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DEA-97

COILED TUBING WELD CYCLE LIFE
Joint Industry Project

Part I : Final Project Report

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COILED TUBING WELD CYCLE LIFE
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Executive Summary

A Joint Industry Project has been undertaken to investigate the cycle life of coiled tubing (CT) welds relative to that of unwelded pipe, under a range of test conditions.

A total of 395 cycle tests have been performed on CT sizes ranging from 1.25" to 3.5" diameter, with a particular focus on 1.75" CT.

Each of the three major weld types were tested, namely bias, orbital butt, and manual butt welds, as well as unwelded pipe from the same source for comparison. Pipe samples were provided by three manufacturers. Welds were variously performed by the pipe manufacturers, a CT welding specialist contracted for the project, and by local welders in several field locations worldwide.

5 tests were typically performed for each CT configuration and weld type. Of these five tests, one was performed at 1500 psi, three at 3000 psi, and one at 5000 psi. For a few selected cases, welds of each type were cycled at 3000 psi to 50%, 75% and 100% of the observed life, and the partially fatigued samples then analyzed in the laboratory for crack initiation and propagation characteristics.

Conclusions reached based on the 395 test results include the following:

- The bias welds performed significantly better[1] than the butt welds, but not as well as unwelded pipe.
- Orbital welds performed somewhat better than equivalent manual welds in most cases, but not as well as expected.
- The majority of bias weld failures occurred in the weld itself, at the junction of the bias weld and longitudinal seam weld. An increase in bias weld performance might be achieved if the fatigue properties at this junction can be improved.
- The majority of failures in manual and orbital butt welds occurred in the Heat Affected Zone (HAZ), not the weld itself, but were distributed and did not favor the longitudinal seam weld. The thermal effect of the welding process on the base metal in the HAZ should be addressed.
- The majority of cracks initiated at the inside surface of the tubing.

[1] survived more cycles without loss of pressure for the same bending conditions

- Radiographic inspection of butt welds was not a reliable predictor of weld performance.

- Tapered[1] butt welds performed significantly worse than untapered butt welds.

- Field welds performed at least as well as those made under controlled conditions.

As anticipated, quite a lot of scatter was observed in the data, resulting in a large difference between the *average* result and *lowest* result for each weld type. For practical reasons it is desirable to model weld life with a general derating factor for a given weld type, for example "50% for orbital butt welds". Basing such a factor only on the lowest test result, which would be the most conservative approach, neglects the fact that the majority of results were significantly better, and does not take into account all the variables which influence the weld life. Each project participant should choose derating factors based on their own assessment of the data. However, if a general derating factor is to be used, CTES proposes the following values, which should be considered conservative.

Relative to unwelded pipe life under the same conditions:

Bias Welds	80%
Tapered Bias Welds	50%
Orbital Butt Welds	45%
Tapered Orbital Welds	20%
Manual Butt Welds	35%
Tapered Manual Butt Welds	15%

CTES is working on a parallel project funded by the Gas Research Institute (GRI) to address several of the technological issues identified above, and to develop a recommended practice for field welding of large diameter coiled tubing. This work is expected to be complete by the end of 1995. At GRI's request, these results will be made available to DEA-97 project participants.

[1] different wall size either side of the weld

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1 INTRODUCTION

1.1 Coiled Tubing (CT) Services

Coiled tubing has joined drillpipe and wireline as a third major alternative for conveying tools and fluids. From 1988-1991 the CT market grew at 20-30% per year, and there are now well over 600 CT units worldwide performing a wide range of services. Most significantly, improvements in CT technology in the last five years are opening the door for new applications such as CT drilling, spoolable completions, and high pressure operations which will result in the market growing still further. These technical developments include:

- Introduction of the bias welding technique for joining strips of base metal prior to forming the tubing, eliminating in most cases the weaker factory tube-to-tube welds previously required.
- Higher yield strength materials, enabling the same tubing pressure and tension specifications to be achieved using thinner-walled pipe (with consequent reduction in weight, allowing use of CT in deeper wells), or higher specifications for the same wall thickness (permitting use of CT at higher pressures, substantially increasing the market by replacing expensive snubbing operations).
- Larger diameter pipe (maximum 1.75" OD in 1991, 4.50" in 1995), permitting the high fluid flow rates required for drilling, completions and flowlines.
- Increased use of tapered strings (variable wall thickness), to reduce string weight (permits use of CT in deeper wells).

Coiled tubing has been in use since the 1960's. Acceptance by the industry was hampered for many years by a reputation for unreliability due to frequent and costly well site failures caused by *fatigue*. When coiled tubing is bent onto and off a reel, and onto and off the guide arch, the metal is repeatedly deformed past its plastic limit. The resulting stresses cause irreversible and cumulative damage to the material, which after continued cycling eventually results in the formation of cracks. These cracks in turn propagate through the tubing wall until one crack penetrates from one side of the tubing wall to the other, resulting in loss of pressure integrity and rendering the CT unfieldworthy. If this occurs during a field operation, the minimum result is delay and inconvenience while replacement tubing is sought, and in extreme cases the viability of the well itself may be compromised.

Inadequate understanding of the contributing factors and an inability to predict the safe working life of a given tubing size and type resulted in large safety margins being applied. Considerable progress has been made in recent years towards understanding the fatigue mechanism in CT and models have been developed by some companies to predict the expected tubing life. The success of these models has contributed to a reduced failure rate and greater confidence in the serviceability of the tubing. At the same time, the newer applications which have been made practical by the improved technology require the fatigue life predictions to remain accurate in increasingly complex situations.

1.2 CT Welds

Welds are required between sections of coiled tubing for several reasons:

- The source strip from which the CT is made is supplied in lengths up to 3,500 ft long, but tubing is required in lengths of up to 25,000 ft. At some point, either while still in strip form or as milled tubing, the individual lengths must be joined to make the longer string.

- Field repairs in existing strings are often required to remove damaged or highly fatigued sections, or for other operational reasons. The two free ends are then welded back together, resulting in a "field butt" weld.

