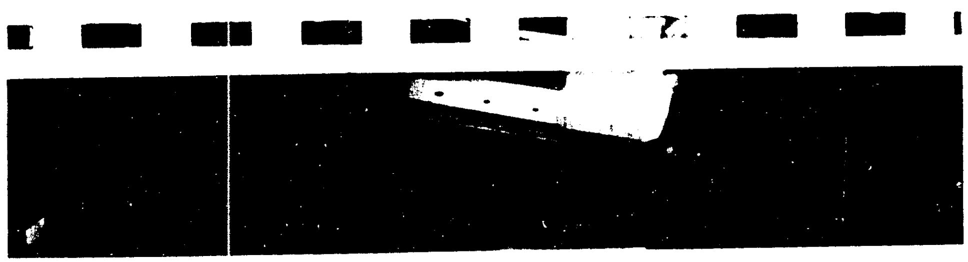


FIGURE B-21A. Headstock of Model 250B Inertia Friction Welder.

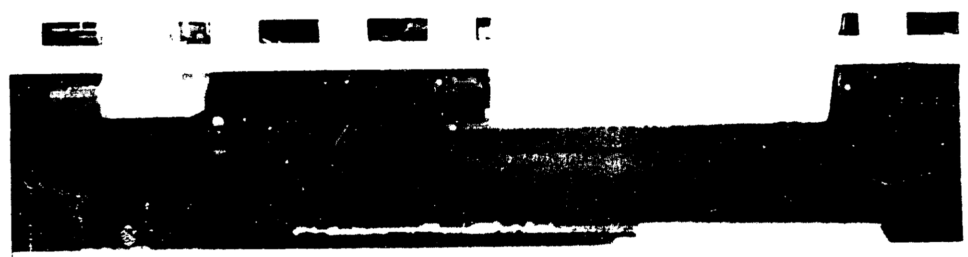


FIGURE B-21B. Tailstock of Model 250B Inertia Friction Welder.

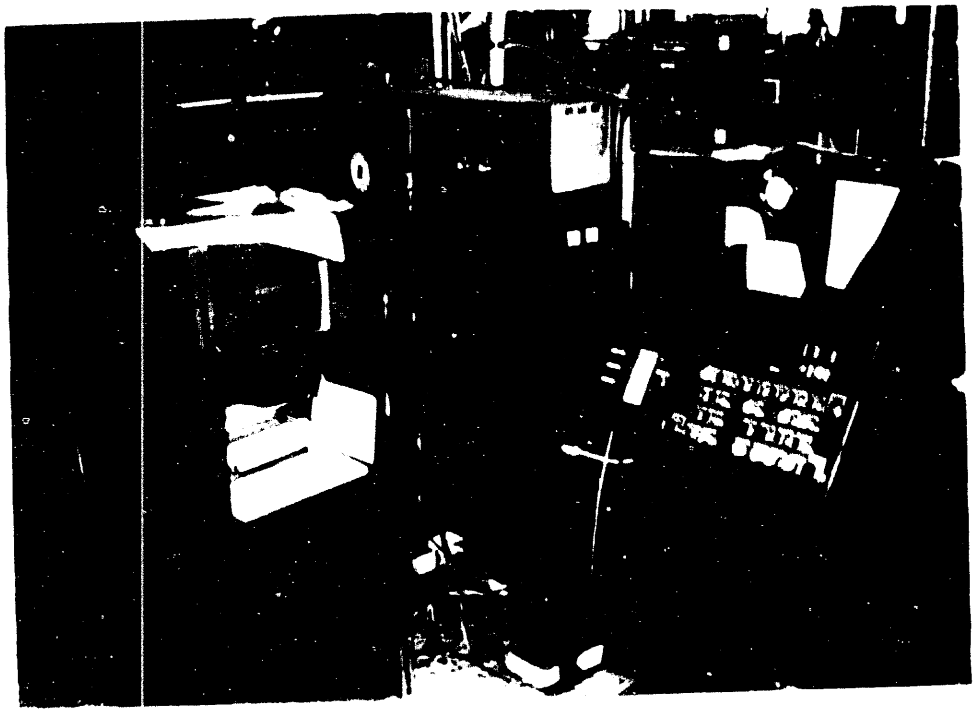


FIGURE B-22A. Controls and Recording Devices for Model 250B Inertia Friction Welder.

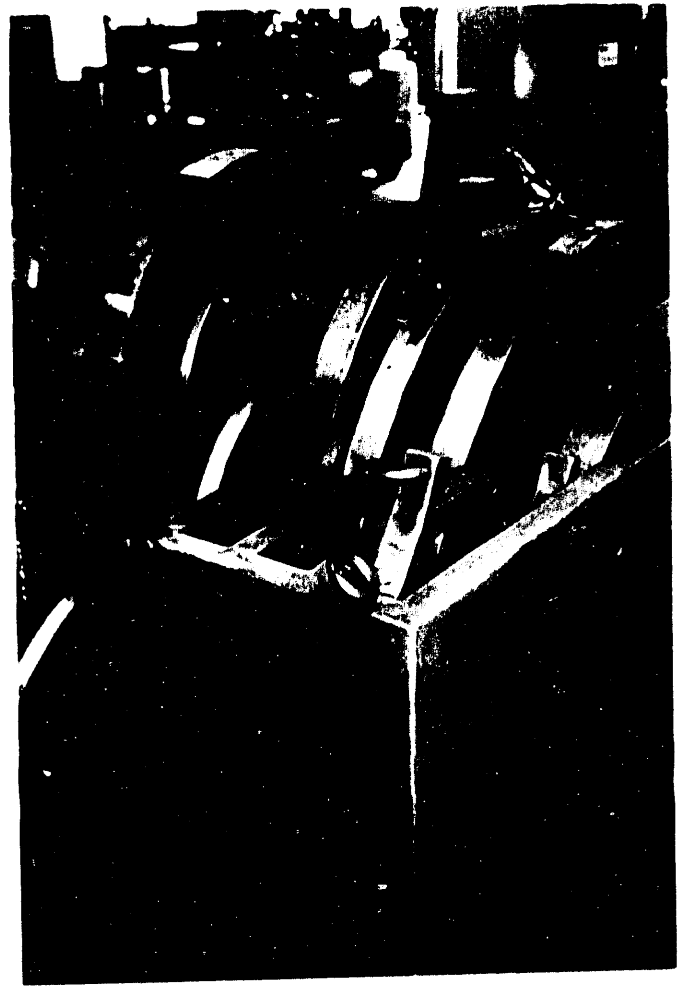
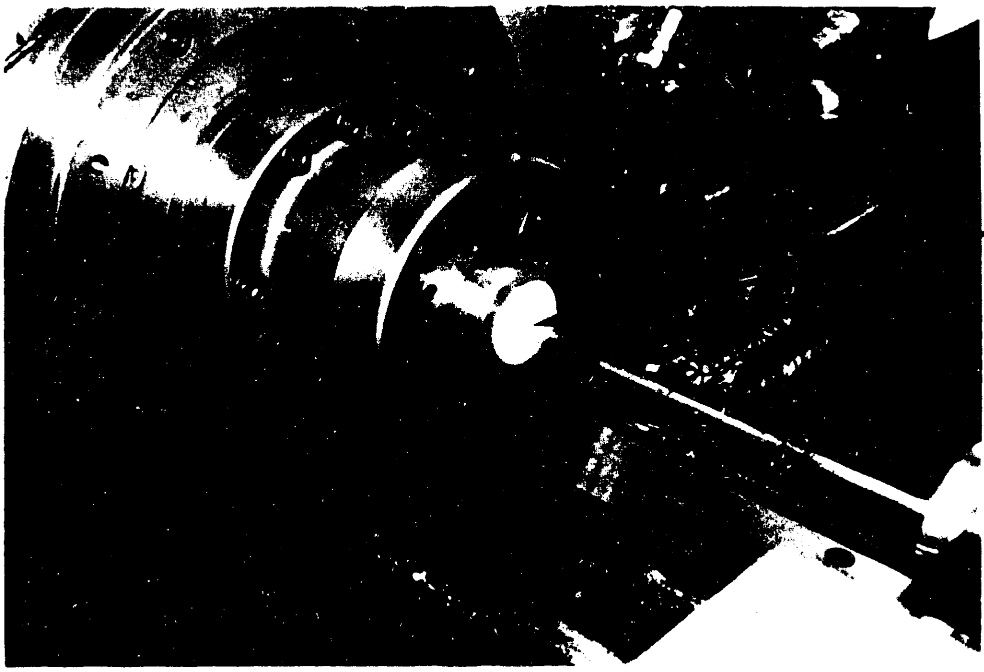


FIGURE B-22B. Flywheels for Model 250B Inertia Friction Welder.



Specimen

FIGURE B-23A. Rotating Chuck With 4" Diameter Specimen in Place.

Specimen

FIGURE B-23B. Stationary Chuck With 4" Diameter Specimen in Place.

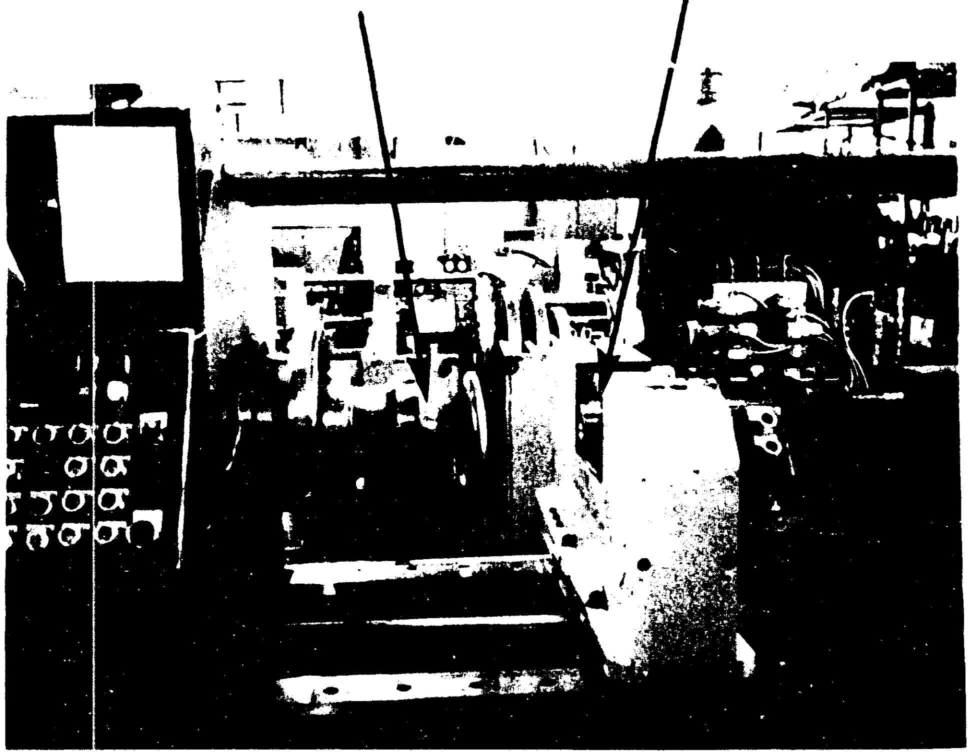


FIGURE B-24A. 4" Diameter Specimens Being Brought Into Position Immediately Prior to Welding.

FIGURE B-24B. Welding in Progress for 4" Diameter Specimen.

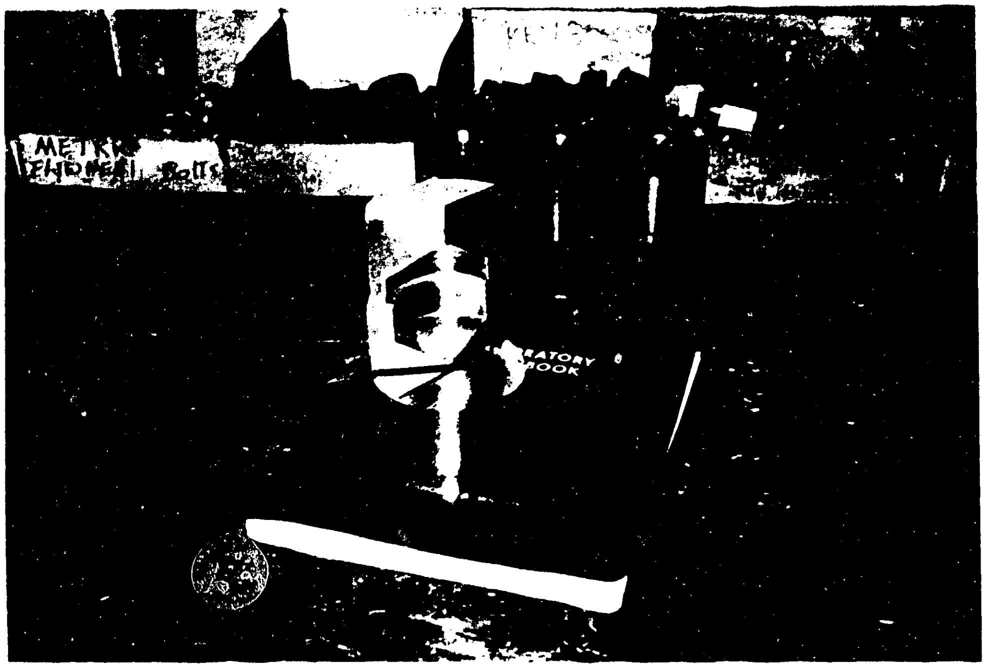
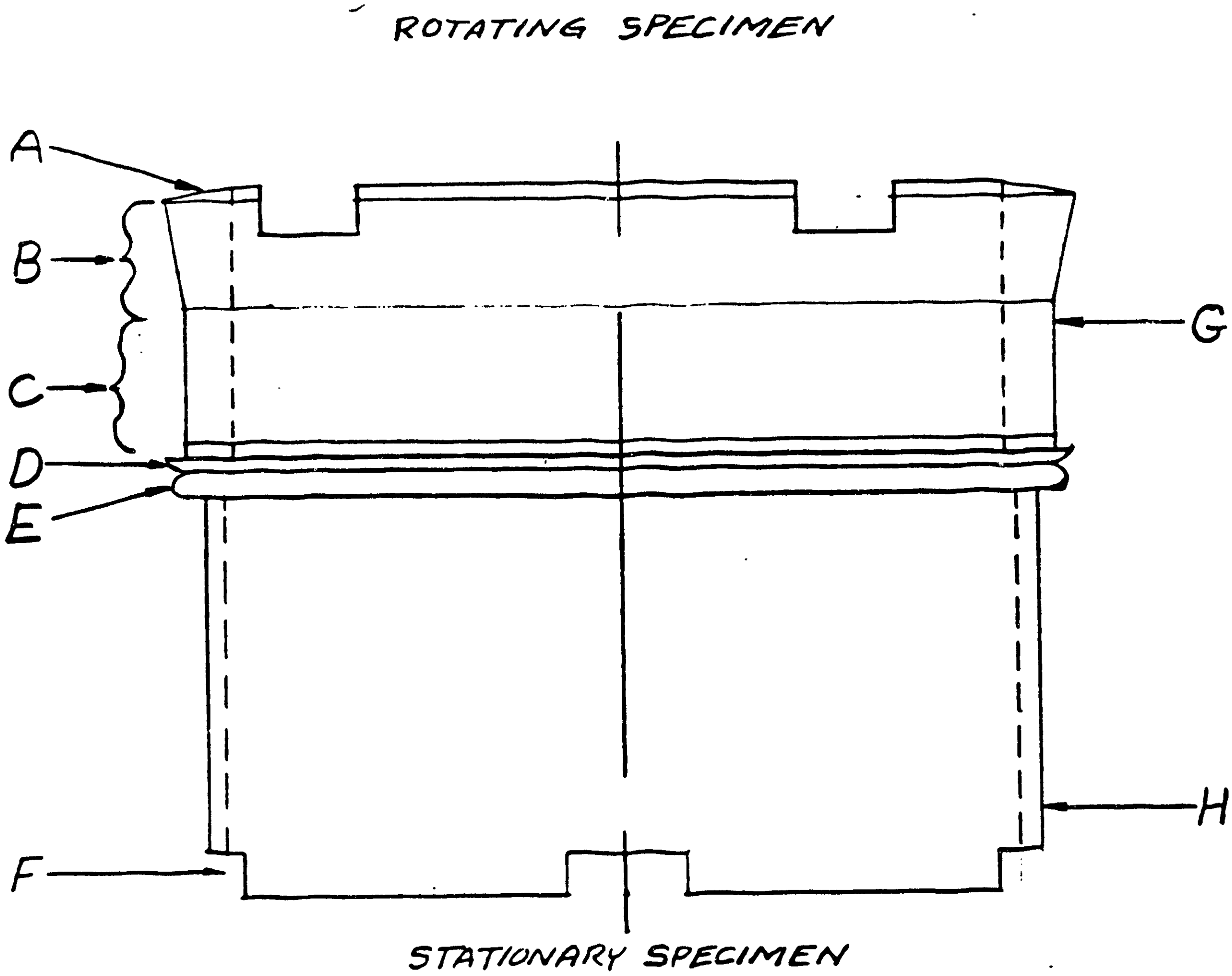


FIGURE B-25. 4" Diameter CDA 952 Specimen Sectioned for Scoping Trials.



A) DISTORTION OF BACK FACE — EXAGGERATED.

B) AREA OF CLAMPING DISTORTION - EXAGGERATED.

C) CLAMP MARKS

D) WELD FLASH

E) WELD FLASH

F) DRIVE KEY SLOT - TYPICAL

G) & H) OVALITY MEASUREMENTS TAKEN IN THESE AREAS.

FIGURE B-26. Distortion Noted in Slotted 18" Diameter Specimens.

APPENDIX C

Summary of Plasma Arc Welding Development Efforts

Author: C. C. Conrardy

APPENDIX C

SUMMARY OF PLASMA ARC WELDING DEVELOPMENT EFFORTS

Author: C. C. Conrardy

1.0 BACKGROUND

This report describes work which was conducted to develop plasma arc welding (PAW) procedures suitable for the closure of nuclear waste containers. Subsequent sections of this document present the testing methodology, a description of the specimens and equipment which were employed, the progress which was made, and the preliminary results of the effort. In order to facilitate these discussions, it is useful to first develop an understanding of the technical aspects of the PAW process which pertain to the welding procedure development efforts. The intent of this section is to provide such an understanding.

1.1 The Plasma Arc Welding Process

Compared to other arc welding processes, the plasma arc welding (PAW) process has a number of advantages, including a stable directional arc, relative insensitivity to variations in torch stand-off distance, and the potential for weld beads having relatively high depth-to-width ratios. Each of these features make the process attractive for closure of waste containers. Further details into the rationale for selection of this process as a candidate for waste container closure can be found in the Phase 1 final report [1].

The advantages of the PAW process are derived from the torch design. Figure C-1 is a simplified schematic representation of a PAW torch cross-section. The welding arc is generated between the non-consumable tungsten electrode and the workpiece. As Figure C-1 shows, the arc passes through an orifice between the electrode and the workpiece. The arc is constricted by the impingement of the plasma gas which flows through the orifice. Constriction of the arc in this manner causes a columnar arc shape having a high core temperature and a high arc force impinging on the weld pool. The columnar shape of the arc is responsible for its characteristic stability and insensitivity to changes in torch height; while the high core temperature and arc force promote the good penetrating capability indicative of PAW.

Clearly, development of the optimum PAW procedures for waste container closure must include selection of those parameters which influence arc constriction. In this study, the two parameters which have the greatest impact on arc constriction were evaluated: (1) the orifice diameter, and (2) the plasma gas flow rate. Additionally, careful attention was given to maintaining constant the other parameters which could affect the arc constriction; those being electrode angle, electrode set back, orifice dimensional tolerance, and the plasma gas composition.

The container closure application is a horizontal weld having a deep penetration root pass followed by several shallow penetration fill passes. For this application, in addition to arc constriction, there are a number of PAW process parameters which can have a critical effect on the weld quality. The parameters which were identified for study included welding current, arc length, travel speed, torch angle, wire feed speed, shielding gas composition, and weld joint geometry. These were selected because they influence the weld bead size, the weld bead shape, the ability to support the pool in the horizontal position, the depth of penetration, and the frequency of defects such as lack of fusion, undercut, or porosity.

2.0 TESTING METHOD

The goal of the work was to develop procedures which produce partial penetration welds that are free of significant defects and possess acceptable mechanical properties. Actual laboratory experimentation was begun on July 12, 1989 and proceeded until September 29, 1989. This section provides a brief overview of the PAW development tasks which would have been performed if the work had been carried out to completion. The actual work which was completed during this period and the preliminary results which were obtained are presented in later sections.

The PAW development procedures which were followed are detailed in the approved technical procedure entitled "Plasma Arc Welding Parameter Development for LLNL Container Closures" (ARC-TP-823, applicable revisions) [2]. This technical procedure provides information about the PAW development experimental method, the welding, measuring, and testing equipment, the weld evaluation procedures, and the documentation requirements. Elaborate testing methods were employed to ensure that all the significant parameters and conditions which could influence the outcome of a particular test were controlled, measured, and documented. This would allow not only the development of the optimum welding procedures, but also the verification of specific test results by independent researchers.

PAW development was to be conducted using three base-metal/filler-metal combinations: Alloy 825 plate/Alloy 825 filler, Alloy 825 plate/Alloy 625 filler, and Alloy 715 plate/70Cu-30Ni filler. These combinations were selected for development with the PAW process by our customer, LLNL.

Figure C-2 shows the testing sequence which was planned for each plate/filler alloy combination. To develop an understanding of the effects of various welding parameters on the weld bead characteristics, preliminary trials were performed prior to official testing; these have been termed "scoping trials". Table C-1 shows the PAW parameters which were systematically varied to determined their effects on weld bead dimension and quality for these trials. The scoping trials were not performed to the requirements of ARC-TP-823, and so were not considered to be official data. The scoping trials were, however, valuable, since the knowledge gained allowed more efficient refinement of the welding parameters during the official testing. After completion of the scoping trials official testing was to be performed to verify the scoping trials under more controlled conditions and to more fully document the conditions and results of each trial.

To minimize material and machining costs, initial work was not performed on the weld joints, instead development progressed as shown in Figure C-2. First, bead-on-plate trials were conducted in the flat position to established stable arc conditions while avoiding significant metallurgical defects such as cracking and porosity. Next, horizontal position bead-on-plate trials were conducted to develop welding parameters which produce adequate penetration and an acceptable weld bead contour. Then these parameters were refined in horizontal weld joint mock-ups (grooves cut into flat plate specimens) to establish the proper conditions which produce acceptable root-pass penetration and fill pass side-wall fusion. The next step was to refine these parameters for actual welding joints, and to mechanically test the resultant welds. After the parameter refinement step, work would have proceeded to the determination of the allowable weld joint fit-up tolerances and the development of weld start and weld stop (i.e., transient, rather than steady state) procedures.

Welds were evaluated predominantly by visual inspection and examination of polished and etched cross-sections. In this manner, both weld bead dimension information (width, depth of penetration, etc.) and weld quality information (occurrence of porosity, cracking, lack of fusion, undercut, etc.) were obtained. Radiographic and mechanical testing were also available for weld evaluation, when appropriate.

3.0 SPECIMEN DESCRIPTION

The basic weld joint design which was intended for the waste container cylinders is shown in Figure C-3. The figure illustrates just one of several possible integrated-lip type joint configurations. The specific joint design would have been selected during the PAW development, if work had continued. As Figure C-3 shows, the design makes use of an integrated backing "lip". The purpose of the integrated backing is to facilitate alignment of the cap on the cylinder and to allow a partial penetration weld of thickness equal to that of the thinner member to be produced; thereby producing a weld of strength comparable to that of the cylinder wall and allowing for easy post weld inspection using ultrasonic techniques. Figure C-4 illustrates how a welded joint cross-section might look. Because partial penetration PAW would be employed, a number of the technical difficulties associated with the use of full penetration (keyhole) PAW would be avoided, simplifying the development effort and reducing the risk involved with actual container closure. These difficulties include the potential for leaving a void in the root of the weld should a perturbation in the welding arc occur.