1.3 Weld Issues

Remembering that every practical effort must be made to avoid field failures, welds in coiled tubing are of major concern because:

- It is known from observation and testing that welds usually fail[1] after fewer bending cycles than unwelded tubing under the same conditions.

- Sophisticated models to predict the fatigue life of coiled tubing are of diminished value if known weak points (e.g. welds) are not taken into account. Likewise, many operating companies and some service companies have a policy of not using strings containing butt welds at all, or else apply large conservative derating factors to the welds such that the fatigue modelling is rendered almost academic.

- The expected working life of a weld is often estimated as a fraction of the corresponding life for unwelded pipe, but in reality this may vary widely according to the weld type, the physical geometry and material properties of the tubing, and the bending conditions.

- No two welds are identical, and fatigue is not a precise process, so some range of observed lives is to be expected even for the same weld type and loading conditions.

Furthermore, several of the development areas identified above have negative implications for welds which may slow the introduction of new technology:

- Higher yield strength materials are generally more difficult to weld.

[1] Failure in this context means loss of pressure integrity due to a crack or other communication path penetrating the CT wall from one side to the other. Such loss of pressure is usually observed to be instantaneous and catastrophic, with little apparent leakage prior to the failure. The crack can range from being microscopic, to extending around the tubing diameter causing the pipe to part, depending on the circumstances.

- Large diameter CT (2.00 in. and bigger) is usually thicker-walled than smaller diameter pipe, and complete weld penetration through the wall becomes a concern.

- Tapered strings require a weld between walls of different thickness, whether as flat strip or milled tubing. Weld penetration may therefore be uneven in the two walls, leading to local stress risers which are prime crack initiation points. A significant number of weld failures in the field in recent years have been observed at tapered welds.

1.4 Derating CT welds

In the absence of a fatigue model specifically addressing welds, the current practice is usually to apply a *derating factor* which reflects the reduced life of the weld compared with the plain pipe. For example, if the derating factor for a given weld type is 50%, then the calculated fatigue at that point in the string is effectively doubled for modeling purposes.

There is limited experimental data to indicate what the derating factor should be for a given weld type, and what physical parameters may have an influence. CT diameter, wall thickness, material type, internal pressure and bending radius are all known to directly influence the fatigue life of unwelded pipe, but it is not known whether these parameters have a greater or lesser effect with regard to welds. Such work as has been done is limited in extent, due to the expense and difficulty of obtaining samples and performing tests in representative conditions. It has been done largely by oil service companies and hence is not always in the public domain. Most importantly, the work predates many of the relevant technological advances of the past few years, in particular large diameter CT and use of high strength materials. In short, more data is required to improve the derating of coiled tubing for the presence of welds.

1.5 DEA-97

Joint Industry Project DEA-97 (Drilling Engineering Association) was proposed specifically to address the need for more cycle life data for CT welds, to determine the derating factors described in the previous section. The primary objective was to enable CT operators to better estimate weld lives according to type of weld and cycling conditions, and hence minimize field failures while maximizing usage of the pipe.

DEA-97 was primarily an experimental program to provide empirical data for statistical analysis and modeling purposes. Project participants at the launch meeting (held on September 29th 1994) requested that some effort be made to investigate weld failure mechanisms and, if appropriate, make recommendations for improved welding techniques, especially with regard to large diameter CT for which it was felt existing procedures might be inadequate. Such work was considered beyond the scope of the project, given the limited resources initially available. However, additional funding from another source (see next page) has enabled much of this work to be undertaken and will be made available to DEA-97 participants shortly.

The original proposal called for 201 tests, covering three pipe sizes and several wall sizes. Three tests were planned for each pipe configuration at three different pressures, and several tapers were to be investigated. Due to strong support from both paying participants and pipe manufacturers, it was possible to undertake significantly more testing than originally planned, and a total of 395 tests were performed, although the budget was significantly overrun.

While the original proposal set out a specific program of tests to perform, in practice it was necessary to accomodate the schedules of the CT manufacturers and work with those samples (both with and without welds) which were available at the time. This resulted in some modifications to the test program, but as mentioned above, almost twice the anticipated number of tests were ultimately performed which not only covered most of the original objectives but also permitted the addition of several new areas of investigation.

1.6 Gas Research Institute (GRI)

The Gas Research Institute (GRI) is an American not-for-profit organization funded by duties levied on gas sales in the United States. GRI's primary mission is to further the interests of the gas industry, which includes the funding of research projects concerning technology which has, or may have in the future, an impact on the production of gas.

GRI expressed a strong interest in the objectives of DEA-97, but as an organization operating in the public domain was unable to join the JIP as such. CTES therefore proposed a GRI project running concurrently with DEA-97 to investigate those issues identified above which were considered beyond the scope of the JIP.

The study was proposed in two phases, the second being contingent on results obtained in the first. Phase I includes the following objectives:

- Gather data on existing techniques and standards for CT welding.
- Study the mechanics of CT weld fatigue compared with unwelded pipe.
- Identify possible improved or alternative welding techniques.
- Write a Recommended Procedure for CT field welding.

Funding for Phase I was approved, and for logistical reasons the work has been performed as an extension to an existing GRI project being run by CTES to develop standards for slim hole and CT drilling. At GRI request, all findings obtained under the auspices of the GRI project will be made available to DEA-97 participants. Phase I will be concluded by the end of 1995.

2 PROJECT ADMINISTRATION

2.1 DEA-97 Participants

The following companies formally participated in the project.

Agip
Amoco
Baker Hughes INTEQ
BP
Cymax*
Dowell**
Exxon
Halliburton
Nowsco
Precision Tube Technology*
Shell
Statoil

* contributed test samples and inspection services in lieu of participation fee
** contributed use of fatigue test machine in lieu of participation fee

Quality Tubing Inc. also provided a large number of welded and unwelded pipe samples and other technical support to this project.

2.2 Correspondence

Copies of the project proposal and subsequent correspondence sent to participants are reproduced for reference in Appendix A.

2.3 Contract

A copy of the Project Agreement is reproduced for reference in Appendix B. Only those companies which returned signed contracts are included in the participant list above. Participants are reminded that, under the terms of clause 7.2 of this contract, data may not be copied or disclosed to any company or persons not taking part in the project for a period of two years after the conclusion of the project (i.e. October 27th 1997).

2.4 Accounts

There were nine paying participants in the project, paying $12,000 each to provide a total available budget of $108,000.

The project expenses shown below are calculated, as per the contract, according to man days worked, usage of the Drexel facility, and other miscellaneous charges such as supplies and meeting costs. Some tests (approximately 10% of the total), specifically those involving detailed examination of selected samples, were designated GRI tests and billed to that project.

Engineer	P. Brown	52		
	D. Van Arnam	25		
	K. Newman	4		
	Total:	81	days at $700/day	**$56,700**
Technician	E. Boaz	132		
	R. Brown	29		
	Total:	161	days at $400/day	**$64,400**
Facility charge		130	days at $100/day	**$13,000**
			Total:	**$134,100**

3 TEST EQUIPMENT AND PROCEDURES

3.1 Fatigue Test Machine

All testing reported here was conducted on Schlumberger-Dowell's Fatigue Test Machine (FTM), which was made available as Dowell's contribution to this project. This purpose-built machine bends a six foot CT sample around a mandrel of fixed radius of curvature using hydraulically powered rollers, and straightens it again against a straight mandrel. The profile of both bending mandrels and rollers is V-shaped to ensure two-point contact. Internal pressure up to 10,000 psi can be applied to the sample. Bending occurs at an approximately constant rate, without applying a tensile or axial load to the specimen other than the end-loading created by the internal pressure. One bending and straightening cycle takes approximately thirty seconds and includes 8 second hold periods at the end of each bend and straightening operation.

The specimen is clamped near the lower end in such a way that at least 6" of tubing is not subject to bending. The sample is sealed using purpose-built end-caps and internally pressurized to a set value which is maintained throughout the test to within ± 5%. The machine design allows for filling the specimen completely with water, while not trapping air in the specimen.

An automatic cycle counter records the total accumulated cycles of bending and straightening.

3.2 Test Specimens

The weld samples tested in this programme were obtained from several sources.

- All bias welds were provided by the CT manufacturers, with samples received in varying quantities from Quality Tubing Inc., Cymax (Southwestern Pipe), and Precision Tube Technology.

- The majority of butt welds (manual and orbital) were provided by a specialist CT welding contractor, Acute Technological Services Inc. of Houston TX. ATS provide welding and consultancy services to Quality Tubing, amongst others. These samples were intended to provide a reference against which field welds could be judged.

- Butt weld samples were also solicited and received from several field locations worldwide. In each case unwelded CT was also provided from the same string, to provide a reference. The purpose was to compare the quality of field welding on used pipe with that obtained under ideal conditions on new pipe.

As stated in the Project Agreement, it is not the intention of this JIP to draw comparisons between different sources of welds, in particular bias welds provided by the respective CT manufacturers. Therefore, the origin of each sample is not identified in this report, either by manufacturer or (where applicable) field location, and Participants are requested not to attempt to differentiate between results on this basis. Unfortunately, despite attempts by CTES to secure an equal distribution of samples, prevailing circumstances meant that the manufacturers did not in fact furnish CTES with equal numbers of samples, although other services (in particular radiographic and other inspection facilities) were furnished in lieu.

The CT specimens used for this programme were typically 5.5 feet long with the welds located at the center of the sample such that the weld was subject to the target bending radius at the center of the bending mandrel.

Where possible, a complete material description was obtained for the specimens. This data included:

- Chemical Analysis
- Mechanical Properties (tensile strength, yield strength, percent elongation, percent reduction of area and hardness)
- Physical properties (Poisson's ratio, Modulus of Elasticity, strain hardening exponent, strength coefficient)
- Microstructural characteristics (grain size, crystallographic structure, preferred orientation, general shape of grains, second phase particles, heat treatment)

Test specimen dimensions were measured and recorded at several positions along the center of the section to be bent, to identify actual OD and the presence of any initial ovality.

3.3 Test Procedure

The sample was introduced into the machine between the bending mandrel and straightening guide with the upper pressure end-cap preinstalled. The lower end of the sample was then firmly clamped with at least twelve inches of tubing extending below the clamp to accept the lower pressure end-cap. The longitudinal seam is usually aligned with the inside radius of bending (this is approximately the situation in field operations) but some tests were performed with other orientations. The top of the clamp was marked on the tubing and this datum subsequently became the reference point for identifying weld and crack locations relative to the bending mandrel.

The sample was then filled with water and the air bled off from the top pressure end-cap. The bleed-off valve was closed and the specimen internally pressurized using a Haskell air-over-water pump to the required level. The majority of tests were performed at 1500, 3000 and 5000 psi, although some tests were performed at 250 and 2500 psi.

The hydraulic bending mechanism was actuated, and cycling continued under automatic control until failure occurred (defined as loss of pressure) or a predetermined number of cycles were reached.

Any remaining pressure was then bled off and the specimen removed from the test machine.

The following results and observations were then recorded for all test specimens.

- Test identification number
- Supplier (not included in this report)
- Material type
- Nominal diameter
- Nominal and measured wall thickness
- Bending radius
- Test pressure
- Orientation of longitudinal seam welds (where applicable, above and below butt weld) with respect to bending plane.
- Final minimum and maximum diameters
- Number of cycles to failure

3.4 Visual Inspection of Samples

In addition to the above measurements, the following visual observations were noted for each sample:

- Fracture axial location relative to the weld (weld, fusion zone, HAZ, parent material)
- Fracture radial location relative to the longitudinal seam weld
- Fracture length
- Fracture appearance

Also recorded but not included in this report (available on request) were:

- Fracture axial location relative to the bending mandrel (zero datum = clamp)
- Fracture radial location relative to the bending mandrel (zero datum = inside radius)

3.5 Selection of Samples for Further Analysis

In order to investigate the progressive development (propagation) of cracks in welds in more detail, 12 tests were performed where, having previously cycled three similar samples to failure and determined a median life expectancy, two more samples were cycled at the same pressure to 50% and 75% respectively of that median life. These samples were then analyzed by Professor Steve Tipton, Associate Professor in the Mechanical Engineering Department at the University of Tulsa. These samples were designated GRI project specimens for accounting purposes.