The specimens used for the PAW development were designed to simulate the expected welding conditions for the actual waste containers. The following characteristics of the actual waste container cylinders were included in the PAW development specimens:

(1) The weld would be produced in the horizontal position so that the waste container could be held vertical during closure.

(2) The weld joint would be preheated to 90°C to simulate radioactive decay of the waste within an actual container.

(3) An integrated-lip type joint design would be used; this design would be used for the actual containers to aid in joint fit-up.

(4) The thickness of the container wall was expected to be 3/8", while the thickness of the cap was expected to be 5/8", thus producing a heat sink difference across the joint. Also, these thicknesses would necessitate several weld passes to be performed.

(5) Termination of the weld would occur in previously deposited weld metal, as would be the case on an actual container.

(6) Weld joint fit-up errors would inevitably exist.

The welding procedure development work made use of flat plate specimens to simulate the welding requirements of the cylindrical containers. Work was initially performed on un-grooved flat plates (see Figure C-5A) to develop preliminary welding parameters which produced stable arc conditions and beads having suitable cross-sectional dimensions without significant defects. Next, parameters were refined and bead placement schemes were developed using preheated grooved plates, such as those illustrated in Figure C-5B. Finally, parameters were to be optimized on preheated flat plate weld joints, as illustrated in Figure C-5C. Welds produced in flat plate joints would then have been mechanically tested to verify that suitable properties were obtained. Additionally, the effect of joint fit-up on weld properties would have been evaluated by producing welds in joints with varying degrees of root gap, backing gap, and mismatch.

4.0 EQUIPMENT DESCRIPTION

This section provides a brief overview of the types of equipment which was employed for the PAW parameter development. Details of the specific welding, testing, and measuring equipment which was used for this effort can be found in ARC-TP-823 and the appropriate laboratory notebooks.

The PAW parameter development welding equipment set-up is shown in the photograph of Figure C-6. The photograph shows the specimen fixture, the welding torch, the sidebeam for linear positioning of the torch, the plasma and shielding gas flow control equipment, the welding controller, and the automatic data recorder. Important equipment not shown in the photo include the welding and plasma power supplies, the gas mixer, the specimen preheating device, and various measuring instruments. This configuration provided the necessary flexibility to conduct the wide array of tests needed for PAW parameter optimization. The paragraphs which follow summarize important features of the various welding equipment.

Welding Fixture

Tooling was constructed to hold weld specimens in both the flat and the horizontal positions, as are shown in Figures C-7A and C-7B, respectively. The fixtures were designed to maximize the repeatability of preheat, heat sinking, specimen constraint, and grounding effects. The horizontal fixture incorporated provisions for electric resistance heaters to preheat the specimens to a predefined temperature.

Torch Manipulator

Tooling was constructed to position the PAW torch for either flat or horizontal position welding, as shown in Figures C-7A and C-7B, respectively. Additionally, the torch-to-workpiece distance and the torch angle were measurable and adjustable. The sidebeam carriage was driven along the sidebeam to move the torch along the work-piece.

Torch

Torch geometry is an extremely important parameter for the PAW process. For this reason, the dimensions of the critical torch components were carefully measured and controlled, including the orifice diameter, the electrode angle, and the electrode set-back from the orifice.

Gas Delivery System

Great care was taken to ensure that gas related parameters were repeatable. The shielding gas flow rate and the plasma gas flow rate were each measured with certified flowmeters. To assure accuracy in the instrument readings, the pressure on the inlet side of each flowmeter was measured with a certified pressure gauge. Gas mixtures were obtained by combining flows in a mixing chamber at 100 psig, and then correcting the output flow reading for the average density of the mixture; this method provides the a sufficiently accurate flow rate value for a given mixture.

Welding Controller

A Merrick Engineering Amptrack Micro II was used to provide automatic control of the welding sequence. Prior to each weld, this device was programmed to provide the appropriate coordination of torch motion, welding current, and wire feed speed commands. This provided a convenient means of adjusting the travel speed, current, and wire feed speed in a repeatable fashion.

Data Logger

A certified device (CRC-Evans Arc Data Monitor - Model II) was used to automatically measure and record the welding current, welding voltage, the wire feed speed, and the travel speed. These parameters were output to a printer once every second. The printed output was then retained in the appropriate laboratory notebook.

5.0 PROGRESS

Section 2.0 described the workscope which was intended for the PAW development effort. This section describes the work which was actually completed. Considerable progress was made in the PAW parameter development effort. In all, 131 welds were produced, evaluated and documented. Table C-2 summarizes these trials. The table lists the number of welds which were produced for each plate/filler metal combination. Weld trials were also performed without filler metal to simulate the root pass condition.

Scoping trials were conducted on each of the three base-metal/filler-metal combinations: Alloy 825 plate/Alloy 825 filler, Alloy 825 plate/Alloy 625 filler, and Alloy 715 plate/70Cu-30Ni filler. The scoping trials proceeded to the point of producing grooved plate weld beads for each base metal/filler metal combination (see Figure C-2). The scoping trials were not, however, completed. When the project was terminated, different groove geometries were being investigated to increase the root pass penetration, and several means of reducing the occurrence of microporosity in Alloy 715 were being evaluated.

In addition to the scoping trials, official data trials were conducted on the Alloy 825 plate. Official parameter development was begun on Alloy 825 plate without filler metal to represent the root pass condition. Official fill pass trials were then performed using Alloy 825 filler metal and Alloy 625 filler metal. The official data trials did not progress to the point of conducting grooved plate trials in Alloy 825. Thus, according to the Alloy

825 testing sequence illustrated in Figure C-2, no trials were performed to optimize the welding parameters on weld joints, or to define the weld joint tolerances, or to develop start/stop procedures. Also, no official data trials were conducted for the Alloy 715 plate.

6.0 PRELIMINARY RESULTS

Scoping trials were performed for each combination of plate and filler alloys. However official testing was begun only for the Alloy 825 plate and its filler alloys. Although the results were preliminary, initial indications were promising. It was found that through application of the proper weld joint configurations, shielding gas compositions, welding parameters, and bead placement schemes, apparently acceptable welds could be produced in both Alloy 825 and Alloy 715. Table C-3 provides the best welding conditions which were found during the limited testing; it is important to note that these results are preliminary (i.e., more development is required to obtain welding parameters which produce acceptable welds) and are mostly based on unofficial scoping trials. Figure C-8 shows a cross section of a typical scoping trial grooved plate specimen. No cracking was found in any of the weld sample cross-sections. Lack of fusion, cold lapping, and undercut were also avoidable. While occasional porosity was encountered in the Alloy 715 grooved plate scoping trials, it is believed this porosity can be eliminated through the application of the proper shielding gas composition. Additional development is also needed to select the optimum weld joint geometry, to refine the welding parameters, to document the data under official test conditions, and to verify the adequacy of the welds for closure of waste containers via mechanical and corrosion testing.

7.0 SUMMARY

A study was begun to develop plasma arc welding procedures for the closure of Alloy 825 and Alloy 715 waste containers. Elaborate testing methods were employed to ensure that all the significant parameters and conditions which could influence the outcome of a particular test were controlled, measured, and documented. This would allow not only the development of the optimum welding procedures, but also the verification of specific test results by independent researchers. A total of 131 weld trials were conducted to develop root pass and fill pass welding parameters for both Alloy 825 and Alloy 715. Preliminary results were promising, since welds could be produced which appeared to be free of significant defects. Further efforts are needed to refine the welding procedures, to document the development data, and to verify the adequacy of the welds for closure of waste containers.

REFERENCES

[1] E.S. Robitz, et.al, "Closure Development for High-Level Nuclear Waste Containers for the Tuff Repository - Phase 1 Final Report", UCRL 15964, Lawrence Livermore National Laboratory, Livermore, CA, 1989.

[2] C.C. Conrardy, "Plasma Arc Welding Parameter Development for LLNL Container Closures", Babcock and Wilcox - Alliance Research Center quality assurance document, technical procedure number ARC-TP-823, original release Feb. 7, 1989; latest revision Aug. 18, 1989.

TABLE C-1
SUMMARY OF PAW TRIALS

PLATE/FILLER	NUMBER OF TRIALS
Bead on Alloy 825 plate / no filler	40
Bead on Alloy 825 plate / 825 filler	15
Bead on Alloy 825 plate / 625 filler	5
Beads in Alloy 825 grooves	18
Bead on Alloy 715 plate / no filler	13
Bead on Alloy 715 plate / 70Cu-30Ni filler	22
Beads in Alloy 715 grooves	18
TOTAL	131

TABLE C-2
INDEPENDENT VARIABLES FOR THE PAW DEVELOPMENT

Torch travel speed	Orifice diameter
Welding current	Torch to work distance
Plasma gas flow rate	Torch angle
% H_2 in Ar shielding	Torch position within groove
% He in Ar shielding	Groove geometry
Specimen preheat	

TABLE C-3
PRELIMINARY PARAMETERS DEVELOPED
FOR WELDING EACH BASE-METAL/FILLER-METAL COMBINATION

I. Alloy 825 - 1/4" deep 60 degree included angle V-groove with a 3/32" flat

ROOT PASS

- Stand-off distance = 11/32"
- Current = 190 Amp
- Shield gas = nominal 95%Ar-5%H_2 at 31 cfh
- Plasma gas = nominal 100%Ar at 1.4 lpm
- Travel Speed = 7.5 ipm
- Torch angles = 90 degrees to the workpiece surface
- Preheat = 90 °C
- Orifice diameter = 1/8"

FILL PASS - Alloy 825 (0.045" diameter)

- Stand-off distance = 11/32"
- Current = 176 Amp
- Shield gas = 100% Ar at 29.8 cfh
- Plasma gas = 100% Ar at 1.4 lpm
- Travel Speed = 5.5 ipm
- Torch angles = 90 degrees to the workpiece surface
- Preheat = 90 °C
- Wire feed speed = 28 ipm

FILL PASS - Alloy 625 (0.035" diameter)

- Stand-off distance = 11/32"
- Current = 197 Amps
- Shield gas = 100% Ar at 29.8 cfh
- Plasma gas = 100% Ar at 1.4 lpm
- Travel Speed = 5.5 ipm
- Torch angles = 90 degrees to the workpiece surface
- Preheat = 90 °C
- Wire feed speed = 66 ipm

III. Alloy 715 - 1/4 "60 degree included angle V-groove

ROOT PASS

- Stand-off distance = 11/32"
- Current = 190 Amps
- Shield gas = 95%Ar-5%H_2 at 29.8 cfh
- Plasma gas = 100%Ar at 2.2 lpm
- Travel Speed = 4.5 ipm
- Torch angles = 90 degrees to the workpiece surface
- Preheat = 90 °C
- Orifice diameter = 1/8"
- Electrode angle = 20 degrees

FILL PASS - 70Cu-30Ni (0.035" diameter)

- Stand-off distance = 1/4"
- Current = 235 Amps
- Shield gas = 100% Ar at 29.8 cfh
- Plasma gas = 100% Ar at 1.4 lpm
- Travel Speed = 5.5 ipm
- Torch angles = 90 degrees to the workpiece surface
- Preheat = 90 °C
- Wire feed speed = 110 ipm

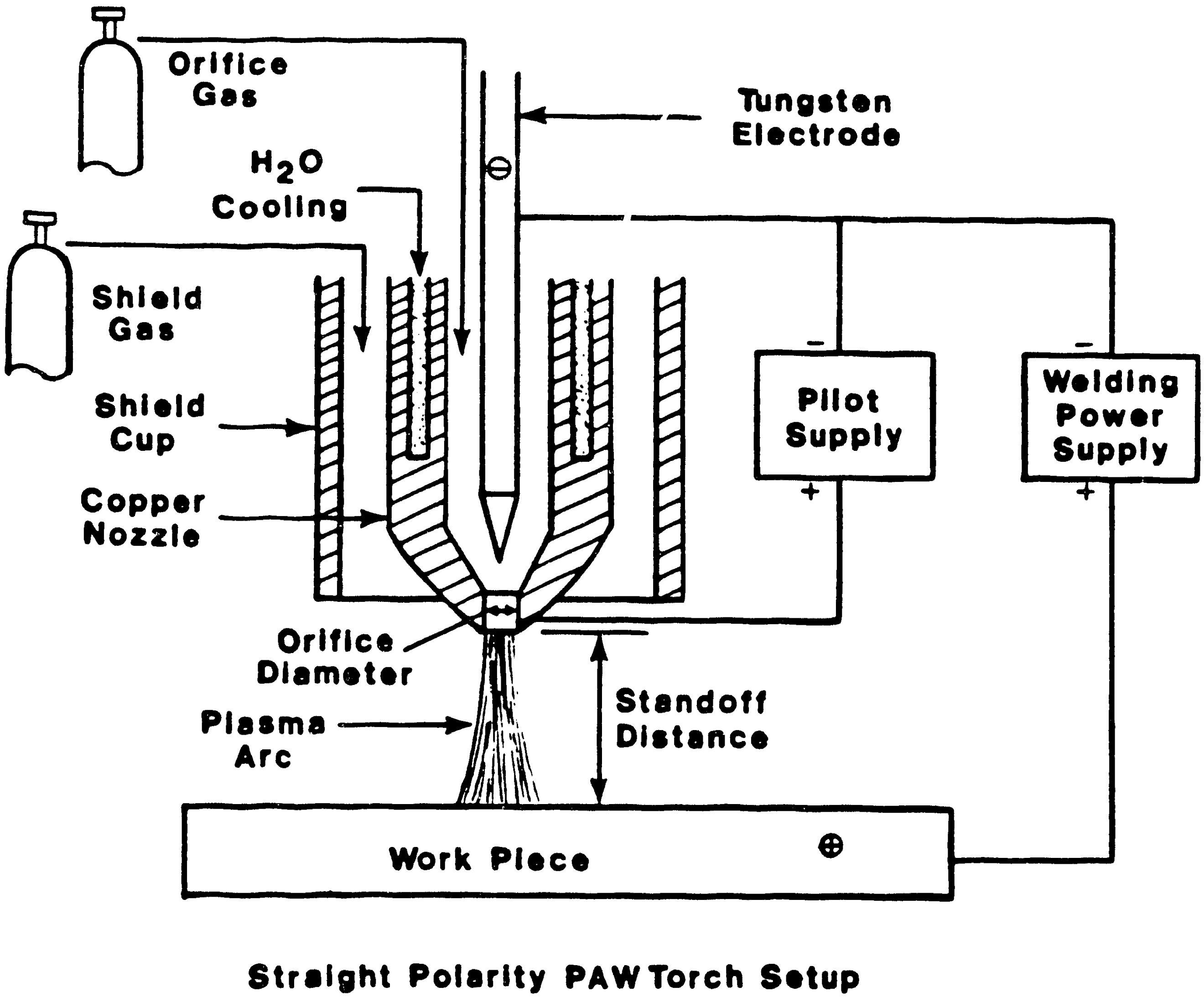


FIGURE C-1. Simplified Schematic Representation of a Plasma Arc Welding Torch Cross-Section.

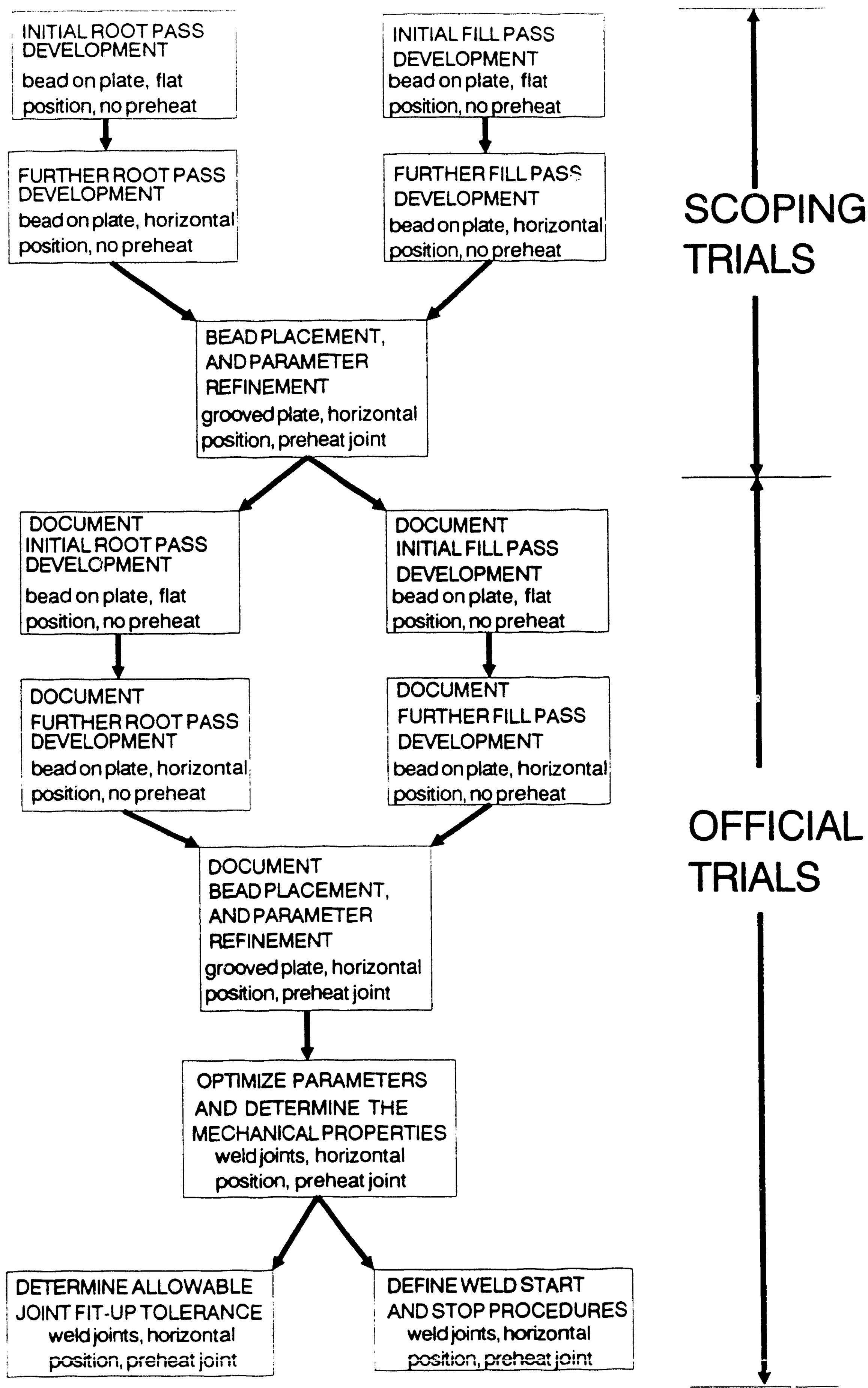


FIGURE C-2. Flowchart to Provide an Overview of the Plasma Arc Welding Procedure Development Methodology.

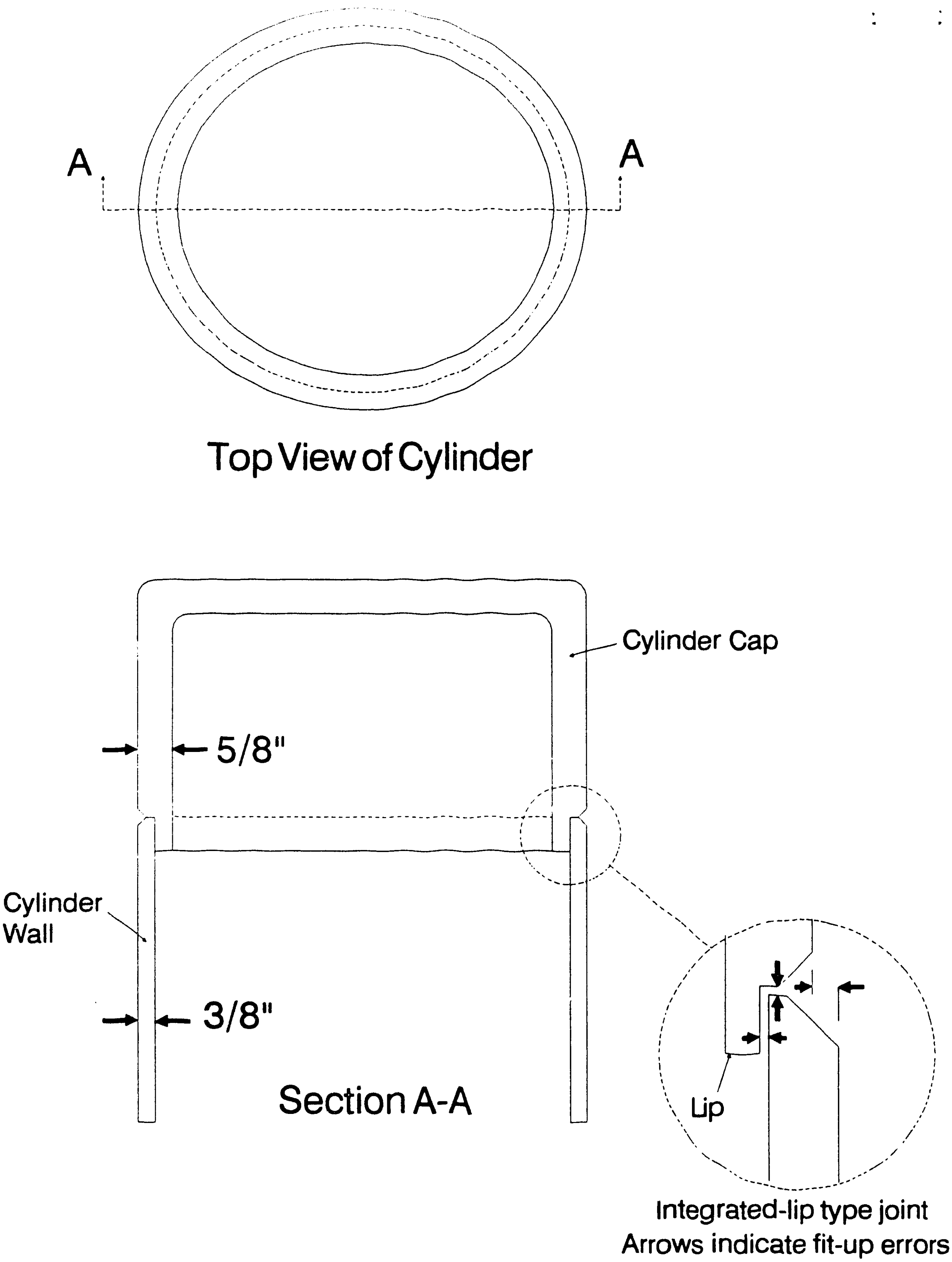


FIGURE C-3. Schematic Representation of the PAW Waste Container Design.