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4 DATA

Results are organized into Data Sets (see next page) according to the type and origin of the samples and without regard to the chronological order in which they were obtained. Data Sets labelled **A-H** are samples provided by the CT manufacturers or welded by ATS for CTES. Data Sets labelled **1-6** are samples provided by field locations using local welders

Results are presented both in tabular form, on the following pages, and in graphical form in Part II of this report.

Tables

Each Data Set is presented in three parts. An identification number has been assigned to each test to facilitate cross-referencing.

- Tables **1-23** cover the primary data, including physical properties, test conditions and the observed cycle life N_{FTM}. This data was released to participants in a preliminary distribution, without analysis.

- Tables **24-46** contain secondary data, including diameter measurements and observations concerning the location and nature of the fractures.

- Tables **47-69** concern the radiographic results, specifically whether the weld passed the inspection and, if not, the reason for the rejection.

Graphs

Graphs **1-185** are essentially the raw data presented in graphical form, grouped by Data Set. There are two main types of graph:

- Pressure vs Cycles to Failure (showing all relevant data)

- Pressure vs Life as a Percentage of Plain Pipe Life (showing median data only)

The latter permits rough comparisons between Data Sets. Given the statistically small number of data points for any one test condition, median values are preferred to minimize the effect of outliers, and improve the readability of the graphs.

Graphs **186-226** are of all Data Sets, grouped by weld type.

Graphs **227-239** show comparisons between Data Sets, in particular control samples and field specimens.

Graphs **240-258** present data for all weld types plotted against CTES' Achilles fatigue model predictions for plain pipe. The model predictions are shown for fracture, crack initiation (the point at which the crack is first supposed to form, and hence is regarded in some quarters as being compromised), and 80% of crack initiation (a typical working limit). Any observed data falling below the 80% crack initiation line thus represents a potential failure in the field if the weld is unaccounted for.

Graphs **259-264** show hardness data for selected specimens.

Graphs **265-319** show diametral growth at fracture for all samples.

Data Sets

Data Sets **A-H** are samples provided by the CT manufacturers or welded by ATS for CTES.

A 1.75" CT in six wall sizes: 0.109", 0.125", 0.134", 0.156", 0.175" and 0.188". 1.75" Tapered CT in five wall size combinations: 0.109"/0.125", 0.125"0.134", 0.134"/0.156", 0.156"/0.175", 0.175"/0.188".

B 1.75" CT in five wall sizes: 0.109", 0.125", 0.134", 0.156" and 0.175".

C 1.25" CT in three wall sizes: 0.087", 0.109", and 0.156".

D 1.75" tapered CT in four wall size combinations: 0.109"/0.116", 0.109"/0.125", 0.116"/0.125" and 0.125"/0.134".

E 1.25" CT in 0.087" wall size with two material strengths obtained by quench and tempering.

F 2.00" CT in 0.190" wall size.

G 1.75" CT in five wall sizes: 0.109", 0.125", 0.134", 0.156" and 0.175".

H 2.375" CT in 0.190" wall size.

Field Data Sets **1-6** are samples provided by field locations using local welders.

1 2.00" CT in 0.190" wall size.

2 2.875" CT in 0.190" wall size

3 1.75" CT in 0.109" wall size and 3.50" CT in 0.190" wall size.

4 2.375" CT in 0.190" wall size

5 1.75" CT in three wall sizes: 0.109", 0.125" and 0.134". Welds were made in previously used coiled tubing with calculated percentage of life used known.

6 2.00" CT in 0.134" wall size.

Data Set "A" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N ftm	Comments
A-1	80	1.75	0.109	none	72	1500	705	
A-2	80	1.75	0.109	none	72	3000	284	
A-3	80	1.75	0.109	none	72	3000	270	
A-4	80	1.75	0.109	none	72	3000	311	
A-5	80	1.75	0.109	none	72	5000	85	
A-6	80	1.75	0.109	bias	72	1500	391	
A-7	80	1.75	0.109	bias	72	2500	320	
A-8	80	1.75	0.109	bias	72	3000	268	
A-9	80	1.75	0.109	bias	72	3000	185	
A-10	80	1.75	0.109	bias	72	3000	317	
A-11	80	1.75	0.109	bias	72	3000	277	
A-12	80	1.75	0.109	bias	72	3000	210	
A-13	80	1.75	0.109	bias	72	3000	280	
A-14	80	1.75	0.109	bias	72	5000	89	
A-15	80	1.75	0.109	bias	72	5000	105	
A-16	80	1.75	0.109	manual	72	1500	222	
A-17	80	1.75	0.109	manual	72	1500	194	
A-18	80	1.75	0.109	manual	72	3000	96	
A-19	80	1.75	0.109	manual	72	3000	78	
A-20	80	1.75	0.109	manual	72	3000	128	
A-21	80	1.75	0.109	manual	72	3000	120	
A-22	80	1.75	0.109	manual	72	3000	126	
A-23	80	1.75	0.109	manual	72	3000	120	
A-24	80	1.75	0.109	manual	72	5000	180	
A-25	80	1.75	0.109	manual	72	5000	35	
A-26	80	1.75	0.109	orbital	72	250	306	
A-27	80	1.75	0.109	orbital	72	1500	167	
A-28	80	1.75	0.109	orbital	72	3000	104	
A-29	80	1.75	0.109	orbital	72	3000	105	
A-30	80	1.75	0.109	orbital	72	3000	123	
A-31	80	1.75	0.109	orbital	72	5000	61	