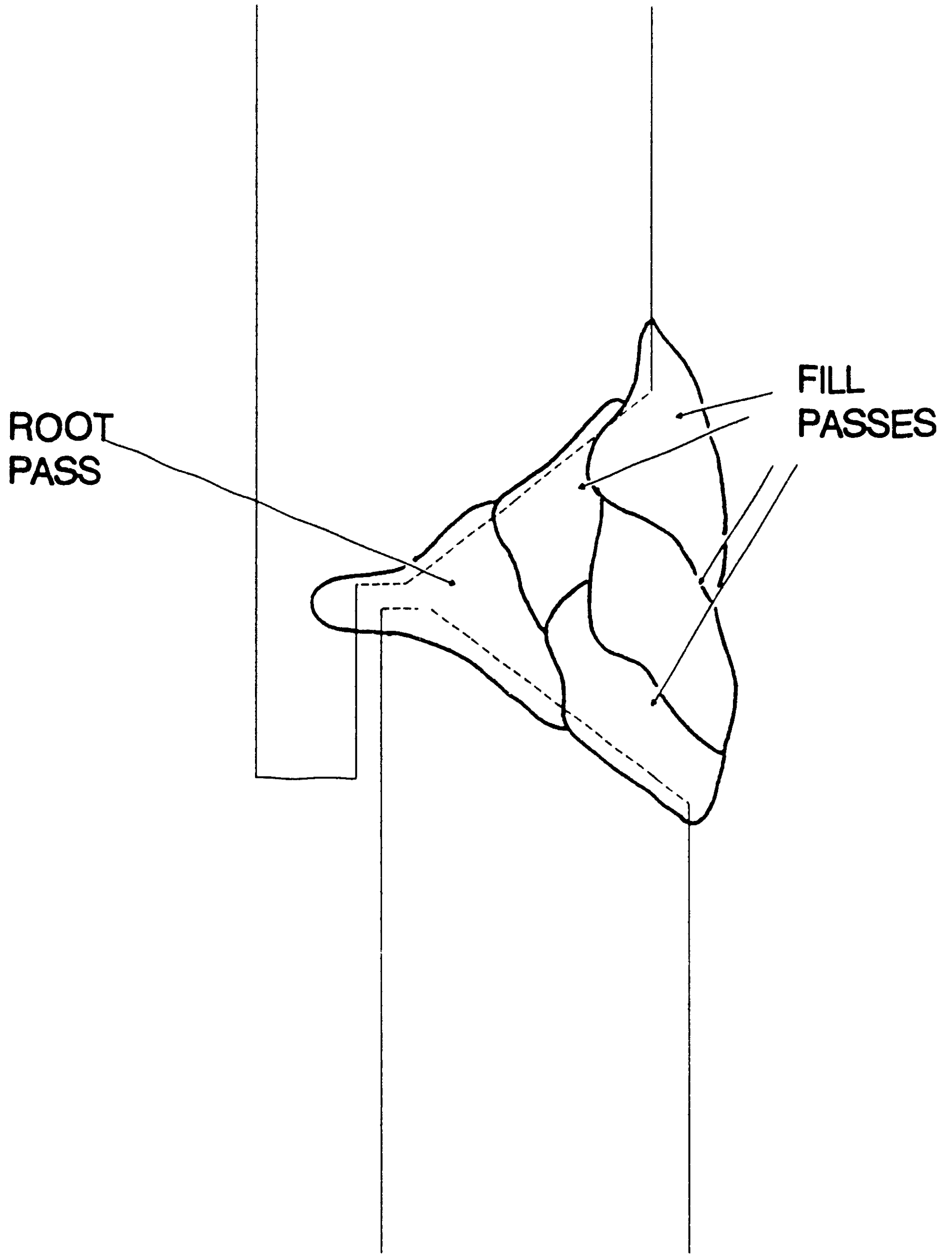


FIGURE C-4. Schematic Illustrating the Cross-Section of a Plasma Arc Welded Waste Container Joint.

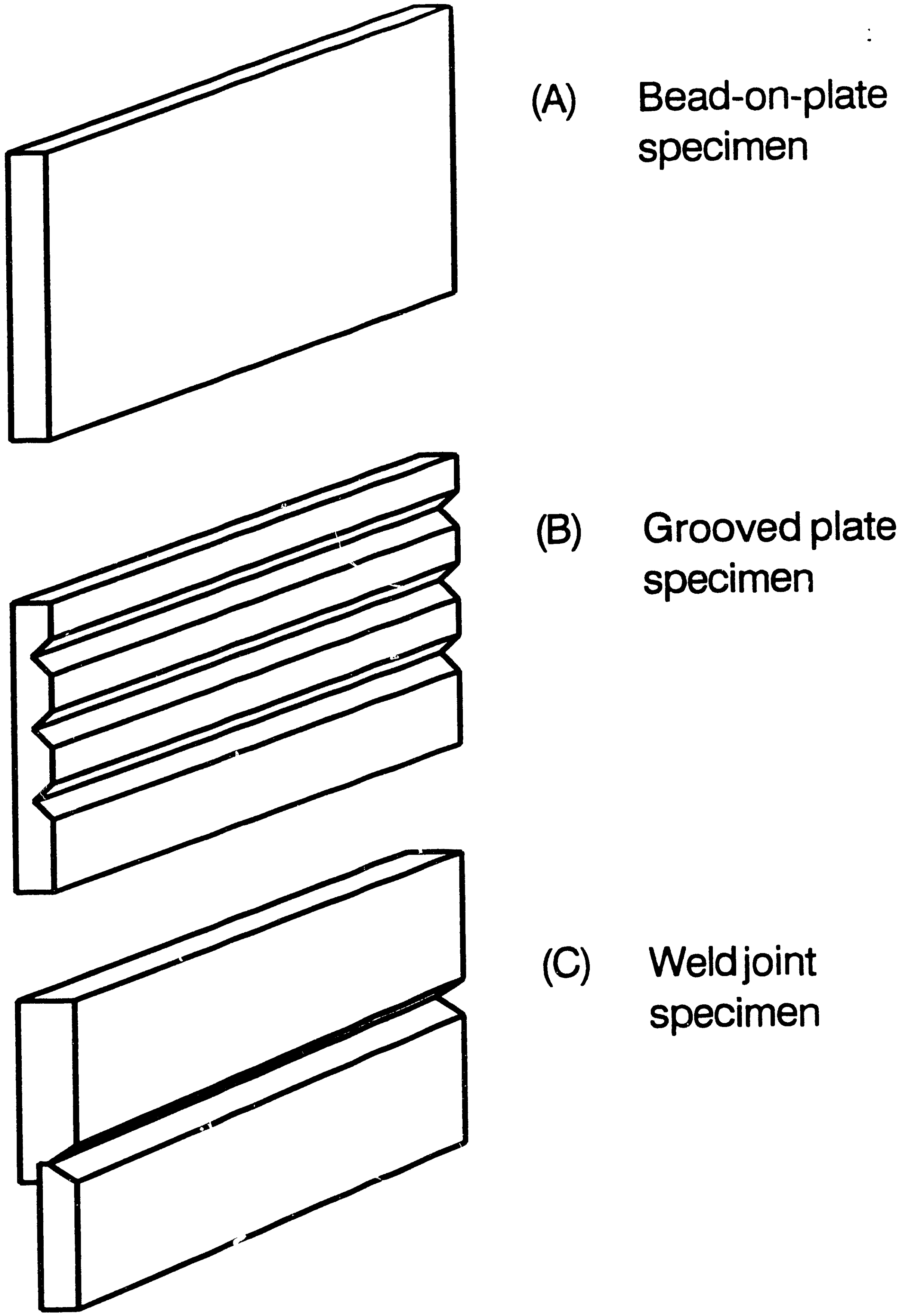


FIGURE C-5. Illustration of the Specimen Types to be Used in the PAW Parameter Development Effort.

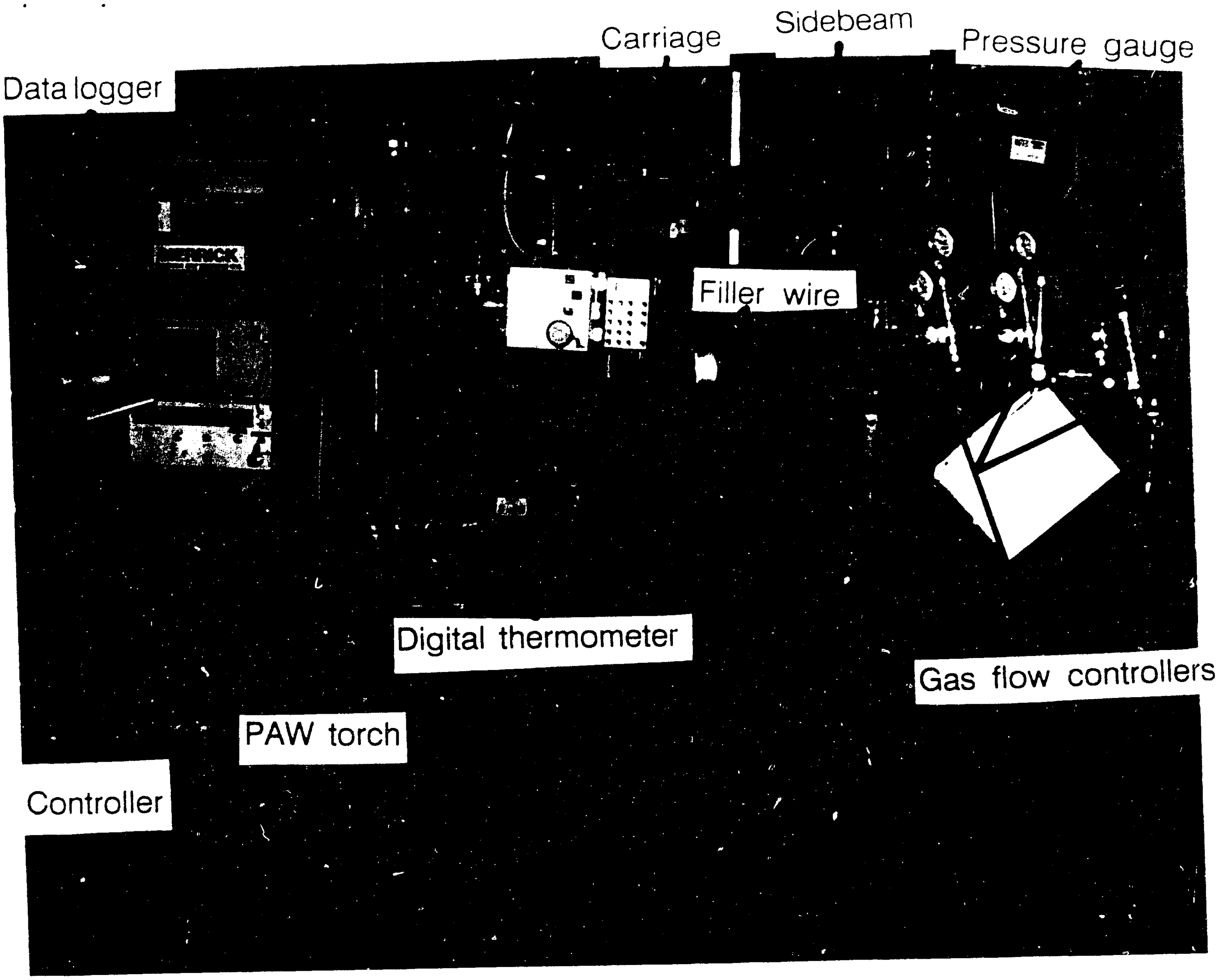


FIGURE C-6. Photograph Showing the Plasma Arc Welding Equipment Set-Up.

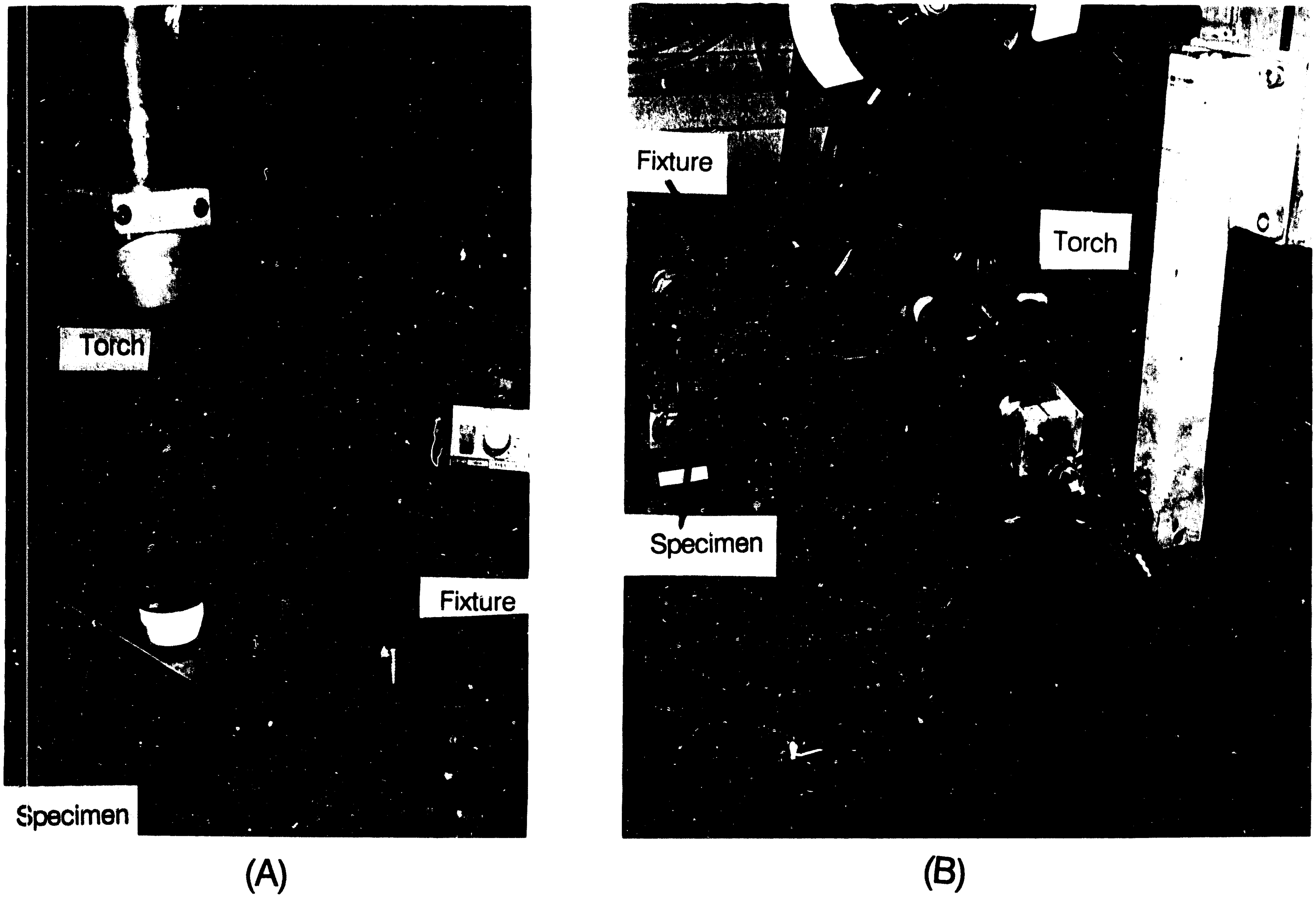


FIGURE C-7. Tooling for Fixturing the Specimen and for Positioning the Torch; (A) Flat Position, (B) Horizontal Position.

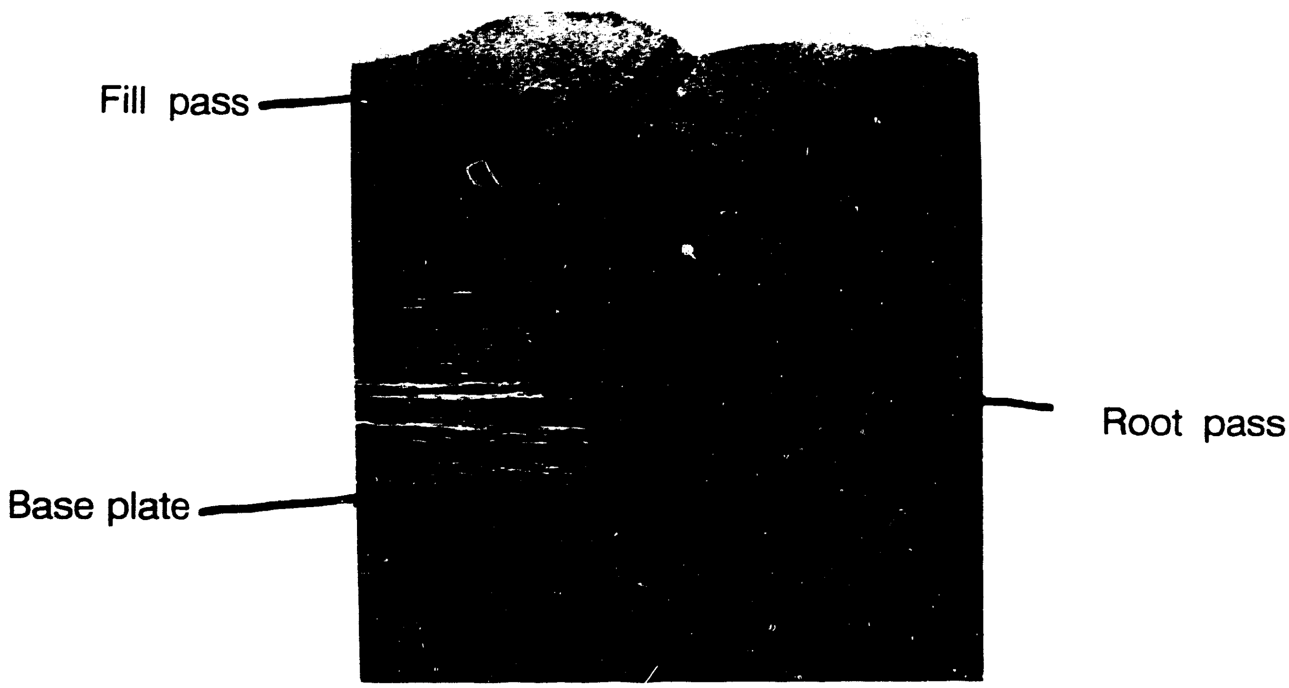


FIGURE C-8. Photograph of an Alloy 715 Grooved Plate Specimen Cross-Section.

APPENDIX D

Summary of Electron Beam Welding Development Efforts

Author: C. C. Conrardy

APPENDIX D

Summary of Electron Beam Welding Development Efforts

Author: C. C. Conrardy

APPENDIX D

SUMMARY OF ELECTRON BEAM WELDING DEVELOPMENT EFFORTS

Author: C. C. Conrardy

1.0 BACKGROUND

An effort was begun to develop electron beam welding (EBW) procedures suitable for the closure of nuclear waste containers. Subsequent sections of this appendix present the testing methodology, a description of the specimens and equipment which were employed, the progress which was made, and the preliminary results of the effort. In order to facilitate these discussions, this section of appendix D first provides an overview of the technical aspects of the EBW process which relate to the welding procedure development efforts.

1.1 The Electron Beam Welding Process

EBW is a fusion welding process in which the heat to melt the metal is obtained from a concentrated beam of high velocity electrons impinging upon the surfaces to be joined. The high power density of the electron beam is responsible for the EB weld characteristics which makes the process desirable for closure of copper waste containers [1],[2]. Compared to other fusion welding processes, EBW has the advantages of low heat input, relatively small fusion and heat affected zones, low residual stresses and distortion, very fast welding speeds, and good inspectibility. Other reasons for which EBW was selected as a candidate closure welding process are discussed in the Phase 1 Final Report [3].

The means by which a diode type of EBW gun (the type used in this development effort) forms the electron beam is depicted in Figure D-1. The gun shown in the figure has two beam forming systems: (1) the pilot or primary cathode, and (2) the filament or hot cathode. The pilot system is a cold cathode discharge type. A high voltage supply ionizes a low-pressure gas and the resultant electrons bombard a tungsten disk filament. As the tungsten disk is bombarded, it becomes heated, and acts as a thermionic emitter of electrons. The electrons emitted from the gun are accelerated by the potential difference (up to 60,000 volts) between the filament and the anode. For a given gun geometry and accelerating voltage, the number of electrons being emitted, i.e., the beam current, is a function of the temperature of the filament; thus, the welding current can be controlled by the voltage applied to the pilot gun. The product of the beam current and the acceleration voltage is the beam power. The ratio of the beam power to the beam cross sectional area is the beam power density.

The beam power and beam power density have a dramatic effect on the weld bead depth of penetration, width, shape, and degree of defects. Thus, it is important to closely control these two beam characteristics. For the waste container development efforts beam power was controlled by maintaining the acceleration voltage constant at 55,000 volts and adjusting the beam current. Additionally, two EBW parameters which affect the beam power density were closely controlled: (1) the gun geometry, i.e., the shapes and relative positions of the primary cathode, the filament, and the anode, and (2) the EBW chamber pressure (maintained at less than 10^{-4} Torr for each weld trial).

Because the electron beam is composed of charged particles it can be influenced by magnetic fields. This principle is used to focus and to deflect the beam. Figure D-1 shows the electron beam focusing and deflection coils. The focusing coils cause the electron beam to converge to a minimum dimension at some point (i.e., the focal point) past the coil. The distance to this focal point is selected by adjusting the current flowing through the focusing coil. The beam deflection coils are used to rapidly sweep the electron beam in some predefined pattern. Figure D-2 is a photograph of a melted zone which was formed by an electron beam deflected in a 0.035" diameter circular pattern, while holding the workpiece stationary and maintaining a beam current just high enough to melt the workpiece surface.

The focus point location with respect to the workpiece surface, the beam deflection pattern, amplitude, and frequency, the welding speed, the angle at which the beam enters the workpiece, the gun to workpiece distance, and the workpiece temperature each influence the weld bead shape, penetration, and degree of defects; and thus must be considered when optimizing EBW parameters. These parameters were therefore incorporated into the welding procedure development.

2.0 TESTING METHOD

The goal of the work was to develop procedures which produce partial penetration welds in copper alloy CDA 122 that are free of significant defects and possess acceptable mechanical properties. Actual laboratory experimentation was begun on July 26, 1989 and proceeded until September 29, 1989. This section provides a brief overview of the EBW development tasks which would have been performed if the work had been carried out to completion. The actual work which was completed during this period and the preliminary results which were obtained are presented in later sections.

The EBW development procedures which were followed are detailed in the approved technical procedure entitled "Electron Beam Welding Parameter Development for LLNL Container Closures" (ARC-TP-813, applicable revisions) [4]. This technical procedure provides information about the EBW development experimental method, the welding, measuring, and testing equipment, the weld evaluation procedures, and the documentation requirements. Elaborate testing methods were employed to ensure that all the significant parameters and conditions which could influence the outcome of a particular test were controlled, measured, and documented. This would allow not only the development of the optimum welding procedures, but also the verification of specific test results by independent researchers.

Figure D-3 is a flowchart which outlines the planned testing sequence. To develop an understanding of the effects of various welding parameters on the weld bead characteristics, preliminary trials were performed prior to official testing; these have been termed "scoping trials". Table D-1 shows the EBW parameters which were systematically varied to determined their effects on weld bead dimension and quality for these trials, and the parameters which were held constant. The scoping trials were not performed to the requirements of ARC-TP-813, and so were not considered to be official data. The scoping trials were, however, valuable, since the knowledge gained allowed more efficient refinement of the welding parameters during the official testing. After completion of the scoping trials official testing was to be performed to verify the scoping trials under more controlled conditions and to more fully document the conditions and results of each trial.

To minimize material and machining costs, initial work was not performed on the weld joints, instead development progressed as shown in Figure D-3. First, full penetration (1" thick) horizontal position bead-on-plate trials were conducted to develop welding parameters which produce adequate penetration and an acceptable weld bead contour. Next, partial penetration beads were produced in 1-1/2" thick plate to establish parameters which avoid defects such as porosity, shrinkage voids, and lack of fusion in the weld root. Then these parameters were to be further refined in weld joint mock-ups to produce consistent penetration into the integrated backing, complete joint fusion, good bead contour, and no significant defects. The next step was to verify the suitability of these parameters on actual flat joints, and to mechanically test the resultant welds. After the parameter verification step, work would have proceeded to the determination of the allowable weld joint fit-up tolerances and the development of weld start and weld stop procedures.

Welds were evaluated predominantly by visual inspection and examination of polished and etched cross-sections. In this manner, both weld bead dimension information (width, depth of penetration, etc.) and weld quality information (occurrence of porosity, cracking, lack of fusion, undercut, etc.) were obtained. Radiographic and mechanical testing were also available for weld evaluation, when appropriate.