Table 1

Data Set "A" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N (m	Comments
A-32	80	1.75	0.125	none	72	1500	552	
A-33	80	1.75	0.125	none	72	3000	348	
A-34	80	1.75	0.125	none	72	3000	350	
A-35	80	1.75	0.125	none	72	3000	340	
A-36	80	1.75	0.125	none	72	5000	163	
A-37	80	1.75	0.125	bias	72	3000	331	
A-38	80	1.75	0.125	bias	72	3000	262	
A-39	80	1.75	0.125	bias	72	3000	298	
A-40	80	1.75	0.125	manual	72	3000	150	
A-41	80	1.75	0.125	manual	72	3000	79	
A-42	80	1.75	0.125	manual	72	3000	210	
A-43	80	1.75	0.125	manual	72	3000	201	
A-44	80	1.75	0.125	orbital	72	1500	308	
A-45	80	1.75	0.125	orbital	72	3000	129	
A-46	80	1.75	0.125	orbital	72	3000	124	
A-47	80	1.75	0.125	orbital	72	3000	145	

Table 2

Data Set "A" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N fm	Comments
A-48	80	1.75	0.134	none	72	1500	667	
A-49	80	1.75	0.134	none	72	3000	523	
A-50	80	1.75	0.134	none	72	3000	399	
A-51	80	1.75	0.134	none	72	3000	567	
A-52	80	1.75	0.134	none	72	5000	299	
A-53	80	1.75	0.134	bias	72	1500	488	
A-54	80	1.75	0 134	bias	72	3000	327	
A-55	80	1.75	0.134	bias	72	3000	372	
A-56	80	1.75	0.134	bias	72	3000	382	
A-57	80	1.75	0.134	bias	72	5000	184	
A-58	80	1.75	0.134	manual	72	1500	147	
A-59	80	1.75	0.134	manual	72	1500	432	
A-60	80	1.75	0.134	manual	72	3000	190	
A-61	80	1.75	0.134	manual	72	3000	270	
A-62	80	1.75	0.134	manual	72	3000	275	
A-63	80	1.75	0 134	manual	72	3000	255	
A-64	80	1.75	0 134	manual	72	5000	204	
A-65	80	1.75	0.134	orbital	72	1500	332	
A-66	80	1.75	0.134	orbital	72	3000	136	
A-67	80	1.75	0.134	orbital	72	3000	217	
A-68	80	1.75	0.134	orbital	72	3000	179	
A-69	80	1.75	0.134	orbital	72	5000	147	

Table 3

Data Set "A" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N fim	Comments
A-70	80	1.75	0.156	none	72	1500	788	
A-71	80	1.75	0.156	none	72	3000	639	
A-72	80	1.75	0.156	none	72	3000	606	
A-73	80	1.75	0.156	none	72	3000	513	
A-74	80	1.75	0.156	none	72	5000	420	
A-75	80	1.75	0.156	bias	72	1500	661	
A-76	80	1.75	0.156	bias	72	3000	532	
A-77	80	1.75	0.156	bias	72	3000	450	
A-78	80	1.75	0.156	bias	72	3000	435	
A-79	80	1.75	0.156	bias	72	5000	316	
A-80	80	1.75	0.156	manual	72	1500	101	
A-81	80	1.75	0.156	manual	72	3000	304	
A-82	80	1.75	0.156	manual	72	3000	169	
A-83	80	1.75	0.156	manual	72	3000	324	
A-84	80	1.75	0.156	manual	72	5000	227	
A-85	80	1.75	0.156	orbital	72	1500	452	
A-86	80	1.75	0.156	orbital	72	3000	338	
A-87	80	1.75	0.156	orbital	72	3000	391	
A-88	80	1.75	0.156	orbital	72	3000	203	
A-89	80	1.75	0.156	orbital	72	5000	208	

Table 4

Data Set "A" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N ftm	Comments
A-90	80	1.75	0.175	none	72	1500	767	
A-91	80	1.75	0.175	none	72	3000	737	
A-92	80	1.75	0.175	none	72	3000	1223	
A-93	80	1.75	0.175	none	72	3000	903	
A-94	80	1.75	0.175	none	72	3000	874	
A-95	80	1.75	0.175	none	72	5000	617	
A-96	80	1.75	0.175	bias	72	3000	580	
A-97	80	1.75	0.175	bias	72	3000	547	
A-98	80	1.75	0.175	bias	72	3000	746	
A-99	80	1.75	0.175	manual	72	3000	118	
A-100	80	1.75	0.175	manual	72	3000	226	
A-101	80	1.75	0.175	manual	72	3000	293	
A-102	80	1.75	0.175	manual	72	3000	300	
A-103	80	1.75	0.175	manual	72	3000	125	
A-104	80	1.75	0.175	orbital	72	3000	353	
A-105	80	1.75	0.175	orbital	72	3000	500	
A-106	80	1.75	0.175	orbital	72	3000	366	

Table 5

Data Set "A" Fatigue Test Data

Identit.	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N (tm	Comments
A-107	80	1.75	0.188	none	72	1500	845	
A-108	80	1.75	0.188	none	72	3000	884	
A-109	80	1.75	0.188	none	72	3000	947	
A-110	80	1.75	0.188	none	72	3000	903	
A-111	80	1.75	0.188	none	72	5000	703	

Table 6

Data Set "A" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N f/m	Comments
A-112	80	1 75	0.125	bias	72	3000	150*	Stopped at 50%
A-113	80	1.75	0.125	bias	72	3000	225*	Stopped at 75%
A-114	80	1.75	0.125	manual	72	3000	100*	Stopped at 50%
A-115	80	1.75	0.125	manual	72	3000	150*	Stopped at 75%
A-116	80	1.75	0.125	orbital	72	3000	65*	Stopped at 50%
A-117	80	1.75	0.125	orbital	72	3000	97*	Stopped at 75%
A-118	80	1.75	0.156-0.175	bias taper	72	1500	127*	Stopped at 50%
A-119	80	1.75	0.156-0.175	bias taper	72	5000	190*	Stopped at 75%
A-120	80	1.75	0.175	bias	72	3000	290*	Stopped at 50%
A-121	80	1.75	0.175	bias	72	3000	435*	Stopped at 75%
A-122	80	1.75	0.175	orbital	72	3000	183*	Stopped at 50%
A-123	80	1.75	0.175	orbital	72	3000	275*	Stopped at 75%

These tests were stopped at the specified number of cycles to allow laboratory analysis of crack development and propagation.

Table 7

Data Set "A" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N (m	Comments
A-124	80	1.75	0.109-0.125	bias taper	72	1500	317	
A-125	80	1.75	0.109-0.125	bias taper	72	3000	139	
A-126	80	1.75	0.109-0.125	bias taper	72	3000	123	
A-127	80	1.75	0.109-0.125	bias taper	72	3000	114	
A-128	80	1.75	0.109-0.125	bias taper	72	5000	80	
A-129	80	1.75	0.109-0.125	manual	72	1500	59	
A-130	80	1.75	0.109-0.125	manual	72	3000	59	
A-131	80	1.75	0.109-0.125	manual	72	3000	58	
A-132	80	1.75	0.109-0.125	manual	72	3000	64	
A-133	80	1.75	0.109-0.125	manual	72	5000	9	
A-134	80	1.75	0.109-0.125	orbital	72	1500	156	
A-135	80	1.75	0.109-0.125	orbital	72	3000	69	
A-136	80	1.75	0.109-0.125	orbital	72	3000	77	
A-137	80	1.75	0.109-0.125	orbital	72	3000	64	
A-138	80	1.75	0.109-0.125	orbital	72	5000	23	
A-139	80	1.75	0.125-0.134	bias taper	72	1500	260	
A-140	80	1.75	0.125-0.134	bias taper	72	3000	160	
A-141	80	1.75	0.125-0.134	bias taper	72	3000	349	
A-142	80	1.75	0.125-0.134	bias taper	72	3000	234	
A-143	80	1.75	0.125-0.134	bias taper	72	5000	99	
A-144	80	1.75	0.134-0.156	bias taper	72	1500	208	
A-145	80	1.75	0.134-0.156	bias taper	72	3000	172	
A-146	80	1.75	0.134-0.156	bias taper	72	3000	242	
A-147	80	1.75	0.134-0.156	bias taper	72	3000	229	
A-148	80	1.75	0.134-0.156	bias taper	72	5000	102	

Table 8

Data Set "A" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N f(m	Comments
A-149	80	1.75	0.156-0.175	bias taper	72	3000	253	
A-150	80	1.75	0.156-0.175	bias taper	72	3000	274	
A-151	80	1.75	0.156-0.175	bias taper	72	3000	230	
A-152	80	1.75	0.156-0.175	manual	72	1500	139	
A-153	80	1.75	0.156-0.175	manual	72	3000	149	
A-154	80	1.75	0.156-0.175	manual	72	3000	127	
A-155	80	1.75	0.156-0.175	manual	72	3000	155	
A-156	80	1.75	0.156-0.175	manual	72	5000	82	
A-157	80	1.75	0.156-0.175	orbital	72	1500	109	
A-158	80	1.75	0.156-0.175	orbital	72	3000	149	
A-159	80	1.75	0.156-0.175	orbital	72	3000	109	
A-160	80	1.75	0.156-0.175	orbital	72	3000	144	
A-161	80	1.75	0.156-0.175	orbital	72	5000	85	
A-162	80	1.75	0.175-0.188	bias taper	72	1500	321	
A-163	80	1.75	0.175-0.188	bias taper	72	3000	565	
A-164	80	1.75	0.175-0.188	bias taper	72	3000	744	
A-165	80	1.75	0.175-0.188	bias taper	72	3000	724	
A-166	80	1.75	0.175-0.188	bias taper	72	5000	359	

Table 9

Data Set "B" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N ftm	Comments
B-1	80	1.75	0.109	bias	72	3000	239	
B-2	80	1.75	0.109	bias	72	3000	243	
B-3	80	1.75	0.109	bias	72	3000	261	
B-4	80	1.75	0.109	bias	72	3000	281	
B-5	80	1.75	0.109	bias	72	3000	309	
B-6	80	1.75	0.125	none	72	3000	405	
B-7	80	1.75	0.125	none	72	3000	441	
B-8	80	1.75	0.125	none	72	3000	498	
B-9	80	1.75	0.125	bias	72	3000	333	
B-10	80	1.75	0.125	bias	72	3000	381	
B-11	80	1.75	0.125	bias	72	3000	397	
B-12	80	1.75	0.125	bias	72	3000	403	
B-13	80	1.75	0.134	bias	72	3000	316	
B-14	80	1.75	0.134	bias	72	3000	317	
B-15	80	1.75	0.134	bias	72	3000	404	
B-16	80	1.75	0.134	bias	72	3000	522	
B-17	80	1.75	0.156	bias	72	3000	482	
B-18	80	1.75	0.156	bias	72	3000	602	
B-19	80	1.75	0.156	bias	72	3000	662	
B-20	80	1.75	0.156	bias	72	3000	671	
B-21	80	1.75	0.175	none	72	3000	586	
B-22	80	1.75	0.175	none	72	3000	611	
B-23	80	1.75	0.175	none	72	3000	693	
B-24	80	1.75	0.175	bias	72	3000	450	
B-25	80	1.75	0.175	bias	72	3000	627	
B-26	80	1.75	0.175	bias	72	3000	670	
B-27	80	1.75	0.175	bias	72	3000	808	

These samples were from a different source material to Data Set "A".