3.0 SPECIMEN DESCRIPTION

The basic weld joint design which was intended for the waste container cylinders is shown in Figure D-4. The figure illustrates just one of several possible integrated-lip type joint configurations. The specific joint design would have been selected during the EBW development. As Figure D-4 shows, the design makes use of an integrated backing "lip". The purpose of the integrated backing is to facilitate alignment of the cap on the cylinder and to allow a partial penetration weld of thickness equal to that of the thinner member to be produced; thereby producing a weld of strength comparable to that of the cylinder wall and allowing for easy post weld inspection using ultrasonic techniques. Figure D-5 illustrates how a welded joint cross-section might look. Because partial penetration EBW would be employed, the risk of the electron beam vaporizing the contents of the waste container or penetrating the opposite wall of the container would be greatly reduced compared to full penetration EBW. Partial penetration EBW does, however, impose a significant technical hurdle; these types of welds can suffer from porosity and lack of fusion in the weld root. This effect is exacerbated by welding in the horizontal position on alloys containing constituents which volatilize during welding - as was the case in this study.

The specimens used for the EBW development were designed to simulate the expected welding conditions for the actual waste containers. The following characteristics of the actual waste container cylinders were included in the EBW development specimens:

(1) The weld would be produced in the horizontal position so that the waste container could be held vertical during closure.

(2) The weld joint would be preheated to 90° to simulate radioactive decay of the waste within an actual container.

(3) An integrated-lip type joint design would be used; this design would be used for the actual containers to aid in joint fit-up and to stop the electron beam from damaging the container contents or the opposite wall of the container.

(4) The thickness of the container wall was expected to be 1", while the thickness of the cap was expected to be 1.5", thus producing heat sink differences across the joint. Also, depending upon the gap between the container wall and the lip of the cap, the joint could require procedures developed for 1.5" thick partial penetration welding or for 1" thick full penetration welding.

(5) Termination of the weld would occur in previously produced weld metal, as would be the case on an actual container.

(6) Weld joint fit-up errors would inevitably exist.

The welding procedure development work made use of flat plate specimens to simulate the welding requirements of the cylindrical containers. Both full penetration and partial penetration trials would be conducted to simulate penetration of the electron beam through the weld joint and then into the integrated backing lip. Work was initially performed on flat 1" thick bead-on-plate specimens (see Figure D-6A) to develop preliminary welding parameters which produced full penetration beads having suitable cross-sectional dimensions without significant defects. Next, partial penetration beads were to be produced on 1.5" thick plate to generate parameters which avoid significant root defects. Then, parameters were to be refined using preheated joint mock-ups, such as those illustrated in Figure D-6B. Finally, parameters were to be verified on preheated flat plate weld joints, as illustrated in Figure D-6C. Welds produced in flat plate joints would then have been mechanically tested to verify that suitable properties were obtained. Additionally, parameters were to be developed for starting and stopping the EB weld without causing the occurrence of weld defects. Also, the effect of joint fit-up (see Figure D-4) on weld properties would have been evaluated by producing welds in joints with varying degrees of root gap, backing gap, and mismatch.

4.0 EQUIPMENT DESCRIPTION

This section provides a brief overview of the types of equipment which were employed for the EBW parameter development. Details of the specific welding, testing, and measuring equipment which was used for this effort can be found in ARC-TP-813 [4] and the appropriate laboratory notebooks.

The EBW parameter development welding equipment set-up is shown in the photograph of Figure D-7. The photograph shows a bead-on-plate specimen held by the fixture within the electron beam vacuum chamber. The electron beam gun, shown in the figure, is stationary while the fixture is moved in front of the gun. A diode type of EB gun was employed at 55,000 volts with a chamber pressure of less than 10^{-4} Torr. The fixture is constructed of non-ferromagnetic materials so that the electron beam will not be influenced by residual magnetic fields, and provides a downward clamping force to prevent welding distortion from producing gaps in weld joints. Important equipment not shown in the photo include the specimen preheating device (electrical resistance heaters), the thermocouples for measuring specimen temperature, and the certified stripchart recorder for recording the electron beam current and voltage traces for each weld trial. This equipment configuration was selected to provide the necessary flexibility to conduct the wide array of tests needed for EBW parameter optimization.

5.0 PROGRESS

Section 2.0 described the workscope which was intended for the EBW development effort. This section describes the work which was actually completed. In all, 60 weld beads were produced, evaluated and documented. Both scoping trials and some official data trials were conducted. The official data included both partial and full penetration weld trials. No weld joint mock-ups or weld joint trials were completed. Work did not proceed past the bead on plate trials for two reasons: (1) excessive spatter produced by the CDA 122 material repeatedly damaged the EBW gun, forcing delays for maintenance, (2) parameters had not been found which consistently produced partial penetration weld beads which were free of porosity in the root region. Several avenues were being investigated to eliminate the porosity, including welding in the flat position and changing the base alloy to oxygen free copper.

6.0 PRELIMINARY RESULTS

Parameters were developed which produced full penetration welds which were free of significant defects. Figure D-8 shows the surface and a cross section of a full penetration weld bead in 1" thick plate. The figure also shows the parameters which were used to produce this bead. When work was suspended parameters had not yet been found which consistently produced partial penetration weld beads without porosity or lack of fusion in the root region. An example of the root porosity which was typically encountered in CDA 122 is shown in Figure D-9. Adjustments were made to each of the independent variables of Table 1 in an attempt to eliminate these defects, without success. This porosity may be reduced by welding in the flat position, however this was not attempted. It is believed that this porosity is a characteristic of the alloy which was employed, and that these problems would be avoided if an oxygen free copper alloy, e.g., CDA 102, was substituted for CDA 122.

REFERENCES

[1] A. Sanderson, T.F. Szluha, J.L. Turner, R.H. Leggatt, "Feasibility Study of Electron Beam Welding of Spent Nuclear Fuel Canisters", The Welding Institute, Cambridge, The United Kingdom, April 1983.

[2] P.Y.Y. Maak, "Electron Beam Welding of Thick-Walled Copper Containers for Nuclear Fuel Waste Disposal - Phase Three B", Ontario Hydro Research Division, April 7, 1986.

[3] E.S. Robitz, et.al, "Closure Development for High-Level Nuclear Waste Containers for the Tuff Repository - Phase 1 Final Report", UCRL 15964, Lawrence Livermore National Laboratory, Livermore, CA, 1989.

[4] C.C. Conrardy, "Electron Beam Welding Parameter Development for LLNL Container Closures", Babcock and Wilcox - Alliance Research Center quality assurance document, technical procedure number ARC-TP-813, original release Nov. 23, 1988; latest revision Aug. 13, 1989.

TABLE D-1

Independent Variables and Constants for the EBW Development Effort

Independent Variables

Beam Current	Travel Speed
Beam Deflection Pattern	Beam Focus Point Location
Beam Deflection Amplitude	Beam Lead Angle
Beam Deflection Frequency	Beam Side Angle
Workpiece Temperature	Weld Joint Geometry

Constants

Gun Geometry	Fixture Geometry
Voltage (55 Kv)	Material Type (CDA 122)
Chamber Pressure ($<10^{-4}$Torr)	Gun to Workpiece Distance
Welding Position (Horizontal)	

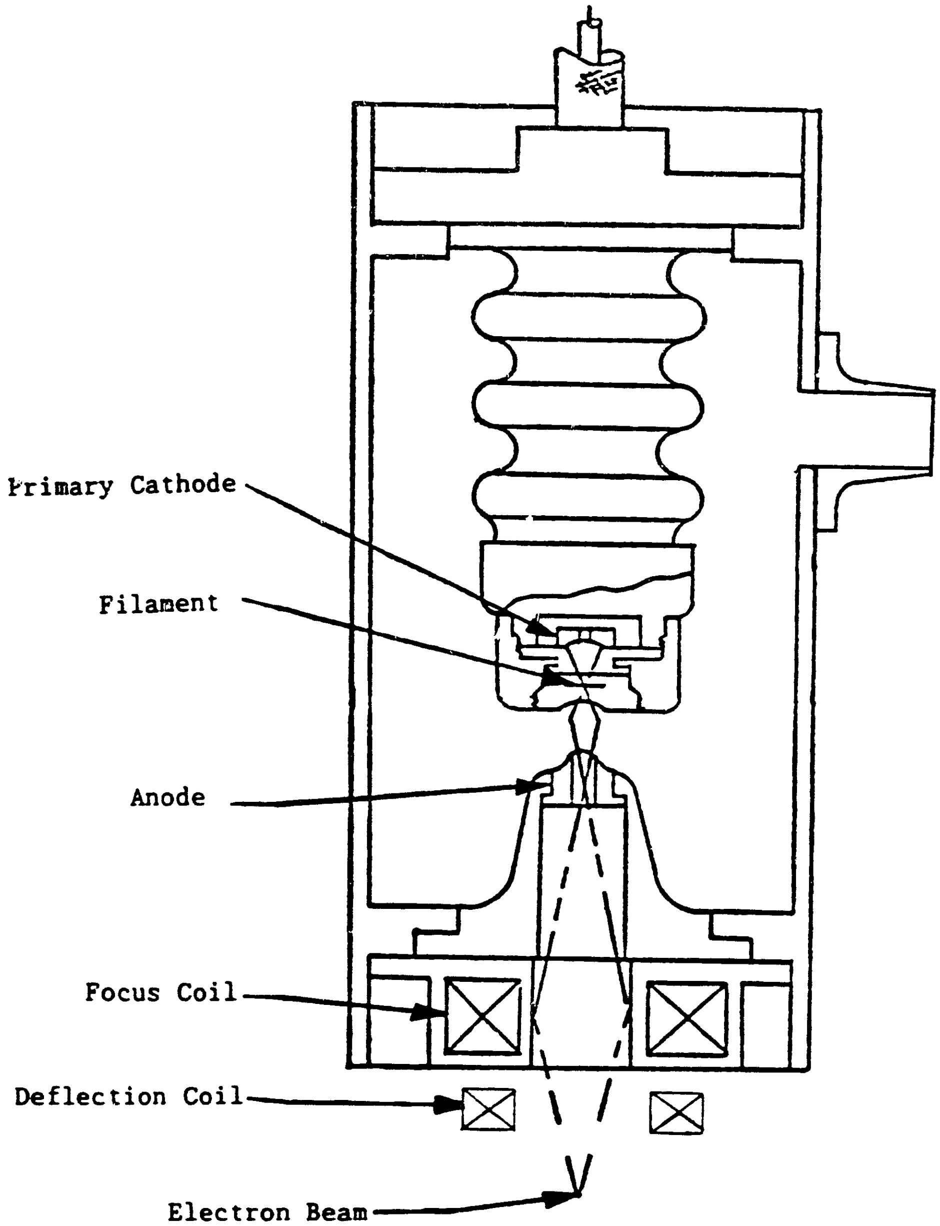
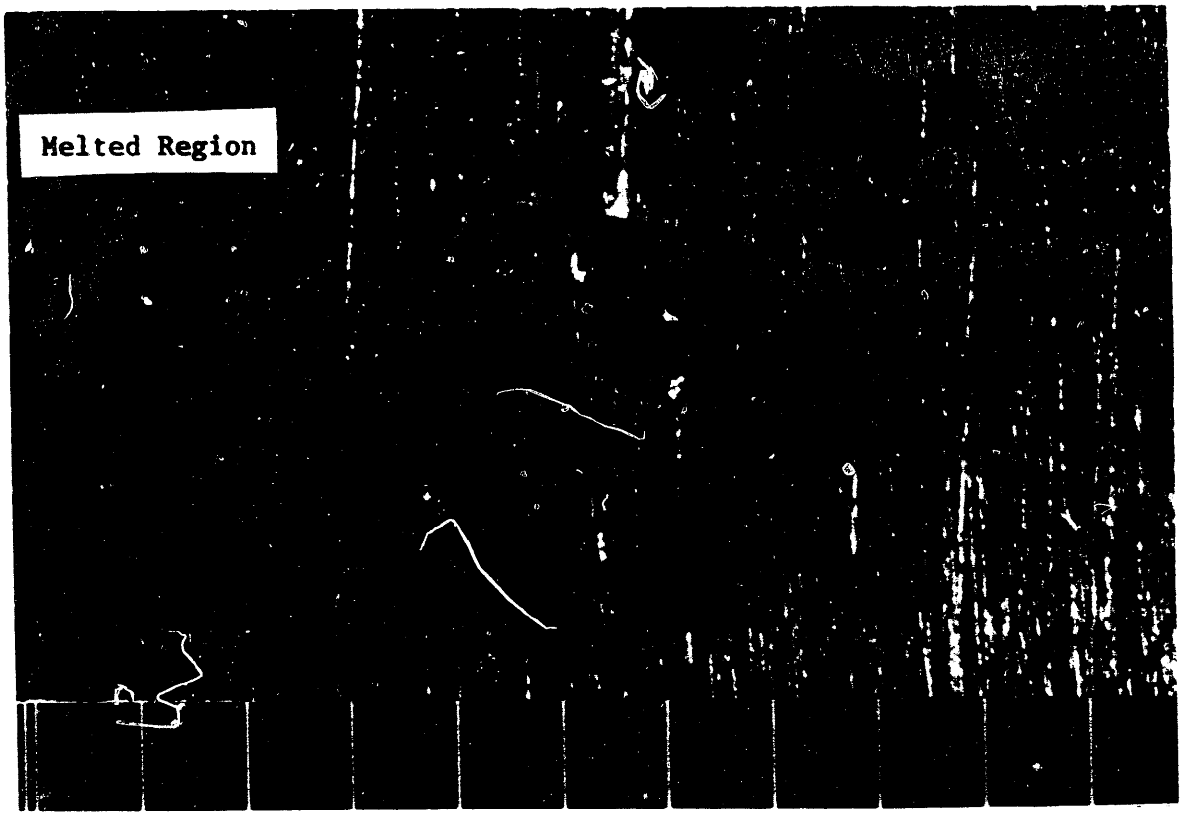


FIGURE D-1. Simplified Cross-Section of a Diode-Type Electron Beam Welding Gun; Illustrating the Beam Forming, Focusing, and Deflection Systems.



0.01"

FIGURE D-2. Photograph Showing a Melted Region Produced by the Circular Deflection of a Low Current Electron Beam.

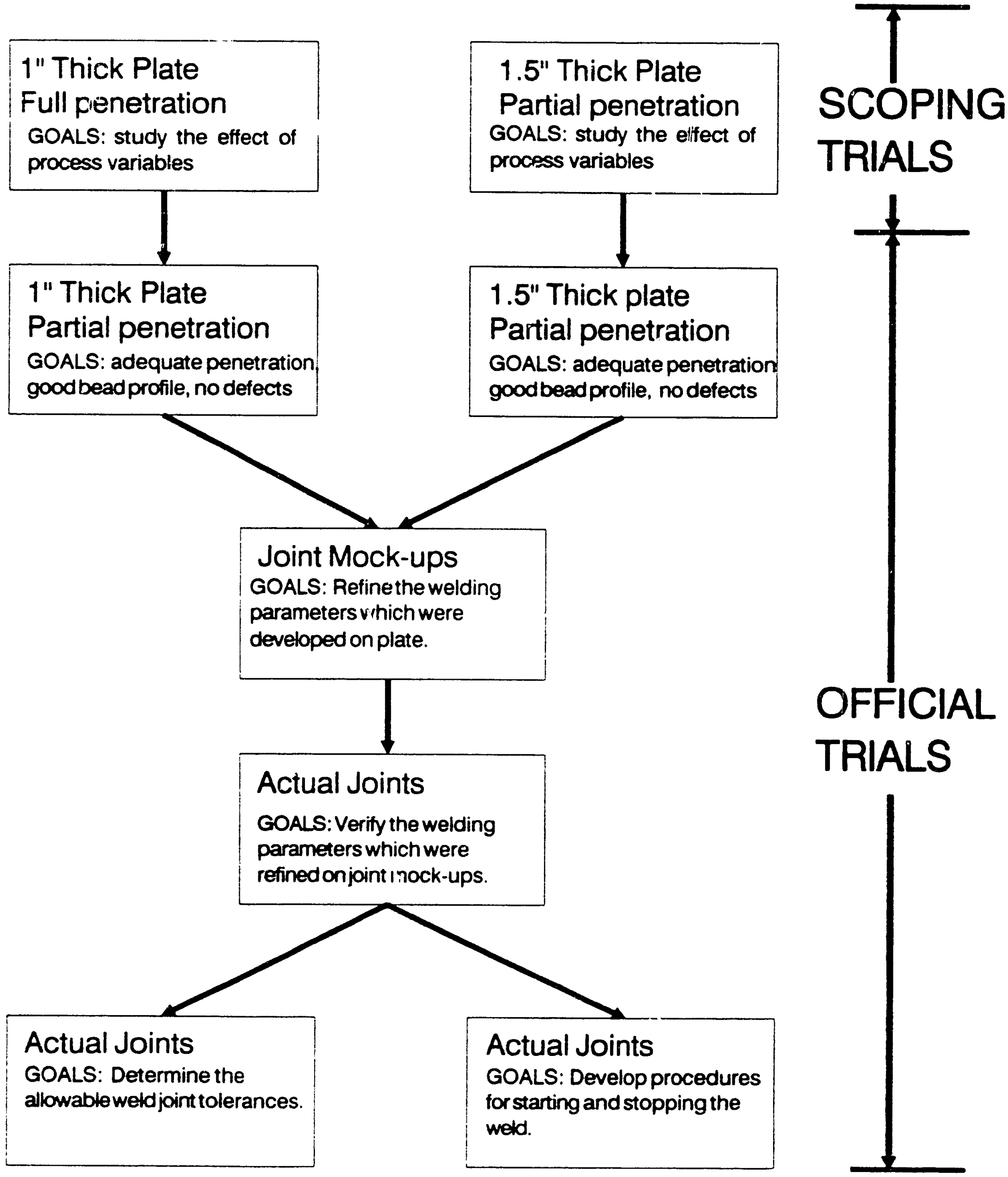


FIGURE D-3. Flowchart to Provide an Overview of the Electron Beam Welding Procedure Development Methodology.

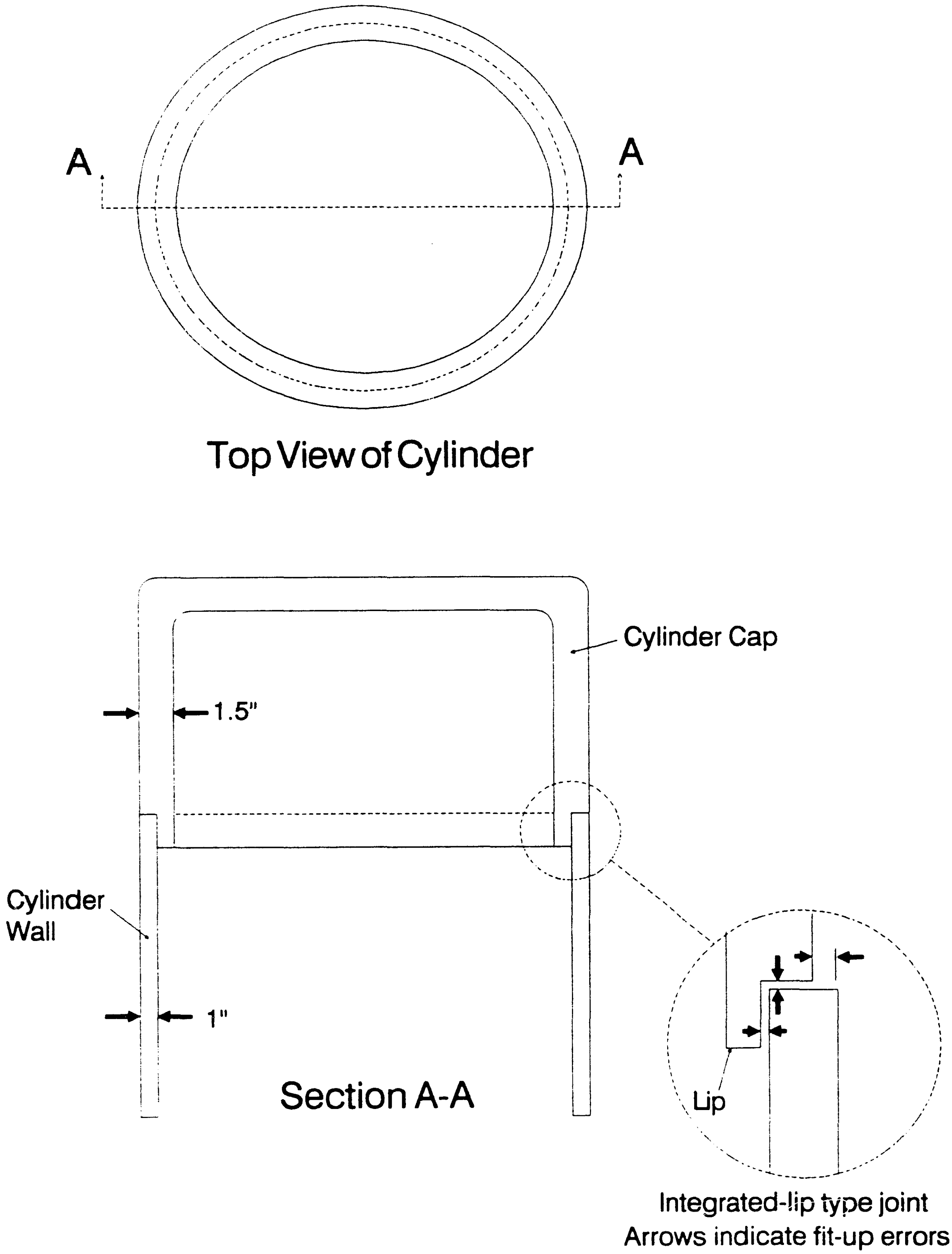


FIGURE D-4. Schematic Representation of the EBW Waste Container Design.

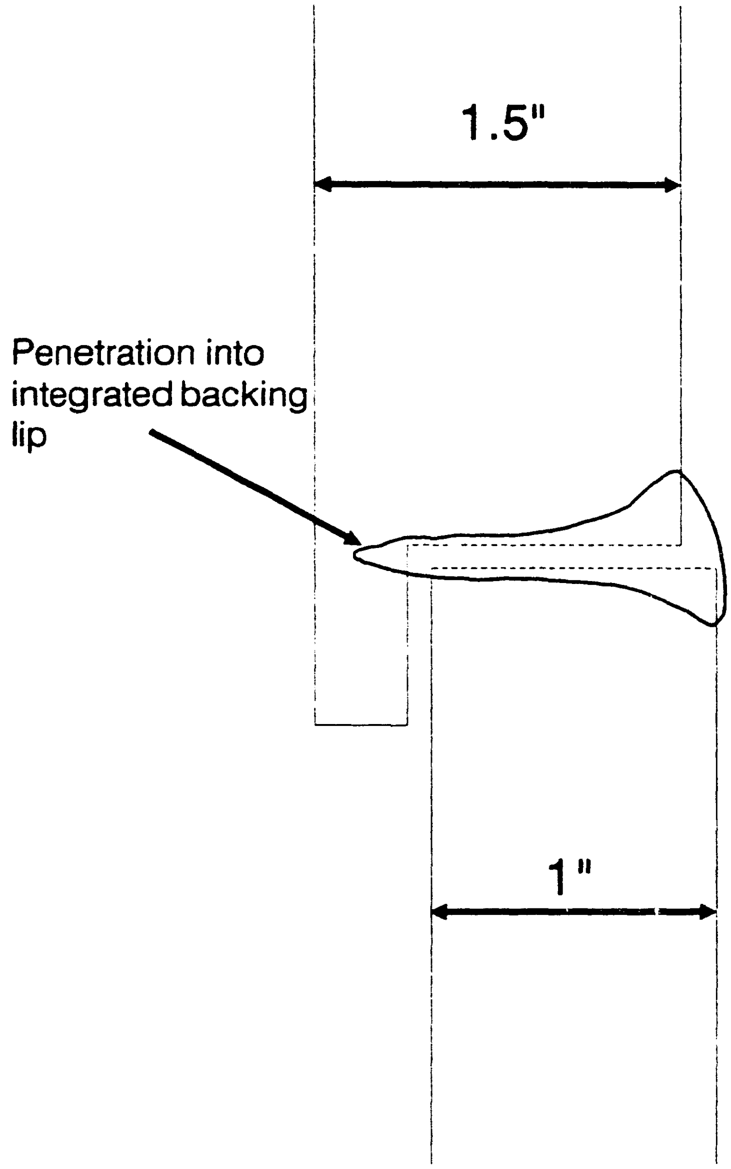


FIGURE D-5. Schematic Illustrating the Cross-Section of an Electron Beam Welded Waste Container Joint.

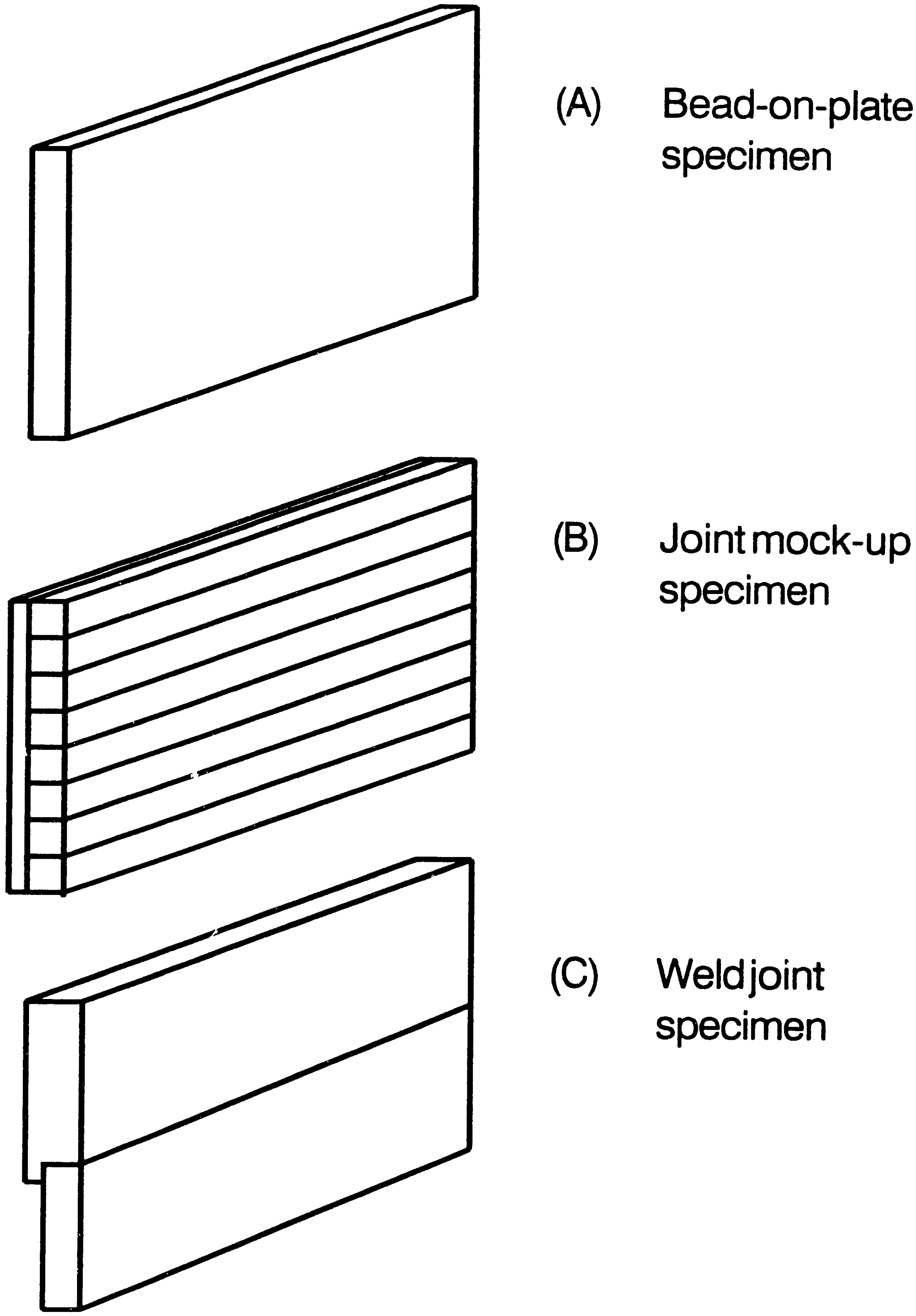


FIGURE D-6. Illustration of the Specimen Types to be Used in the EBW Parameter Development Effort.

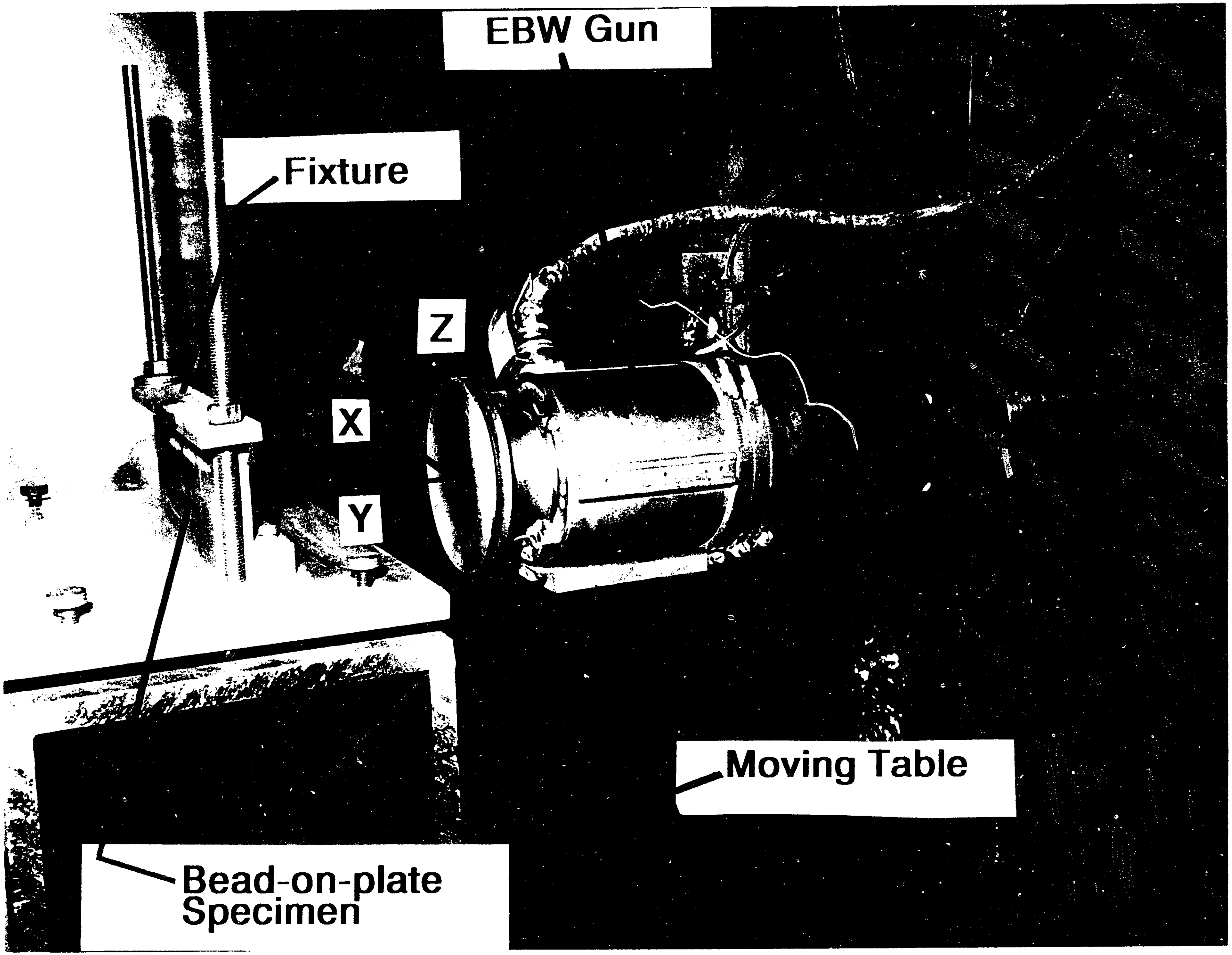
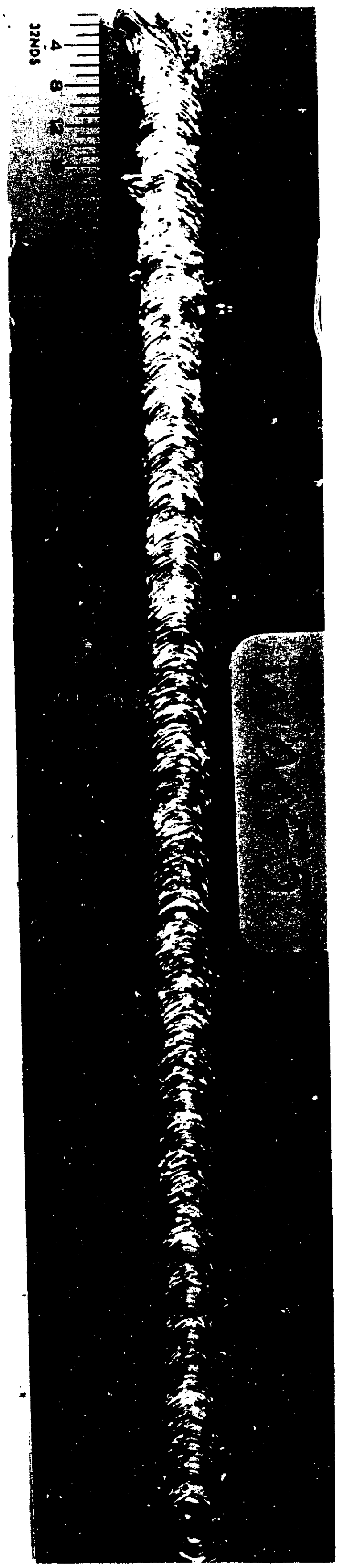
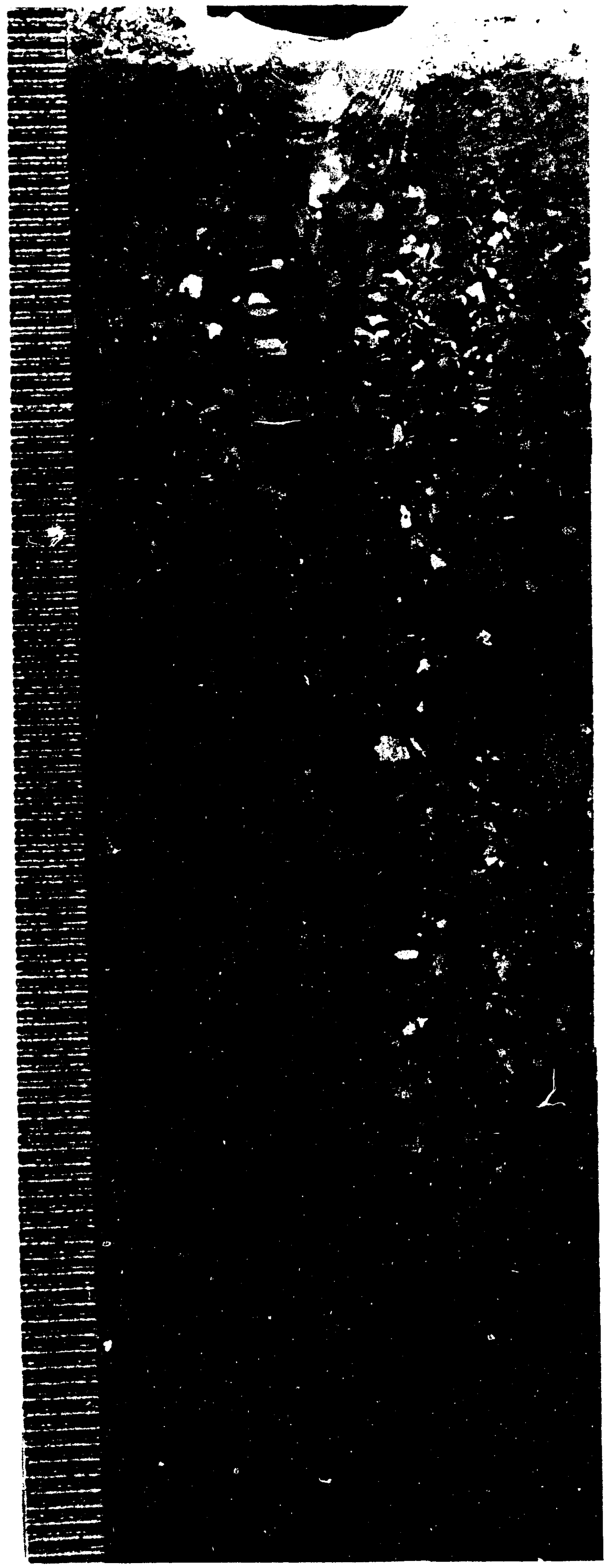


FIGURE D-7. Photograph of the EBW Chamber Interior.



(A)



(B)

Welding Parameters

Travel speed = 10 ipm
Current = 300 mA
Voltage = 55 KV
Focus = 1.4" below the specimen surface
Beam pattern = circle
Deflection frequency = 140 Hz
Deflection amplitude = 0.03"
Preheat = none
Beam angle = 90 degrees to the specimen surface

(C)

FIGURE D-8. Photograph of a Full Penetration EBW Bead Produced in 1" Thick CDA 122; (A) The Top Bead Surface, (B) an Etched Cross-Section, (C) the Welding Parameters Which Were Employed.

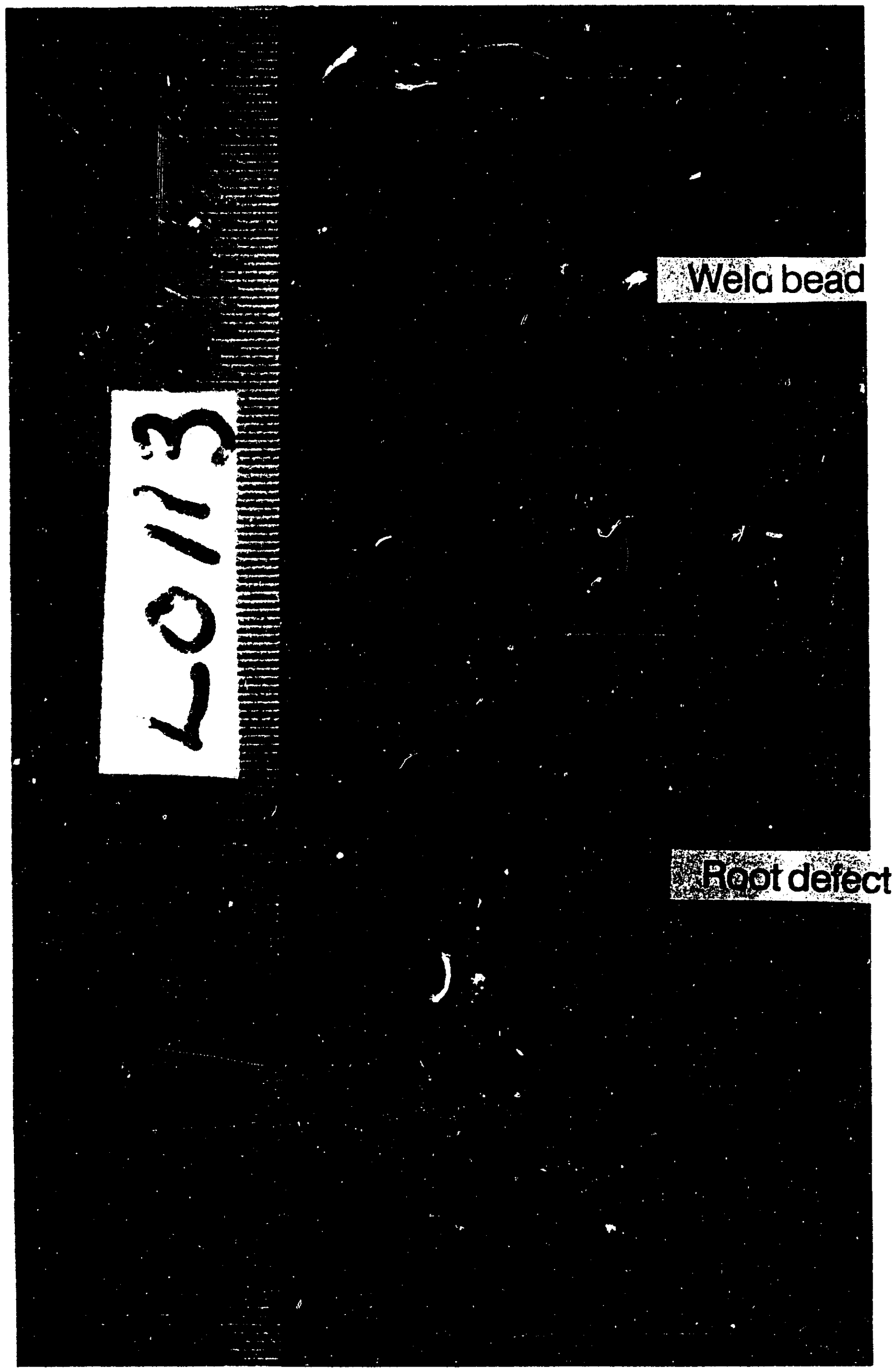


FIGURE D-9. Photograph of an Etched Cross-Section of a Partial Penetration EBW Bead Produced in 1.5" Thick CDA 122. Note the Presence of a Defect in the Weld Pool.

APPENDIX E

Specimen Length Determination

Letters By: C. C. Schultz
D. R. Lee

To E. S. ROBITZ - METALLURGY & MANUFACTURING SECTION

From C. C. SCHULTZ - STRUCTURAL MECHANICS SECTION

Cust.	**File No.** 4544-11
Subj. SPECIMEN LENGTH FOR WELD TESTS OF NUCLEAR WASTE CONTAINMENT VESSELS	**Date** NOVEMBER 23, 1988

This letter to cover one customer and one subject only

This letter is in response to your request for assistance in defining acceptable specimen lengths for your weld tests that are a part of the program for the development of radioactive waste containment vessels for the DOE. The containment vessels are to be right-circular cylindrical shells with welded closure heads.

As a result of our recent discussions, it is my understanding that your efforts are directed to the evaluation of four candidate materials and three candidate welding processes. Each electron beam welding specimen is to consist of an 18-inch OD x 1.00-inch wall-thickness cylinders girth-welded to an 18-inch OD x 1.50-inch wall-thickness cylinder. The plasma arc welding specimens are to consist of 18-inch OD x 0.375-inch wall-thickness cylinder girth-welded to 18-inch OD x 0.625-inch wall-thickness cylinders. The friction welding specimens are to be constructed by joining an 18-inch OD x 0.375-inch wall-thickness cylinder to an 18.25-inch OD x 0.625-inch wall-thickness cylinder.

Since some of these weld test specimens are to be used in a comparison study of welding-induced residual stresses, it is necessary that the cylinders be of sufficient length to assure that the welded juncture is not affected by the conditions existing at the "free" ends of the specimens. However, the high costs of test materials and the anticipated large test matrix dictates that consideration be given to avoiding the specification of unnecessarily long test specimens.

Acceptable specimen lengths have been estimated using standard equations for the analysis of cylindrical shells. These estimates are provided in Table 1. For the cases of the electron beam and plasma arc welding processes, the recommended specimen lengths represent the length of the uniform section extending between the weld prep area at one end and any fixture or method of restraint at the other end. That is, additional length should be provided to accommodate weld preparation, fixturing, wastage and any additional requirements of subsequent usages. The specimen lengths recommended for the friction welding process represent the lengths of the uniform sections that extend beyond the flanges (i.e., on the side of the flange away from the weld interface). As with the other weld processes, provision should be made for fixturing, wastage and any requirements of subsequent usage.

cc: K. Aral
T. S. Brown
J. M. Nielsen
D. Peterson

E. S. ROBITZ
NOV 2_ 1988

The standard equations for the analysis of cylindrical shells were obtained from the 1986 edition of the ASME Boiler and Pressure Vessel Code, Section III, Class 1 Components, Appendices, Article A-2000. Specifically, the equations of A-2243 define the edge displacements and rotations in terms of uniformly distributed edge shear and moment loads. For example, the radial displacement at one end is defined as

$$w_o = B_{11}C_1Q_o + B_{12}C_2M_o + G_{11}C_1Q_L + G_{12}C_2M_L$$

where Q_o & M_o = edge loads at the end of interest
Q_L & M_L = edge loads at the opposite end
C_1 & C_2 = functions of the cylinder diameter, wall-thickness, Poisson's ratio and the elastic modulus
B_{11}, B_{12}, G_{11} & G_{12} = influence coefficients that are functions of the diameter, wall-thickness, Poisson's ratio and the cylinder length.

As the cylinder length increases, the coefficients B_{ij} approach unity and the coefficients G_{ij} approach zero. The cylinder characteristic, β, defines how rapidly the influence coefficients approach their limiting values. This characteristic is defined as

$$\beta = \left[\frac{3(1-\nu^2)}{R_m^2\ t^2}\right]^{1/4}$$

where ν = Poisson's ratio
R_m = mean radius
t = wall thickness

The influence coefficients, B_{ij} and G_{ij}, are then functions of only the product βL (where L is the cylinder length). For example,

$$B_{11} = (\text{SINH } 2\beta L - \text{SIN } 2\beta L)/2(\text{SINH}^2\beta L - \text{SIN}^2\beta L)$$

The influence coefficients B_{11}, B_{12} and B_{22} have been calculated for values of βL ranging from 1 to 10. The results of the calculations (all with ν=0.3) are shown in Table 2. Note that the influence coefficients are within 1 percent of unity for βL values of 3 and greater; indicating that the cylinder is effectively of infinite length when $\beta L \geq 3$.

Since influence coefficients convergence may seem somewhat abstract, additional calculations were performed to illustrate this convergence using the model of Figure 1. This model is a rough approximation of the type of loading that might be encountered during welding. The model represents the material to the right-hand side of the centerline of a girth weld between two identical cylinders. The short cylindrical segment represents the metal that becomes molten during welding. It is assumed that this molten zone extends for a length of t/2 (where t is the wall thickness) to either side of the weld centerline. The length of the remainder of the model is varied from βL=10 to βL=0.1. A boundary condition of zero rotation is assumed at the weld centerline. The material that had been molten is given an initial radial displacement (inward) of 0.01 R_m (where R_m is the mean radius) to simulate shrinkage. All results (deflection, rotation, shear, moment and stresses) are calculated at the interface (between the solid and molten material) and normalized by dividing by the solution for a cylinder of infinite length. Typical results are shown in Table 3. Figures 2 through 5 illustrate the results for all specimens. Note that for $\beta L \geq 3$ the normalized values are all within approximately 1% of unity, indicating that those lengths respond nearly as if they were infinite. Although the actual numerical results are a function of the assumed shrinkage, assumed weld width and the assumption that the cylinders being joined are identical, the normalized results are independent of those assumptions.

The result that a dimensionless length of $\beta L=3$ is adequate to assure negligible effects is based on purely elastic analysis. In actuality, plastic straining will occur near the interface. Since these plastic strains are, in effect, a source of loading, the specimen length should be increased by an amount corresponding to the length of the plastic zone. The results of Rybicki* are used to help estimate this additional length. Rybicki performed inelastic analyses for eight cases of girth welding. The results (i.e., axial stress along the inner surface) for those eight cases are reproduced in Figure 6. These same eight cases have been solved elastically, using the simple model of Figure 1 (assuming an infinite length). Those results are shown in Figures 7 and 8. Comparing the axial positions where the peak in compressive stresses occurs (as calculated by each method) is considered indicative of length that is required to be added to account for the plastic zone. For example, with an OD of 4.50 inches and a wall thickness of 0.531 inch, Rybicki's compressive peak occurs at approximately 1.5 inches from the weld centerline. Figure 7 shows a corresponding distance of approximately 1 inch from the interface; or (1 + t/2) from the weld centerline. This comparison indicates a difference of about 1/4 inch. The axial position of the maximum compressive stress is easily identified in the ARC solutions. That identification is not so clear in the case of Rybicki's results of Figure 6. A comparison of the results for the two methods of solution is shown in Table 4. The difference in estimated axial location of the maximum compressive axial bending stress appears to decrease as β decreases for similar diameters. That difference also appears to increase with diameter for similar values of β. An approximation of this difference is

$$\beta \sqrt{R_m/t}/10$$

The recommended specimen lengths are then calculated (for Table 1) as

$$L = 3/\beta + \beta\sqrt{R_m/t}/10$$

Note that the units of β are inches^{-1}, so that the correction term is dimensionally incorrect. Figure 9 illustrates the axial stress variation along the inner surface for the 18-inch OD specimens.