Table 10

Data Set "C" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N ftm	Comments
C-1	80	1 25	0.087	none	48	250	423	
C-2	80	1.25	0.087	none	48	2500	242	
C-3	80	1.25	0.087	none	48	2500	324	
C-4	80	1.25	0 087	none	48	2500	474	
C-5	80	1 25	0 087	none	48	5000	76	
C-6	80	1.25	0.087	manual	48	2500	67	
C-7	80	1.25	0.087	manual	48	2500	92	
C-8	80	1.25	0.087	manual	48	2500	119	
C-9	80	1.25	0.087	manual	48	2500	146	
C-10	80	1.25	0.087	manual	48	2500	147	
C-11	80	1.25	0.087	manual	48	2500	173	
C-12	80	1.25	0.087	manual	48	2500	203	
C-13	80	1.25	0.087	manual	48	2500	275	
C-14	80	1.25	0.087	manual	48	2500	285	
C-15	80	1.25	0.087	manual	48	2500	395	
C-16	80	1.25	0.087	orbital	48	2500	42	
C-17	80	1.25	0.087	orbital	48	2500	148	
C-18	80	1.25	0.109	orbital	48	2500	0	leaked
C-19	80	1.25	0.109	orbital	48	2500	107	
C-20	80	1.25	0.156	bias	48	3000	945	
C-21	80	1.25	0.156	bias	48	3000	949	
C-22	80	1.25	0.156	bias	48	3000	1046	

Table 11

Data Set "D" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N ftm	Comments
D-1	70	1.75	0.109-0.116	bias taper	72	1500	562	
D-2	70	1.75	0.109-0.116	bias taper	72	3000	245	
D-3	70	1.75	0.109-0.116	bias taper	72	3000	306	
D-4	70	1.75	0.109-0.116	bias taper	72	3000	360	
D-5	70	1.75	0.109-0.116	bias taper	72	5000	120	
D-6	70	1.75	0.109-0.125	bias taper	72	1500	474	
D-7	70	1.75	0.109-0.125	bias taper	72	3000	256	
D-8	70	1.75	0.109-0.125	bias taper	72	3000	280	
D-9	70	1.75	0.109-0.125	bias taper	72	3000	288	
D-10	70	1.75	0.109-0.125	bias taper	72	3000	299	
D-11	70	1.75	0.109-0.125	bias taper	72	5000	78	
D-12	70	1.75	0.116-0.125	bias taper	72	1500	580	
D-13	70	1.75	0.116-0.125	bias taper	72	3000	315	
D-14	70	1.75	0.116-0.125	bias taper	72	3000	316	
D-15	70	1.75	0.116-0.125	bias taper	72	3000	377	
D-16	70	1.75	0.116-0.125	bias taper	72	5000	115	
D-17	70	1.75	0.125-0.134	bias taper	72	1500	501	
D-18	70	1.75	0.125-0.134	bias taper	72	3000	278	
D-19	70	1.75	0.125-0.134	bias taper	72	3000	322	
D-20	70	1.75	0.125-0.134	bias taper	72	3000	346	
D-21	70	1.75	0.125-0.134	bias taper	72	5000	106	

Table 12

Data Set "E" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N fm	Comments
E-1	80 Q & T	1.25	0.087	none	48	1500	317	
E-2	80 Q & T	1.25	0.087	none	48	3000	355	
E-3	80 Q & T	1.25	0.087	none	48	3000	392	
E-4	80 Q & T	1.25	0.087	none	48	3000	427	
E-5	80 Q & T	1.25	0.087	none	48	5000	171	
E-6	80 Q & T	1.25	0.087	bias	48	1500	127	
E-7	80 Q & T	1.25	0.087	bias	48	3000	106	
E-8	80 Q & T	1.25	0.087	bias	48	3000	127	
E-9	80 Q & T	1.25	0.087	bias	48	5000	4	
E-10	80 Q & T	1.25	0.087	bias	48	3000	197	
E-11	80 Q & T	1.25	0.087	manual	48	1500	100	
E-12	80 Q & T	1.25	0.087	manual	48	3000	5	
E-13	80 Q & T	1.25	0.087	manual	48	3000	72	
E-14	80 Q & T	1.25	0.087	manual	48	3000	73	
E-15	80 Q & T	1.25	0.087	manual	48	5000	52	
E-16	100 Q & T	1.25	0.087	none	48	1500	306	
E-17	100 Q & T	1.25	0.087	none	48	3000	220	
E-18	100 Q & T	1.25	0.087	none	48	3000	232	
E-19	100 Q & T	1.25	0.087	none	48	3000	270	
E-20	100 Q & T	1.25	0.087	none	48	5000	275	
E-21	100 Q & T	1.25	0.087	bias	48	1500	43	
E-22	100 Q & T	1.25	0.087	bias	48	3000	177	
E-23	100 Q & T	1.25	0.087	bias	48	3000	232	
E-24	100 Q & T	1.25	0.087	bias	48	3000	273	
E-25	100 Q & T	1.25	0.087	bias	48	5000	161	
E-26	100 Q & T	1.25	0.087	manual	48	3000	14	
E-27	100 Q & T	1.25	0.087	manual	48	3000	80	
E-28	100 Q & T	1.25	0.087	manual	48	3000	86	
E-29	100 Q & T	1.25	0.087	manual	48	5000	85	

Q & T indicated quenched and tempered heat treatment.
Material listed as 80 ksi measured 103,000 actual yield and material listed as 100 ksi measured 108,000 actual

Table 13

Data Set "F" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N fm	Comments
F-1	80	2.00	0.190	none	72	1500	404	
F-2	80	2.00	0.190	none	72	1500	527	
F-3	80	2.00	0.190	none	72	3000	453	
F-4	80	2.00	0.190	none	72	3000	596	
F-5	80	2.00	0.190	none	72	5000	140	
F-6	80	2.00	0.190	none	72	5000	144	
F-7	80	2.00	0.190	manual	72	3000	205	
F-8	80	2.00	0.190	manual	72	5000	82	

This pipe was supplied distorted by a slaightener

Table 14

Data Set "G" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N ftm	Comments
G-1	80	1.75	0.109	none	48	2500	152	
G-2	80	1.75	0.109	none	48	2500	160	
G-3	80	1.75	0.109	none	48	2500	175	
G-4	80	1.75	0.109	none	48	2500	175	
G-5	80	1.75	0.109	none	48	2500	180	
G-6	80	1.75	0.125	none	48	2500	207	
G-7	80	1.75	0.125	none	48	2500	218	
G-8	80	1.75	0.125	none	48	2500	219	
G-9	80	1.75	0.125	none	48	2500	221	
G-10	80	1.75	0.125	none	48	2500	231	
G-11	80	1.75	0.134	none	48	2500	194	
G-12	80	1.75	0.134	none	48	2500	238	
G-13	80	1.75	0.134	none	48	2500	287	
G-14	80	1.75	0.134	none	48	2500	332	
G-15	80	1.75	0.156	none	48	250	335	
G-16	80	1.75	0.156	none	48	250	341	
G-17	80	1.75	0.156	none	48	2500	279	
G-18	80	1.75	0.156	none	48	2500	302	
G-19	80	1.75	0.156	none	48	2500	308	
G-20	80	1.75	0.156	none	48	2500	315	
G-21	80	1.75	0.156	none	48	2500	349	
G-22	80	1.75	0.156	none	48	2500	367	
G-23	80	1.75	0.156	none	48	5000	146	
G-24	80	1.75	0.175	none	48	2500	283	
G-25	80	1.75	0.175	none	48	2500	300	
G-26	80	1.75	0.175	none	48	2500	302	
G-27	80	1.75	0.175	none	48	2500	347	
G-28	80	1.75	0.175	none	48	2500	430	