The model of Figure 10 was used to approximate the friction welding process. The applied force F was modeled as a concentrated, axisymmetric, bending moment (i.e., ignoring the effects of the axial membrane stress). The length, L, was varied from an effective infinite length to a negligible length. All results

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* "The Effect of Pipe Thickness on Residual Stresses Due to Girth Welds," E. F. Rybicki, et al., Transactions of the ASME, Vol. 104, August 1982, p. 204-209.

at the weld centerline were normalized by dividing by the results for the infinite length solution. Both free-ended and fixed-ended conditions were considered at the weld centerline. As shown in Tables 5 and 6, the interaction forces and moments are within 1% of the results for an infinite cylinder when $\beta L>2$ for the fixed-ended condition. Tables 7 and 8 provide the results for the free-ended solution. In this case, the moment and shear at the left-hand face of the flange (M_{22} and Q_{22}) are well behaved for $\beta L>2$. However, the displacement and rotation at the weld centerline (W_{11} and T_{11}) require longer lengths to become within 1% of the infinite length solution. Additional cases were run to consider a shorter length of cylinder (1 inch) between the weld centerline and the flange. These results are shown in Tables 9 through 12. In all cases, the moment and shear at the left face of the flange (M_{22} and Q_{22}) are within 1% of the infinite length solution for $\beta L>2$. However, errors of up to about 4% exist at the weld interface. Regardless, the use of lengths of $\beta L=2$ are considered acceptable. The recommendations of Table 1 for the friction welding process are based on the use of $\beta L=2$.

A listing of each computer program used in this study is attached for your reference. Included with those listings is all pertinent inputs and outputs. A copy of all hand calculations used to verify those programs is also attached for your reference.

C C Schultz
C. C. Schultz

CCS:bay
Attachments

Table 1. Recommended Specimen Lengths

Process	OD (inches)	Wall Thickness (inches)	Length (inches)
EBW	18.	1.00	7
	18.	1.50	8-3/8
PAW	18.	0.375	4-5/8
	18.	0.625	5-3/4
FRICTION	18.	0.375	2-7/8
	18.25	0.625	3-5/8

Table 2. Convergence of Influence Coefficients as Cylinder Length Increases

Dimensionless Length βL	Influence Coefficients		
	B11	B12	B22
0.5	4.002380	12.026181	24.185669
1.0	2.018919	3.104154	3.369980
1.5	1.395481	1.562330	1.435359
2.0	1.137586	1.134145	1.076194
2.5	1.036810	1.019763	1.010355
3.0	1.006562	1.000397	1.003777
3.5	1.001075	1.000900	1.003477
4.0	1.000777	1.001539	1.002106
4.5	1.000617	1.000944	1.000821
5.0	1.000307	1.000334	1.000208
6.0	1.000021	1.000004	1.000008
7.0	1.000001	1.000003	1.000005
8.0	1.000001	1.000001	1.000001
9.0	1.000000	1.000000	1.000000
10.0	1.000000	1.000000	1.000000

WELD VARIABLE LENGTH CYLINDER

OD = 18.000
T = 0.375
V = 0.300
K = 0.010
E = 0.250E+08
BETA = 0.7071

Centerline of Weld : Deflection = -0.1161554F-01
Rotation = 0.0000000F+00
Moment = 1231.732
Shear = 0.0000000F+00
Hoop Memb Strs = 217036.8
Hoop Bend Strs (ID) = 15766.17
Axial Bend Strs (ID) = 52553.91

Interface (Infinite Lgth) : Deflection = -0.1144414E-01
Rotation = 0.1828899E-02
Moment = 1069.325
Shear = 1733.012
Hoop Memb Strs = -32465.65
Hoop Bend Strs (ID) = 13687.36
Axial Bend Strs (ID) = 45624.52

		INTERFACE (NORMALIZED TO BL = 1000)				STRESS AT ID (PSI)		
BL	L	DEFLECTION	ROTATION	SHEAR	MOMENT	HOOP MEMBRANE	HOOP BENDING	AXIAL BENDING
0.1	0.1414245	4.389466	0.9698063E-01	0.4547363	0.5669179E-01	4.389466	0.5669179E-01	0.5669179E-01
0.2	0.2828489	3.072240	0.2074075	0.6914526	0.1583783	3.072240	0.1583783	0.1583783
0.3	0.4242734	2.369242	0.3212898	0.7963573	0.2731700	2.369242	0.2731700	0.2731700
0.4	0.5656979	1.937880	0.4353610	0.8606613	0.3922821	1.937880	0.3922821	0.3922821
0.5	0.7071223	1.652744	0.5473629	0.9031123	0.5113288	1.652744	0.5113288	0.5113288
0.6	0.8485468	1.457150	0.6550080	0.9321864	0.6269325	1.457150	0.6269325	0.6269325
0.7	0.9899712	1.321555	0.7557728	0.9523029	0.7358662	1.321555	0.7358662	0.7358662
0.8	1.131396	1.228641	0.8469998	0.9660542	0.8349407	1.228641	0.8349407	0.8349407
0.9	1.272820	1.167048	0.9261803	0.9751420	0.9212209	1.167048	0.9212209	0.9212209
1.0	1.414245	1.128487	0.9913327	0.9808085	0.9923987	1.128487	0.9923987	0.9923987
1.2	1.697094	1.095388	1.076285	0.9856289	1.085468	1.095388	1.085468	1.085468
1.4	1.979942	1.090112	1.106220	0.9863727	1.118359	1.090112	1.118359	1.118359
1.6	2.262791	1.089388	1.098702	0.9864921	1.110067	1.089388	1.110067	1.110067
1.8	2.545640	1.083676	1.073965	0.9873828	1.082735	1.083676	1.082735	1.082735
2.0	2.828489	1.072173	1.046756	0.9891427	1.052592	1.072173	1.052592	1.052592
2.2	3.111338	1.057551	1.024529	0.9913614	1.027889	1.057551	1.027889	1.027889
2.4	3.394187	1.042736	1.009402	0.9935983	1.011003	1.042736	1.011003	1.011003
2.6	3.677036	1.029703	1.000683	0.9955594	1.001202	1.029703	1.001202	1.001202
2.8	3.959885	1.019357	0.9966656	0.9971118	0.9966205	1.019357	0.9966205	0.9966205
3.0	4.242734	1.011814	0.9955910	0.9982408	0.9953226	1.011814	0.9953226	0.9953226
3.5	4.949856	1.002507	0.9976745	0.9996288	0.9974766	1.002507	0.9974766	0.9974766
4.0	5.656979	1.000366	0.9996722	0.9999458	0.9996444	1.000366	0.9996444	0.9996444
4.5	6.364101	1.000161	1.000185	0.9999756	1.000206	1.000161	1.000206	1.000206
5.0	7.071223	1.000145	1.000118	0.9999781	1.000132	1.000145	1.000132	1.000132
6.0	8.485468	1.000031	0.9999927	0.9999953	0.9999925	1.000031	0.9999925	0.9999925
7.0	9.899712	1.000061	0.9999987	0.9999998	0.9999985	1.000001	0.9999985	0.9999985
8.0	11.31396	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
9.0	12.72820	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
10.0	14.14245	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000

Table 3. Approximation of Conditions at Weld Interface for Different Length Cylinders

Table 4. Axial Position of Maximum Compressive Stress

OD	WT	β	Axial Position B&W	Axial Position Rybicki	Difference	$\beta\sqrt{Rm/t}/10$
4.50	0.120	2.5074	0.62	1.25	0.63	1.07
4.50	0.237	1.8085	0.89	1.25	0.36	0.54
4.50	0.337	1.5347	1.08	1.50	0.42	0.38
4.50	0.531	1.2522	1.22	1.50	0.28	0.24
10.75	0.165	1.3755	1.10	1.75	0.65	0.78
10.75	0.365	0.9337	1.68	2.	0.32	0.35
10.75	0.593	0.7407	2.19	2.	—	0.22
10.75	1.125	0.5524	2.73	2.	—	0.11
18.00	0.375	0.7071	2.17	—	—	0.34
18.00	0.625	0.5516	2.85	—	—	0.21
18.00	1.00	0.4409	3.68	—	—	0.13
18.00	1.50	0.3654	4.58	—	—	0.09

F L A N G E F I X E D

Cylinder	OD =	18.000
	T =	0.375
	L =	2.000
	B =	0.707
Flange	OD =	21.000
	T =	1.875
	L =	1.500
	B =	0.304
Extended cylinder	OD =	18.000
	T =	0.375
	B =	0.707

E = 0.250E+08 V = 0.3 Mo = 1000.

RESULTS NORMALIZED TO INFINITE CYLINDER

BL	L	Q11	M11	Q22	M22	Q44	M44
10.000	14.14245	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
9.000	12.72820	1.000000	1.000000	1.000000	1.000000	0.9999999	1.000000
8.000	11.31396	1.000000	1.000000	1.000000	1.000000	0.9999999	1.000000
7.000	9.899712	1.000001	1.000001	1.000001	1.000001	0.9999992	0.9999971
6.000	8.485468	1.000010	1.000008	1.000009	1.000011	0.9999786	0.9999852
5.000	7.071223	1.000016	1.000012	1.000013	1.000017	0.9999446	0.9999917
4.500	6.364101	1.000061	1.000057	1.000058	1.000062	0.9999804	0.9998379
4.000	5.656979	1.000408	1.000372	1.000380	1.000415	0.9997958	0.9989731
3.500	4.949856	1.001676	1.001463	1.001514	1.001720	0.9980362	0.9965214
3.000	4.242734	1.004447	1.003692	1.003871	1.004596	0.9916639	0.9928642
2.500	3.535612	1.007553	1.005864	1.006264	1.007884	0.9789752	0.9924503
2.000	2.828489	1.008093	1.005822	1.006359	1.008538	0.9696599	0.9971078
1.500	2.121357	1.018309	1.016253	1.016740	1.018713	0.9835153	0.9587589
1.000	1.414245	1.111404	1.102268	1.104439	1.113197	0.9567923	-0.7110827
0.500	0.7071223	1.353774	1.311187	1.321266	1.362133	0.6330630	0.2353384
0.100	0.1414245	1.549484	1.465834	1.485631	1.565903	0.1338476	0.9380940E-02
0.010	0.1414245E-01	1.580873	1.488243	1.510166	1.599054	0.1326864E-01	0.9133809E-04
0.000	0.1414245E-03	1.583970	1.490380	1.512530	1.602339	0.1324962E-03	0.9101672E-08
Results for Infinite Cylinder		199.8016	-167.3927	-286.8077	289.7405	215.0785	-221.4028

Table 5. Friction Welding. Fixed-Ended
Wall-Thickness = 0.375 Inch
Weld Centerline-to-Flange Face = 2 Inches

F L A N G E   F I X E D

Cylinder	OD =	19.250
	T =	0.625
	L =	2.000
	B =	0.548
Flange	OD =	21.000
	T =	2.000
	L =	1.500
	B =	0.295
Extended cylinder	OD =	18.250
	T =	0.625
	B =	0.548

E = 0.250E+08   V = 0.3   Mo = 1000.

RESULTS NORMALIZED TO INFINITE CYLINDER

RL	L	Q11	M11	Q22	M22	Q44	M44
10.000	18.25782	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
9.000	16.43204	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
8.000	14.60626	1.000000	1.000000	1.000000	1.000000	0.9999999	1.000000
7.000	12.78047	1.000001	1.000001	1.000001	1.000001	0.9999996	0.9999975
6.000	10.95469	1.000008	1.000003	1.000006	1.000010	0.9999833	0.9999894
5.000	9.128910	1.000009	0.9999986	1.000006	1.000013	0.9999543	0.9999993
4.500	8.216019	1.000063	1.000051	1.000059	1.000068	1.000001	0.9999544
4.000	7.303128	1.000404	1.000315	1.000375	1.000443	0.9999303	0.9990949
3.500	6.390237	1.001496	1.000967	1.001325	1.001729	0.9986799	0.9971089
3.000	5.477346	1.003511	1.001656	1.002910	1.004327	0.9936306	0.9946388
2.500	4.564455	1.004977	1.000830	1.003633	1.006802	0.9828907	0.9959199
2.000	3.651564	1.004230	0.9986660	1.002428	1.006679	0.9745944	1.001263
1.500	2.738673	1.017270	1.012242	1.015641	1.019483	0.9904885	0.9641268
1.000	1.825782	1.115806	1.092592	1.108286	1.126023	0.9921628	0.7350787
0.500	0.9128910	1.365832	1.246456	1.327160	1.418369	0.7300087	0.2699166
0.100	0.1825782	1.581166	1.317332	1.495698	1.697280	0.1759292	0.1227202E-01
0.010	0.1825782E-01	1.616097	1.316049	1.518897	1.748148	0.1797934E-01	0.1232940E-03
0.000	0.1825782E-03	1.619495	1.315468	1.521006	1.753298	0.1801322E-03	0.1232841E-07
Results for Infinite Cylinder		251.5147	-192.3701	-283.0602	332.5686	199.7818	-266.4818

Table 5. Friction Welding. Fixed-Ended
Wall-Thickness = 0.375 Inch
Weld Centerline-to-Flange Face = 2 Inches

FLANGE FREE

Cylinder	OD =	18.000
	T =	0.375
	L =	2.000
	B =	0.707
Flange	OD =	21.000
	T =	1.875
	L =	1.500
	B =	0.304
Extended cylinder	OD =	18.000
	T =	0.375
	B =	0.707

E = 0.250E+08 V = 0.3 Mo = 1000.

RESULTS NORMALIZED TO INFINITE CYLINDER

BL	L	W11	T11	Q22	M22	Q44	M44
10.000	14.14245	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
9.000	12.72820	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
8.000	11.31396	1.000000	1.000000	1.000000	1.000000	0.9999999	1.000000
7.000	9.899712	1.000002	1.000000	1.000001	1.000001	0.9999994	0.9999973
6.000	8.485468	1.000015	0.9999973	1.000010	1.000012	0.9999802	0.9999872
5.000	7.071223	1.000026	0.9999876	1.000016	1.000019	0.9999511	0.9999917
4.500	6.364101	1.000084	1.000040	1.000072	1.000076	0.9999983	0.9998381
4.000	5.656979	1.000561	1.000203	1.000464	1.000494	0.9998632	0.9990280
3.500	4.949856	1.002400	1.000285	1.001825	1.002002	0.9982725	0.9968274
3.000	4.242734	1.006626	0.9992927	1.004633	1.005246	0.9923179	0.9937526
2.500	3.535612	1.011852	0.9957303	1.007471	1.008819	0.9803973	0.9938803
2.000	2.828489	1.013437	0.9924096	1.007723	1.009481	0.9724108	0.9976881
1.500	2.121367	1.026151	1.007698	1.021137	1.022680	0.9901484	0.9576948
1.000	1.414245	1.155996	1.064580	1.131155	1.138797	0.9776369	0.7162530
0.500	0.7071223	1.537717	1.091192	1.416382	1.453710	0.6665090	0.2430216
0.100	0.1414245	1.890401	0.9945547	1.646972	1.721860	0.1425298	0.9741221E-02
0.010	0.1414245E-01	1.952374	0.9589426	1.682428	1.765474	0.1410460E-01	0.9448313E-04
0.001	0.1414245E-03	1.958621	0.9548309	1.685860	1.769772	0.1408004E-03	0.9409729E-08
Results for Infinite Cylinder		-0.8159455E-03	-0.2763109E-03	-234.6299	231.9011	248.3875	-262.8217

Table 7. Friction Welding. Free-Ended
Wall-Thickness = 0.375 Inch
Weld Centerline-to-Flange Face = 2 Inches

F L A N G E F R E E

Cylinder	OD	=	18.250
	T	=	0.625
	L	=	2.000
	B	=	0.548
Flange	OD	=	21.000
	T	=	2.000
	L	=	1.500
	B	=	0.295
Extended cylinder	OD	=	18.250
	T	=	0.625
	B	=	0.548

E = 0.250E+08 V = 0.3 Mo = 1000.

RESULTS NORMALIZED TO INFINITE CYLINDER

BL	L	W11	T11	Q22	M22	Q44	M44
10.000	18.25782	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
9.000	16.43204	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
8.000	14.60625	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
7.000	12.78047	1.000002	1.000004	1.000002	1.000002	0.9999999	0.9999978
6.000	10.95469	1.000014	1.000044	1.000009	1.000011	0.9999857	0.9999926
5.000	9.128910	1.000022	1.000078	1.000012	1.000016	0.9999690	0.9999940
4.500	8.216019	1.000106	1.000171	1.000094	1.000099	1.000044	0.9998457
4.000	7.303128	1.000652	1.001233	1.000545	1.000586	1.000062	0.9991820
3.500	6.390237	1.002591	1.006187	1.001877	1.002118	0.9990557	0.9976267
3.000	5.477346	1.006237	1.018697	1.004128	1.004941	0.9945902	0.9960543
2.500	4.564455	1.009924	1.036379	1.005446	1.007171	0.9851950	-0.9977241
2.000	3.651564	1.010507	1.042697	1.005058	1.007157	0.9804170	1.000114
1.500	2.738673	1.031412	1.057459	1.027002	1.028701	1.007062	0.9579745
1.000	1.825782	1.197126	1.364760	1.168746	1.179680	1.040423	0.7387816
0.500	0.9128910	1.702343	2.654041	1.541222	1.603301	0.8127042	0.2832652
0.100	0.1825782	2.259517	4.460504	1.886893	2.030463	0.2020538	0.1307572E-01
0.010	0.1825782E-01	2.368608	4.880384	1.943368	2.107211	0.2062151E-01	0.1305440E-03
0.001	0.1825782E-03	2.379771	4.925328	1.948812	2.114858	0.2065208E-03	0.1304035E-07
Results for Infinite Cylinder		-0.6654797E-03	0.9322651E-04	-218.0428	238.6680	243.6722	-352.2985

Table 8. Friction Welding. Free-Ended
Wall-Thickness = 0.625 Inch
Weld Centerline-to-Flange Face = 2 Inches

F L A N G E   F I X E D

Cylinder	OD	=	18.000
	T	=	0.375
	L	=	1.000
	R	=	0.707
Flange	OD	=	21.000
	T	=	1.875
	L	=	1.500
	B	=	0.304
Extended cylinder	OD	=	18.000
	T	=	0.375
	B	=	0.707

E = 0.250E+08   V = 0.3   Mo = 1000.

RESULTS NORMALIZED TO INFINITE CYLINDER

BL	L	Q11	M11	Q22	M22	Q44	M44
10.000	14.14245	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
9.000	12.72820	1.000000	1.000000	1.000000	1.000000	0.9999999	1.000000
8.000	11.31396	1.000000	1.000000	1.000000	1.000000	0.9999999	1.000000
7.000	9.899712	1.000001	1.000001	1.000001	1.000001	0.9999991	0.9999971
6.000	8.485468	1.000007	1.000003	1.000007	1.000009	0.9999779	0.9999833
5.000	7.071223	1.000009	0.9999977	1.000008	1.000015	0.9999335	0.9999988
4.500	6.364101	1.000040	1.000027	1.000039	1.000047	0.9999554	0.9998632
4.000	5.656979	1.000286	1.000207	1.000281	1.000328	0.9997557	0.9989766
3.500	4.949856	1.001182	1.000704	1.001154	1.001442	0.9979726	0.9962957
3.000	4.242734	1.003088	1.001351	1.002985	1.004031	0.9914191	0.9920442
2.500	3.535612	1.005035	1.000975	1.004793	1.007239	0.9777671	0.9913453
2.000	2.828489	1.004777	0.9989035	1.004428	1.007966	0.9653297	0.9989002
1.500	2.121367	1.011130	1.005434	1.010792	1.014223	0.9728719	0.9693336
1.000	1.414245	1.075358	1.055207	1.074160	1.086298	0.9400160	0.7275835
0.500	0.7071223	1.225664	1.144840	1.230262	1.284972	0.6256718	0.2459015
0.100	0.1414245	1.357607	1.175845	1.346797	1.456286	0.1368487	0.1028724E-01
0.010	0.1414245E-01	1.376127	1.173277	1.364062	1.486254	0.1373804E-01	0.1018857E-03
0.000	0.1414245E-03	1.377920	1.172777	1.365718	1.489291	0.1373902E-03	0.1017345E-07
Results to Infinite C ?inder		429.7909	-156.4861	-437.9428	276.2405	188.4830	-179.9953

Table 9. Friction Welding. Fixed-Ended
Wall-Thickness = 0.375 Inch
Weld Centerline-to-Flange Face = 1 Inch

F L A N G E F I X E D

Cylinder	OD =	18.250
	T =	0.625
	L =	1.000
	B =	0.548
Flange	OD =	21.000
	T =	2.000
	L =	1.500
	B =	0.295
Extended cylinder	OD =	18.250
	T =	0.625
	B =	0.548

E = 0.250E+08 V = 0.3 Mo = 1000.

RESULTS NORMALIZED TO INFINITE CYLINDER

BL	L	Q11	M11	Q22	M22	Q44	M44
10.000	18.25782	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
9.000	16.43204	1.000000	0.9999999	1.000000	1.000000	1.000000	1.000000
8.000	14.60626	1.000000	0.9999999	1.000000	1.000000	0.9999999	1.000000
7.000	12.78047	1.000001	0.9999991	1.000001	1.000001	0.9999996	0.9999976
6.000	10.95469	1.000004	0.9999748	1.000004	1.000012	0.9999831	0.9999891
5.000	9.128910	0.9999993	0.9999251	0.9999984	1.000019	0.9999458	1.000007
4.500	8.216019	1.000044	0.9999607	1.000043	1.000066	0.9999839	0.9998791
4.000	7.303128	1.000314	0.9997663	1.000307	1.000459	0.9999188	0.9991320
3.500	6.390237	1.001086	0.9977816	1.001044	1.001960	0.9987016	0.9970921
3.000	5.477346	1.002196	0.9902735	1.002044	1.005350	0.9935926	0.9944702
2.500	4.564455	1.002039	0.9744352	1.001687	1.009341	0.9821199	0.9959666
2.000	3.651564	0.9996101	0.9603521	0.9991104	1.009996	0.9712815	1.003735
1.500	2.738673	1.009937	0.9723700	1.009459	1.019875	0.9828285	0.9738853
1.000	1.825782	1.088848	0.9434267	1.086998	1.127319	0.9839119	0.7538256
0.500	0.9128910	1.266015	0.5242652	1.256574	1.462243	0.7307670	0.2833326
0.100	0.1825782	1.381234	-0.2862281	1.360011	1.822357	0.1779902	0.1314434E-01
0.010	0.1825782E-01	1.391188	-0.5114752	1.366971	1.894532	0.1822266E-01	0.1325648E-03
0.000	0.1825782E-03	1.391832	-0.5367238	1.367286	1.902027	0.1826016E-03	0.1326066E-07
Results for Infinite Cylinder		362.1620	-76.68822	-361.3302	285.5375	205.0419	-257.7560

Table 10. Friction Welding. Fixed-Ended
Wall-Thickness = 0.625 Inch
Weld Centerline-to-Flange Face = 1 Inch

F L A N G E F R E E

Cylinder	OD =	18.000
	T =	0.375
	L =	1.000
	B =	0.707
Flange	OD =	21.000
	T =	1.875
	L =	1.500
	B =	0.304
Extended cylinder	OD =	18.000
	T =	0.375
	B =	0.707

E = 0.250E+08 V = 0.3 Mo = 1000.

RESULTS NORMALIZED TO INFINITE CYLINDER

BL	L	W11	T11	Q22	M22	Q44	M44
10.000	14.14245	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
9.000	12.72820	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
8.000	11.31396	1.000000	1.000000	1.000000	1.000000	0.9999999	1.000000
7.000	9.899712	1.000002	1.000002	1.000002	1.000002	0.9999997	0.9999977
6.000	8.485468	1.000015	1.000022	1.000012	1.000013	0.9999830	0.9999905
5.000	7.071223	1.000023	1.000037	1.000019	1.000020	0.9999585	0.9999946
4.500	6.364101	1.000096	1.000113	1.000091	1.000093	1.000022	0.9998497
4.000	5.656979	1.000617	1.000763	1.000575	1.000592	0.9999820	0.9991395
3.500	4.949856	1.002468	1.003324	1.002219	1.002317	0.9987261	0.9973366
3.000	4.242734	1.006395	1.009337	1.005537	1.005876	0.9935301	0.9951497
2.500	3.535612	1.010620	1.017013	1.008756	1.009492	0.9826678	0.9962039
2.000	2.828489	1.011393	1.019541	1.009017	1.009956	0.9757697	0.9995719
1.500	2.121367	1.028860	1.035846	1.026823	1.027628	0.9983196	0.9603151
1.000	1.414245	1.180984	1.219230	1.169832	1.174239	1.013771	0.7354156
0.500	0.7071223	1.635379	1.839219	1.575942	1.599434	0.7441887	0.2677888
0.100	0.1414245	2.080376	2.517659	1.952870	2.003266	0.1685700	0.1132068E-01
0.010	0.1414245E-01	2.157778	2.647480	2.014987	2.071424	0.1679416E-01	0.1103522E-03
0.000	0.1414245E-03	2.165466	2.660729	2.021053	2.078131	0.1677408E-03	0.1099375E-07
Results for Infinite Cylinder		-0.2148141E-02	0.9645222E-03	-199.1038	109.9171	302.9539	-326.8701

Table 11. Friction Welding. Free-Ended
Wall-Thickness = 0.375 Inch
Weld Centerline-to-Flange Face = 1 Inch

F L A N G E   F R E E

Cylinder	OD	=	18.250
	T	=	0.625
	L	=	1.000
	B	=	0.548
Flange	OD	=	21.000
	T	=	2.000
	L	=	1.500
	B	=	0.295
Extended cylinder	OD	=	18.250
	T	=	0.625
	B	=	0.548

E = 0.250E+08   V = 0.3   Mo = 1000.

RESULTS NORMALIZED TO INFINITE CYLINDER

BL	L	W11	T11	Q22	M22	Q44	M44
10.000	18.25782	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
9.000	16.43204	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
8.000	14.60626	1.000000	1.000000	1.000000	1.000000	1.000000	1.000000
7.000	12.78047	1.000002	1.000003	1.000002	1.000002	1.000000	0.9999983
6.000	10.95469	1.000013	1.000023	1.000010	1.000011	0.9999986	0.9999961
5.000	9.128910	1.000021	1.000036	1.000016	1.000018	0.9999807	0.9999945
4.500	8.216019	1.000136	1.000155	1.000131	1.000133	1.000088	0.9998618
4.000	7.303128	1.000772	1.000976	1.000711	1.000735	1.000241	0.9993416
3.500	6.390237	1.002689	1.003872	1.002337	1.002476	0.9996132	0.9982908
3.000	5.477346	1.006074	1.009588	1.004907	1.005367	0.9958922	0.9976806
2.500	4.564155	1.008519	1.016570	1.006118	1.007065	0.9875747	0.9999228
2.000	3.651564	1.008859	1.019003	1.006132	1.007208	0.9850719	1.000876
1.500	2.738673	1.040480	1.047229	1.038467	1.039261	1.022923	0.9605727
1.000	1.825782	1.255774	1.312657	1.238811	1.245505	1.107800	0.7685279
0.500	0.9128910	1.961756	2.338497	1.849412	1.893747	0.9817219	0.3314940
0.100	0.1825782	2.885855	3.889148	2.586672	2.704740	0.2759413	0.1712119E-01
0.010	0.1825782E-01	3.077283	4.249229	2.727808	2.865722	0.2864405E-01	0.1731660E-03
0.0001	0.1825782E-03	3.096719	4.287038	2.741766	2.881842	0.2872734E-03	0.1731388E-07
Results for Infinite Cylinder		-0.1115082E-02	0.5112500E-03	-172.2988	94.92718	302.7437	-458.5731

Table 12. Friction Welding. Free-Ended
Wall-Thickness = 0.625 Inch
Weld Centerline-to-Flange Face = 1 Inch

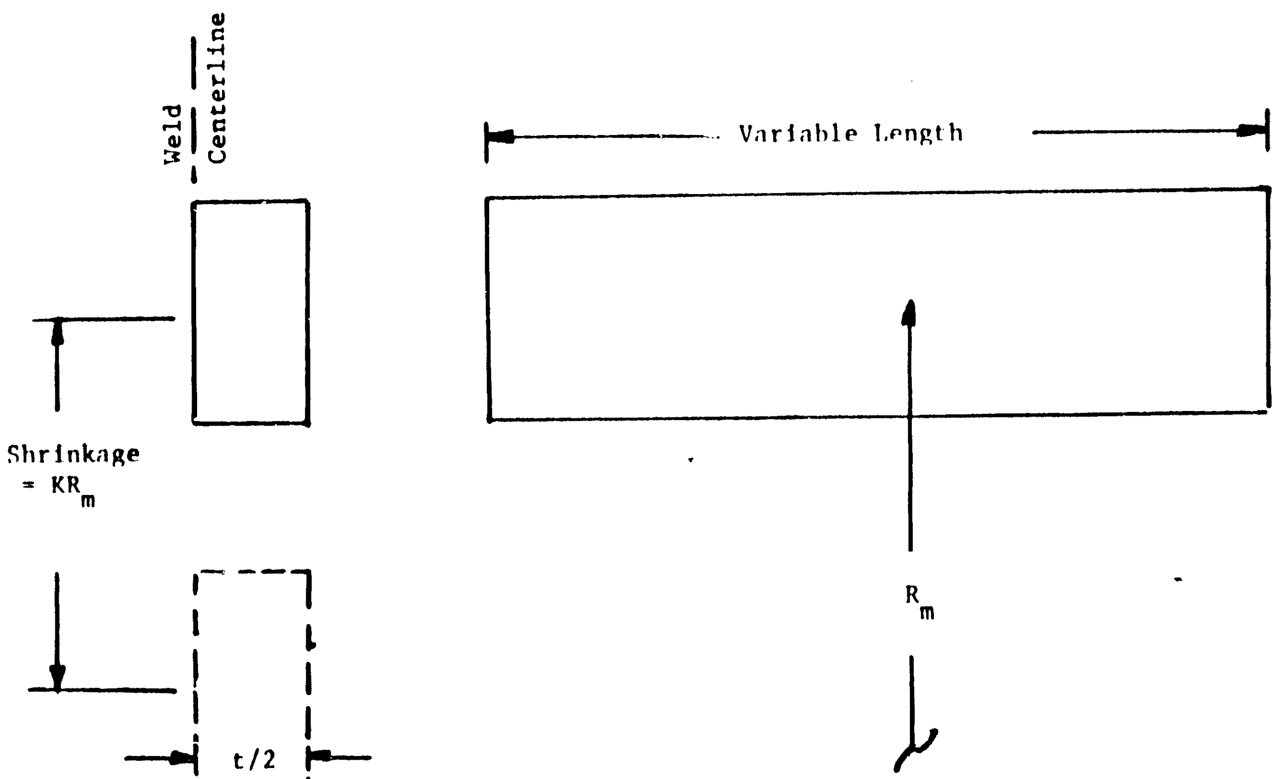

Figure 1. Model for Weld Approximation

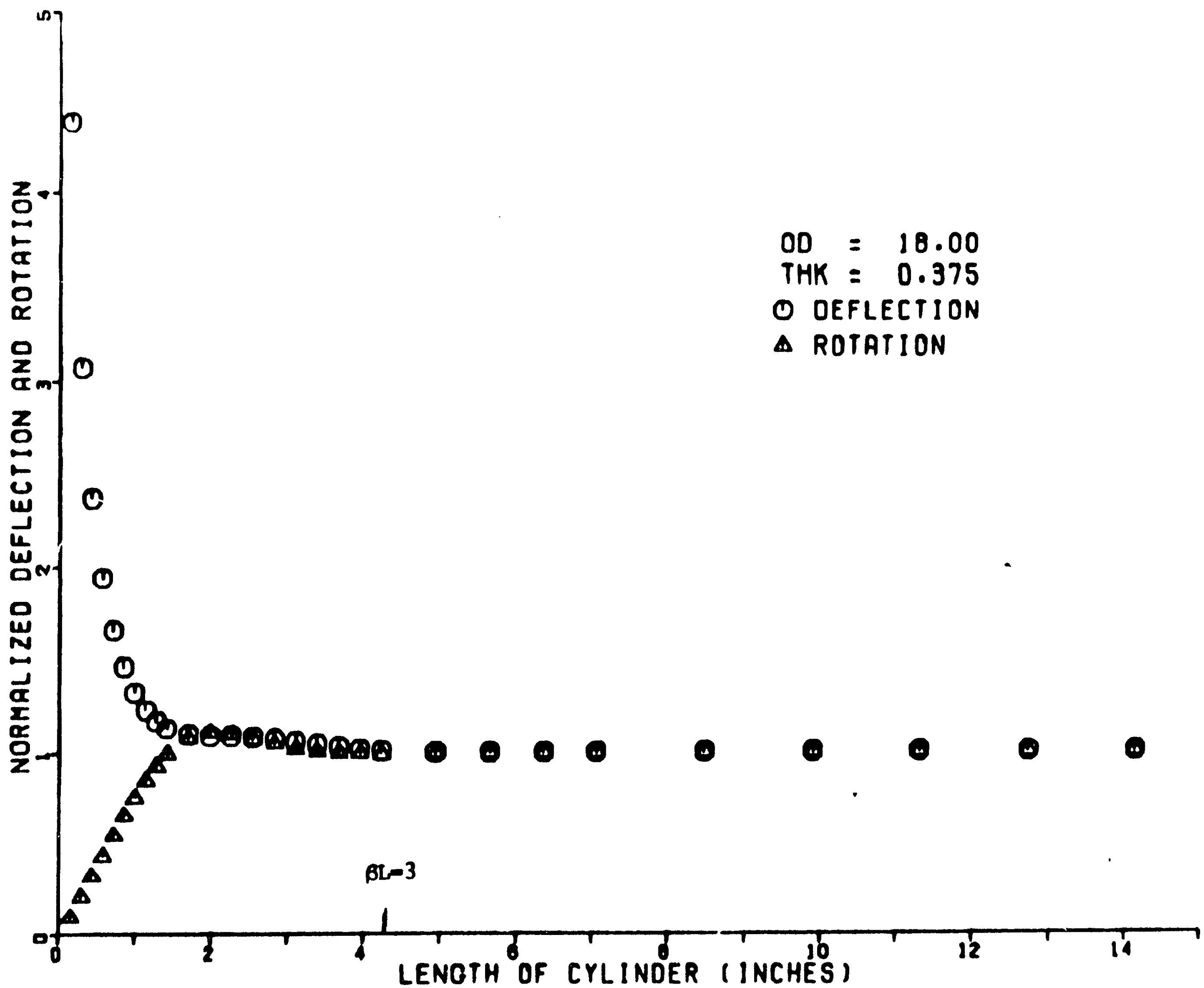

Figure 2. Effect of Cylinder Length on Motions at Interface
Wall Thickness = 0.375 inch

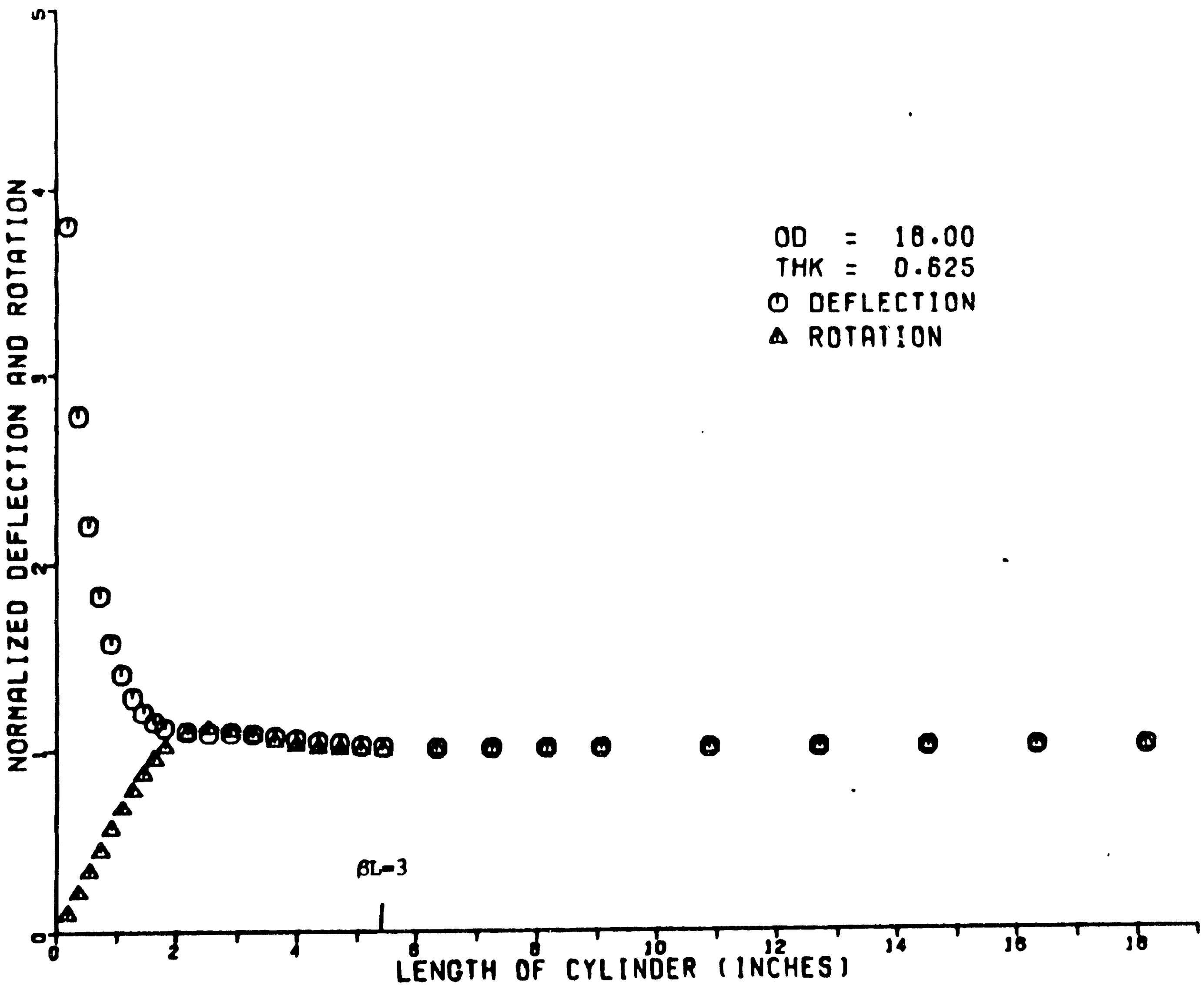

Figure 3. Effect of Cylinder Length on Motions at Interface
Wall Thickness = 0.625 inch

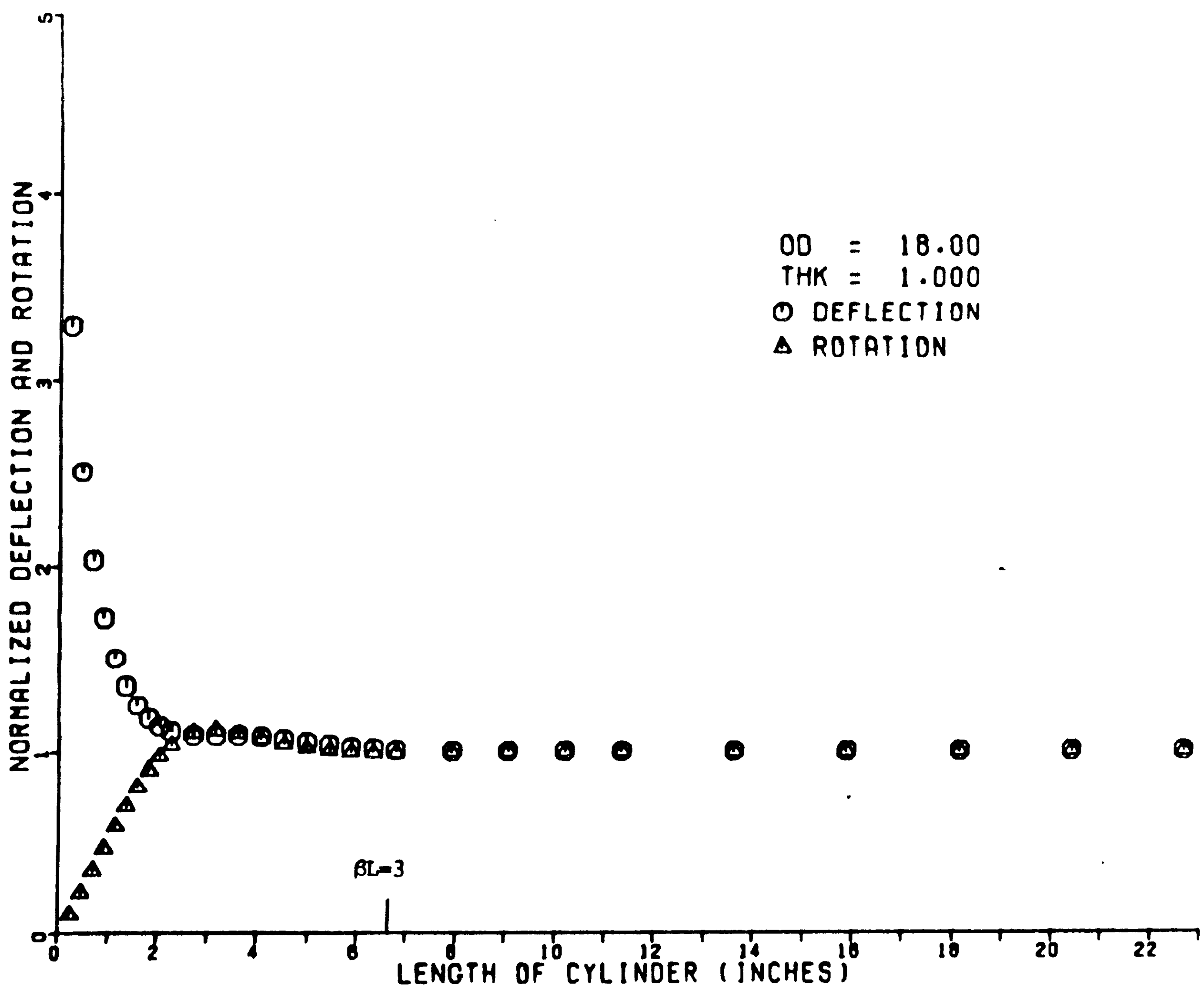

Figure 4. Effect of Cylinder Length on Motions at Interface
Wall Thickness = 1.00 inch

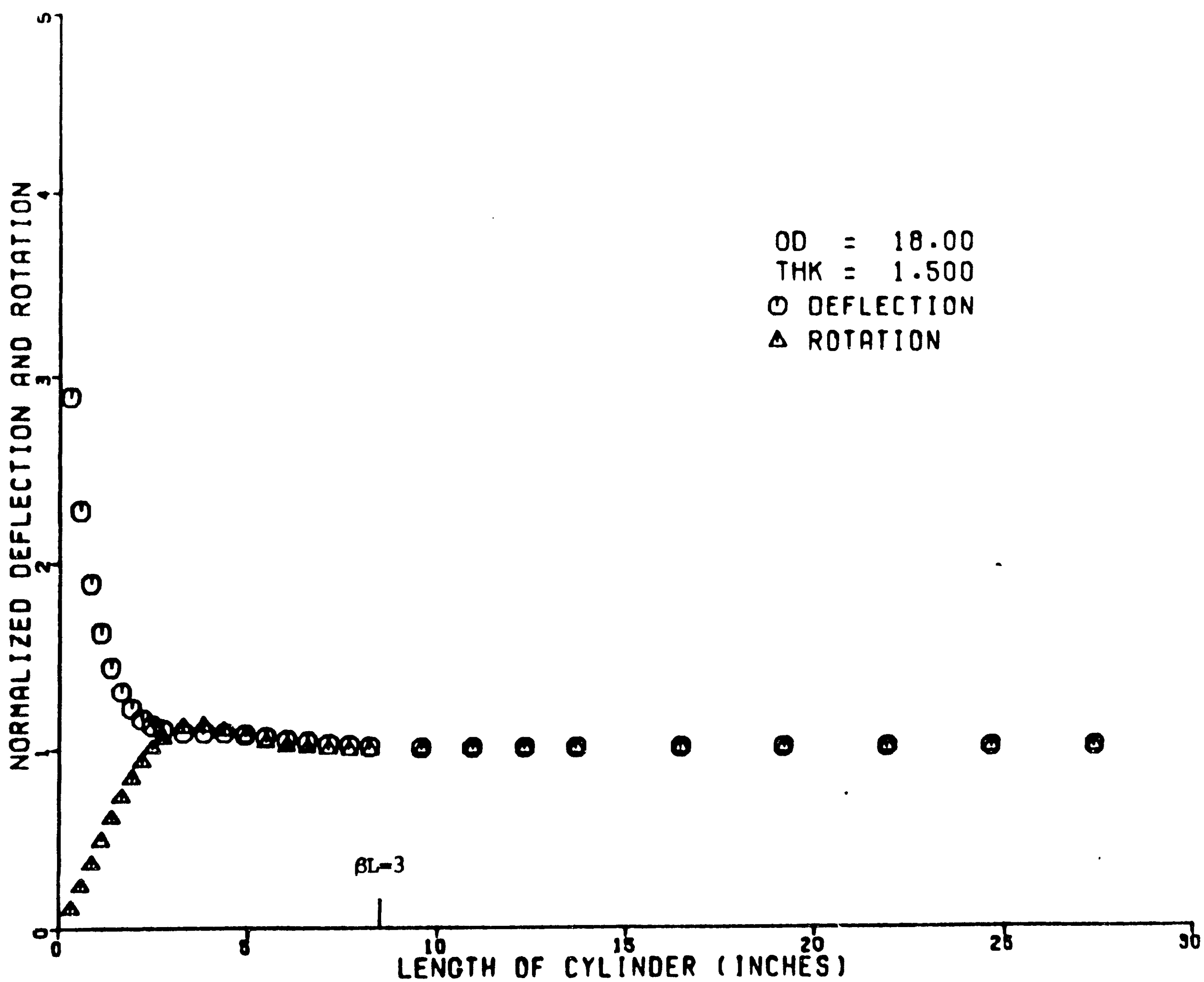

Figure 5. Effect of Cylinder Length on Motions at Interface
Wall Thickness = 1.50 inches

Table 1 Pipes for residual stress analysis

Nominal diameter (in.)	Wall thickness, in. (cm)			
	Schedule 10	Schedule 40	Schedule 80	Schedule 160
4	0.120 (0.305)	0.237 (0.602)	0.337 (0.856)	0.531 (1.349)
10	0.165 (.419)	0.365 (0.927)	0.593 (1.506)	1.125 (2.858)

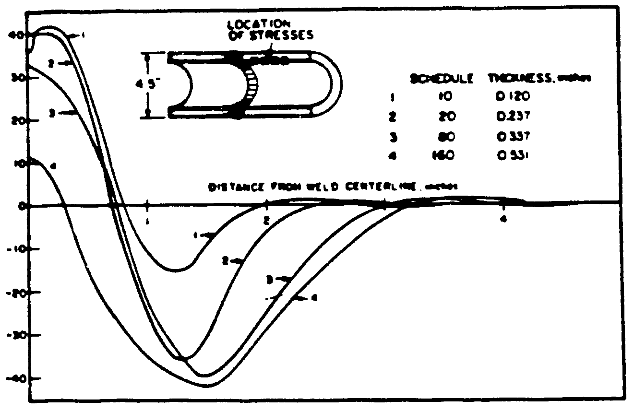

Fig. 5 Residual axial stress along inner surface of 4-in. pipes after welding

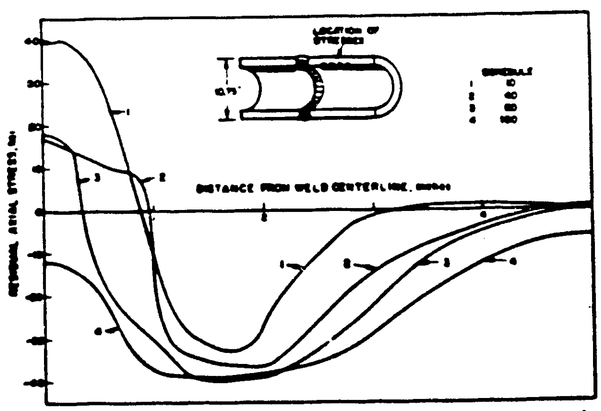

Fig. 6 Residual axial stress along inner surface of 10-in. pipes after welding

Figure 6. Results of Rybicki, et al.

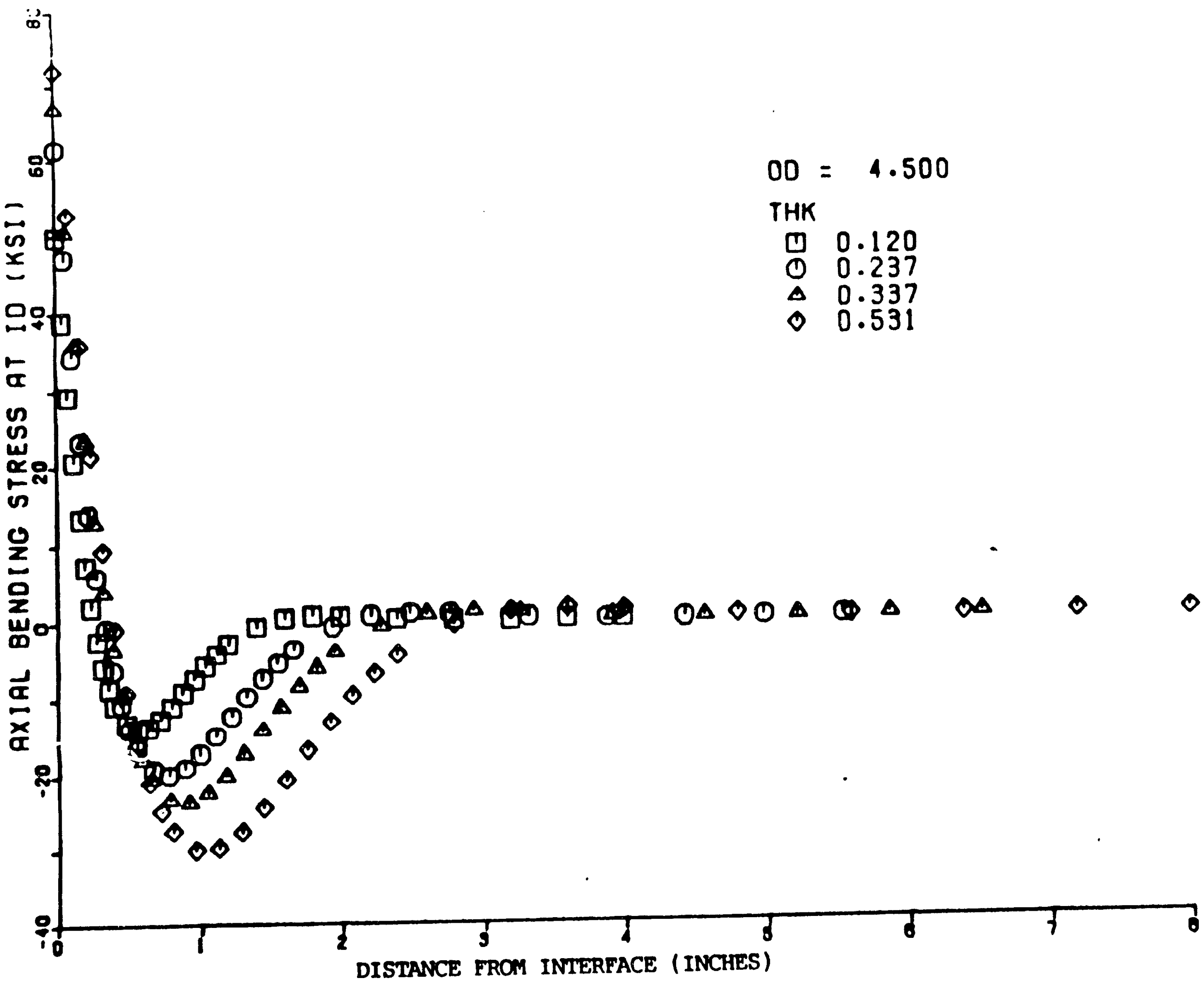

Figure 7. Variation of Axial Stress Along Length of Cylinder
O.D. = 4.50 inches

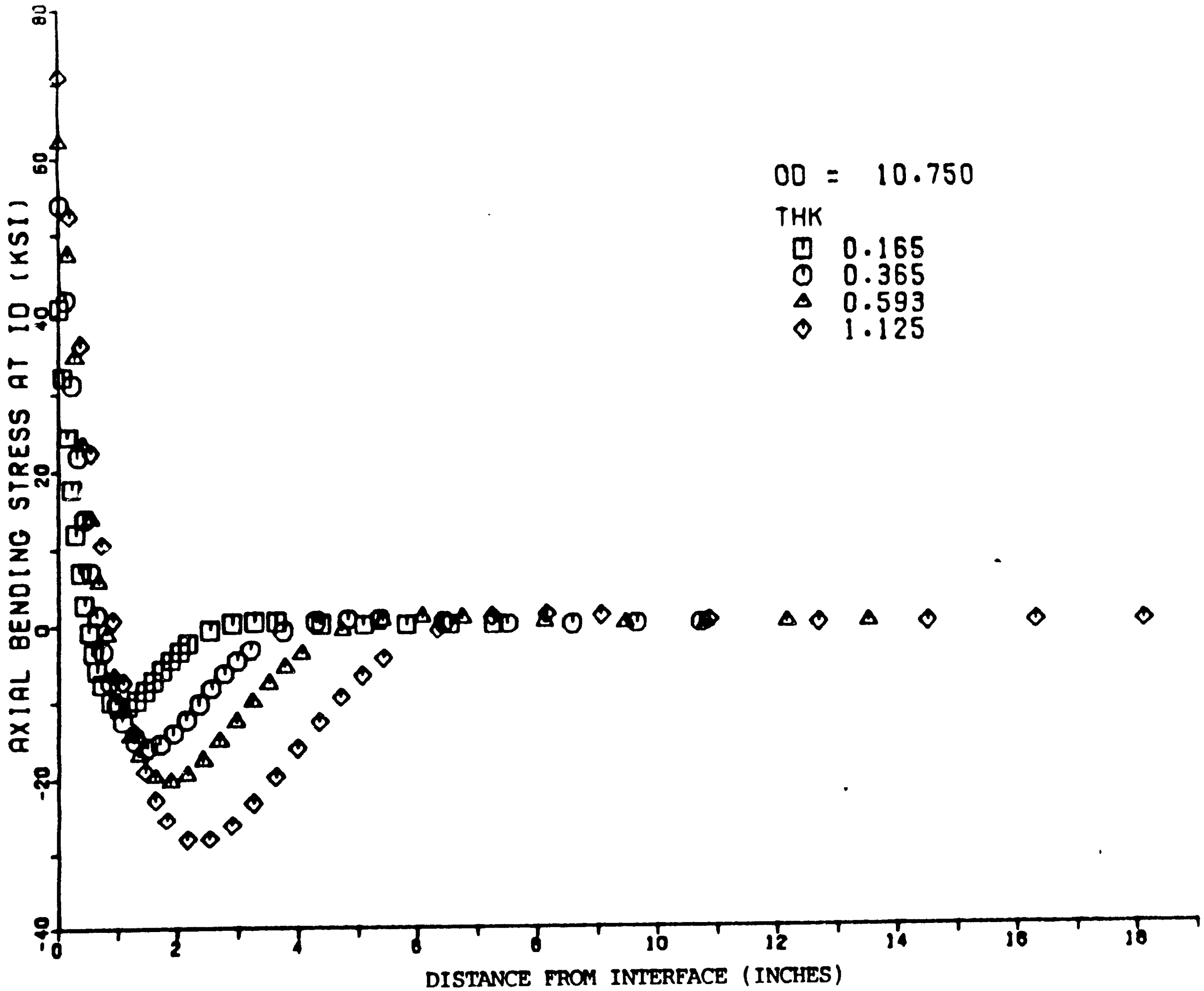

Figure 8. Variation of Axial Stress Along Length of Cylinder
O.D. = 10.75 inches

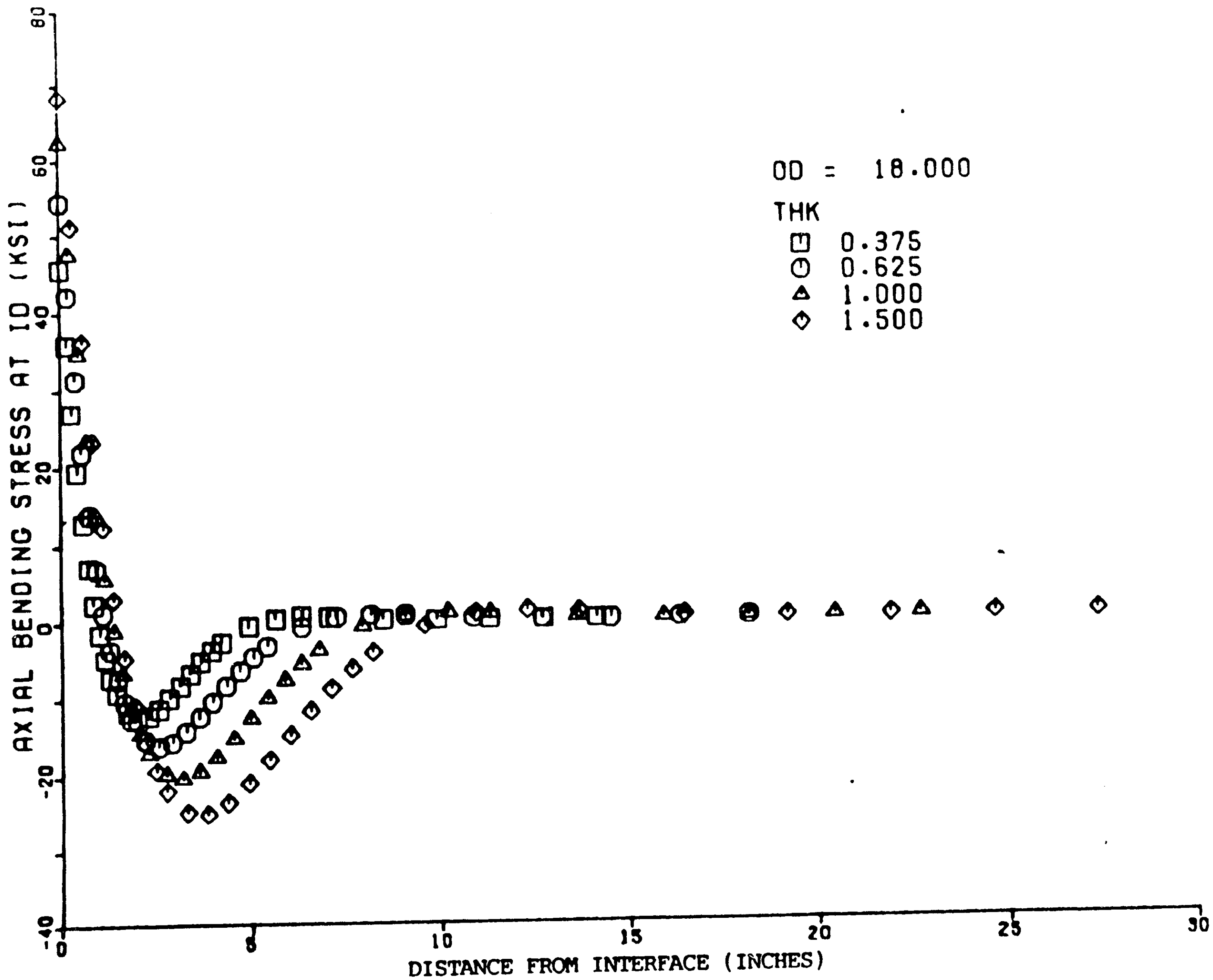

Figure 9. Variation of Axial Stress Along Length of Cylinder
O.D. = 18 inches

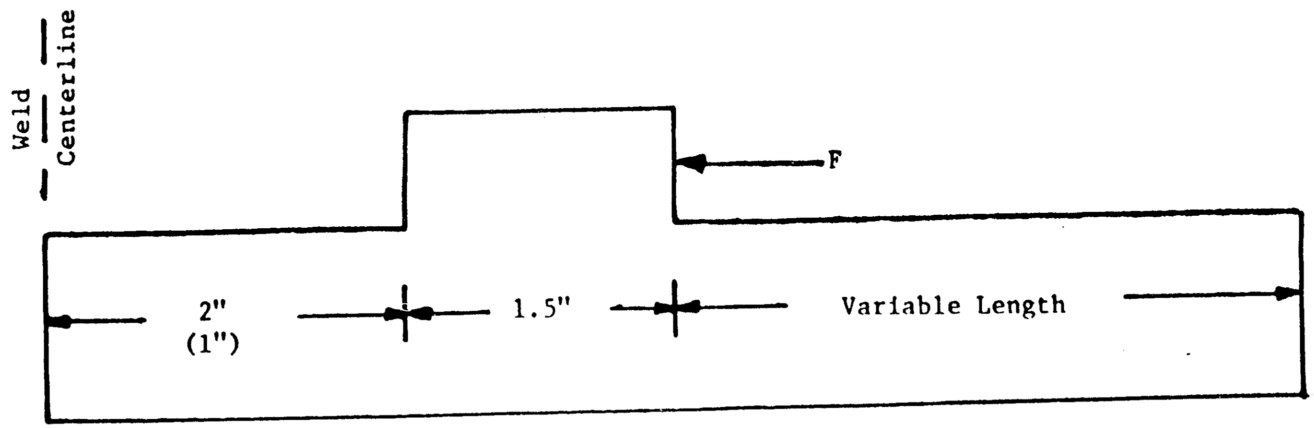

Figure 10. Model for Friction Welding

Babcock & Wilcox
a McDermott company

Research and Development Division
Alliance, Ohio 44601

RC-1 (Rev. 3-84)

To
E. S. ROBITZ - METALLURGY & MANUFACTURING SECTION

From
D. R. LEE - STRUCTURAL MECHANICS SECTION

Cust.	File No.
Subj. REVIEW OF CALCULATIONS FOR WELD SPECIMEN LENGTH	Date DECEMBER 19, 1988

This letter to cover one customer and one subject only

Reference 1) C. C. Schultz to E. S. Robitz, "Specimen Length for Weld Tests of Nuclear Waste Containment Vessels," File No. 4544-11, dated Nov. 23, 1988.

During November, 1988, C. C. Schultz issued a letter report to E. S. Robitz (Ref. 1) concerning the required length of weld test specimens. The length of the specimen was required to be long enough such that the weld residual stresses would be unaffected by the conditions existing at the free ends of the test specimen. During December, 1988, I reviewed the equations and calculations used to determine the lengths of the cylindrical test specimens.

Attached are the review sheets used to spot check some of the calculations. The sources of the equations used are well documented in the calculation sheets. I checked the equations used and spot checked the algebra and calculations and did not find any errors. The approach used was technically correct and complete.

Darrell Lee

D. R. Lee

cc: K. Aral
T. S. Brown
J. M. Nielsen
D. Peterson
C. C. Schultz

FC-306

PROJECT TITLE Nuclear Waste Containment

PROJECT NO.

SUBJECT Items Checked

REVIEW

PAGE 1 OF 1

ck source of equations in ASME code

ck modification of B_{11}, B_{12}, + B_{22} terms

ck verification of equations from ASME code

ck values of B_{11}, B_{12}, + B_{22} for $\beta L = 3$

ck example with $\beta L = 3$ page 6 of 10 to 10 of 10 11-16-88
(Mismatched cylinder program)

ck equations to determine load at weld interface
(Kabetz weld long cylinder program)

ck equations to determine load at various locations along cylinder

ck equations for friction welding

PERFORMED BY Darrell Lee DATE 12-11-88

REFERENCE SOURCE

FC-366

REVIEW

PROJECT TITLE: Nuclear Waste Containment

PROJECT NO.:

SUBJECT: Calculations Check of B_{11}, B_{12}, B_{22}

PAGE 1 OF 1

Page 3 of 4 11-16-88

$\beta L = 3$

$$B_{11} = \frac{\sinh(2\beta L) - \sin(2\beta L)}{2(\sinh^2 \beta L - \sin^2 \beta L)}$$

$$= \frac{\sinh 6 - \sin 6}{2(\sinh^2 6 - \sin^2 6)} = 1.0065617$$

Program output (RBTZ_MISMATCH.FOR): 1.006562

$$B_{12} = \frac{\cosh(2\beta L - \cos(2\beta L)}{2(\sinh^2 \beta L - \sin^2 \beta L)}$$

$$= \frac{\cosh(6) - \cos(6)}{2(\sinh^2(6) - \sin^2 6)} = 1.000397$$

Program output: 1.000397

$$B_{22} = \frac{\sinh(2\beta L) + \sin(2\beta L)}{2(\sinh^2(\beta L) - \sin^2(\beta L))}$$

$$= \frac{\sinh(6) + \sin(6)}{2(\sinh^2(6) - \sin^2(6))} = 1.0037769$$

Program output: 1.003777

Values compare

PERFORMED BY: Darrell Lee DATE: 12-11-88

REFERENCE SOURCE:

REVIEW

PROJECT TITLE Nuclear Waste Containment

PROJECT NO.

SUBJECT Calculations Check of $\beta L = 3$

PAGE 1 OF 3

for very long cylinder from P. 8 of 10

$Q = -2.6429214 \times 10^{-3}$

$M = 9.4419877 \times 10^{-4}$

$W = 0.42150101/E$

$\theta = 0.27079466/E$

for $\beta L = 3$

$$C_{11} = \frac{(\sinh 6 - \sin 6)}{2(\sinh^2 3 - \sin^2 3)} = 1.006562$$

$$C_{12} = \frac{(\cosh 6 - \cos 6)}{2(\sinh^2 3 - \sin^2 3)} = 1.000397$$

$$C_{22} = \frac{(\sinh 6 + \sin 6)}{2(\sinh^2 3 - \sin^2 3)} = 1.003777$$

$OD_1 = 18" = OD_2$

$t_1 = 0.375"$

$t_2 = 0.625"$

$\nu = .3$

$\delta_0 = 1/E$

$$D_1 = \frac{E(.375)^3}{12(1-.3^2)} = 4.829155 \times 10^{-3} E$$

$$D_2 = \frac{E(.625)^3}{12(1-.3^2)} = 2.23572 \times 10^{-2} E$$

$$\beta_1 = \left[\frac{3(1-\nu^2)}{R_m^2 t^2}\right]^{1/4} = \left[\frac{3(1-.3^2)}{8.8125^2(.375^2)}\right]^{1/4} = 0.707091$$

$$\beta_2 = \left[\frac{3(1-.3^2)}{8.6875^2(.625^2)}\right]^{1/4} = 0.551637$$

PERFORMED BY Darrell Lee DATE 12-11-88

REFERENCE SOURCE

F C - 306

PROJECT TITLE

PROJECT NO.

SUBJECT *Calculations Check of βL=3*

REVIEW

$\omega_1 = \omega_2$

$$\left[\left(\frac{1.006562}{2(.707091)^3} 4.829155\times10^{-3} E\right) + \left(\frac{1.006562}{2(.551637)^3} 2.23572\times10^{-2} E\right)\right] Q =$$

$$\left[\left(\frac{-1.000397}{2(.707091)^2} 4.829155\times10^{-3} E\right) + \left(\frac{1.000397}{2(.551637)^2} 2.23572\times10^{-2} E\right)\right] M - 1/E$$

$$(428.8916)\, Q = (-133.6448)\, M - 1$$

$$Q = -.311605\, M - .00233159 \qquad (1)$$

$\theta_1 = \theta_2$

$$\left[\left(\frac{-1.000397}{2(.707091^2)} 4.829155\times10^{-3} E\right) + \left(\frac{1.000397}{2(.551637)^2} 2.23572\times10^{-2} E\right)\right] Q =$$

$$\left[\left(\frac{1.003777}{.707091(4.829155\times10^{-3} E)}\right) + \left(\frac{1.003777}{.551637(2.23572\times10^{-2} E)}\right)\right] M$$

$$(-133.6448)\, Q = 375.3508\, M$$

substitute (1) in for Q

$$(-133.6448)(-.311605M - .00233159) = 375.3508M$$

$$.3116 = 333.706M$$

$$M = 9.33771\times10^{-4}$$

$$Q = -2.62256\times10^{-3}$$

PERFORMED BY *Darrell Lee* DATE 12-11-88

REFERENCE SOURCE

PROJECT TITLE

PROJECT NO.

SUBJECT Calculations Check of $\beta L = 3$ **REVIEW** PAGE 3 OF 3

$$\omega = \left(\frac{1.006562}{2(.707091)^2(4.829155\times10^{-3}E)}\right)q + \left(\frac{1.000397}{2(.707091)^2\,4.829155\times10^{-3}E}\right)M + 1/E$$

$$\omega = \frac{294.79}{E}(-2.62256\times10^{-3}) + \frac{207.167}{E}(9.33771\times10^{-4}) + 1/E$$

$$\omega = .420342/E$$

$$-\theta = \left(\frac{1.000397}{2(.707091)^2(4.829155\times10^{-3}E)}\right)q + \left(\frac{1.003777}{(.707091)\,4.829155\times10^{-3}E}\right)M$$

$$-\theta = -.54331/E + .274493/E$$

$$\theta = .26882/E$$

normalize with long cylinder results

$M = .98895$	(.988954)*	* from program "Rabity Mismatched Cylinders" with $\beta L = 3$
$q = .99229$	(.992296)	
$\omega = .99725$	(.997249)	
$\theta = .99271$	(.99269)	

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REFERENCE SOURCE

RC-366

REVIEW

PROJECT TITLE

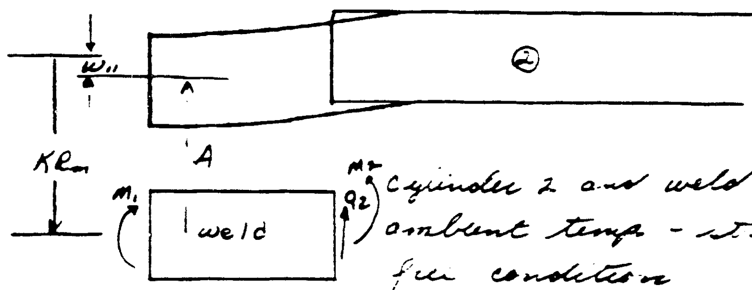
PROJECT NO.

SUBJECT: Stress Equation for Hoop Bending

PAGE ____ OF ____

Page 2 of 6 & 3 of 6 "Weld variable Length Cylinders"

KR_m is deflection of weld due to cooling



Distance A is due to the application of M_1, Q_2, and M_2

$w_{11} = A - KR_m$

or

$w_{11} = C_{12} M_1 + C_{13} Q_2 + C_{14} M_2 - KR_m$

The stress in the weld is due to the displacement A which is why the stress is given as $\sigma = \frac{E(w_{11} + KR_m)}{R_m}$

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