After these early tests, a decision to change the bending radius for this size CT was made. Hence there is no comparable weld data for this configuration in the study. This plain pipe data may be of value for fatigue modeling purposes.

Table 15

Data Set "H" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N ftm	Comments
H-1	80	2.375	0.190	none	72	1500	688	
H-2	80	2.375	0.190	none	72	1500	433	
H-3	80	2.375	0.190	none	72	1500	693	
H-4	80	2.375	0.190	none	72	3000	260	
H-5	80	2.375	0.190	manual	72	1500	222	
H-6	80	2.375	0.190	manual	72	1500	262	
H-7	80	2.375	0.190	manual	72	1500	328	
H-8	80	2.375	0.190	manual	72	3000	171	
H-9	80	2.375	0.190	orbital	72	1500	235	
H-10	80	2.375	0.190	orbital	72	1500	248	
H-11	80	2.375	0.190	orbital	72	1500	249	
H-12	80	2.375	0.190	orbital	72	3000	138	

Table 16

Field Data Set "1" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N f(m
FS1-1	80	2.00	0.134	none	72	3000	180
FS1-2	80	2.00	0.134	none	72	3000	194
FS1-3	80	2.00	0.134	none	72	3000	199
FS1-4	80	2.00	0.134	none	72	3000	235
FS1-5	80	2.00	0.134	manual	72	3000	132
FS1-6	80	2.00	0.134	manual	72	3000	114
FS1-7	80	2.00	0.134	manual	72	3000	151
FS1-8	80	2.00	0.134	manual	72	3000	153
FS1-9	80	2.00	0.134	manual	72	3000	101

Table 17

Field Data Set "2" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N fim	Comments
FS2-1	80	2.875	0.190	none	72	1500	235	
FS2-2	80	2.875	0.190	none	72	1500	236	
FS2-3	80	2.875	0.190	none	72	1500	256	
FS2-4	80	2.875	0.190	none	72	1500	298	
FS2-5	80	2.875	0.190	none	72	1500	352	
FS2-6	80	2.875	0.190	none	72	1500	355	
FS2-7	80	2.875	0.190	none	72	3000	97	
FS2-8	80	2.875	0.190	none	72	3000	121	
FS2-9	80	2.875	0.190	manual	72	250	52	
FS2-10	80	2.875	0.190	manual	72	1500	42	
FS2-11	80	2.875	0.190	manual	72	1500	55	
FS2-12	80	2.875	0.190	manual	72	1500	73	
FS2-13	80	2.875	0.190	manual	72	1500	74	
FS2-14	80	2.875	0.190	manual	72	1500	104	
FS2-15	80	2.875	0.190	manual	72	1500	144	
FS2-16	80	2.875	0.190	manual	72	3000	49	

Table 18

Field Data Set "3" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N ftm	Comments
FS3-1	80	1.75	0 109	none	72	1500	859	
FS3-2	80	1.75	0.109	none	72	3000	322	
FS3-3	80	1.75	0.109	none	72	3000	326	
FS3-4	80	1.75	0.109	none	72	3000	346	
FS3-5	80	1.75	0 109	none	72	5000	94	
FS3-6	80	1.75	0 109	manual	72	1500	177	
FS3-7	80	1.75	0.109	manual	72	3000	92	
FS3-8	80	1.75	0.109	manual	72	3000	154	
FS3-9	80	1.75	0.109	manual	72	3000	162	
FS3-10	80	1.75	0 109	manual	72	5000	56	

Table 19

Field Data Set "3" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N ftm	Comments
FS3-11	80	3.50	0 190	none	72	250	182	
FS3-12	80	3.50	0 190	none	72	3000	45	
FS3-13	80	3 50	0.190	manual	72	250	123	
FS3-14	80	3.50	0.190	manual	72	1500	51	
FS3-15	80	3 50	0.190	manual	72	1500	55	
FS3-16	80	3.50	0 190	manual	72	1500	68	
FS3-17	80	3.50	0 190	manual	72	3000	21	

We wish to extend our appreciation to Schlumberger - Dowell for the 3.5" plain pipe data.

Table 20

Field Data Set "4" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N ftm	Comments
FS4-1	80	2.375	0.190	manual	72	250	113	
FS4-2	80	2.375	0.190	manual	72	1500	139	
FS4-3	80	2.375	0.190	manual	72	1500	148	
FS4-4	80	2.375	0.190	manual	72	1500	148	
FS4-5	80	2.375	0.190	manual	72	3000	95	

Table 21

Field Data Set "5" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N fm	Comments
FS5-1	80	1.75	0.109	none	72	3000	117	7% life used
FS5-2	80	1.75	0 109	none	72	3000	134	7% life used
FS5-3	80	1.75	0.109	none	72	3000	278	26% life used
FS5-4	80	1.75	0.109	manual	72	3000	4	7% life used
FS5-5	80	1.75	0 109	manual	72	3000	51	7% life used
FS5-6	80	1.75	0.109	manual	72	3000	106	7% life used
FS5-7	80	1.75	0.109	manual	72	3000	190	26% life used
FS5-8	80	1.75	0.109	manual	72	3000	231	26% life used
FS5-9	80	1.75	0.109	orbital	72	3000	252	0% life used
FS5-10	80	1.75	0.109	orbital	72	3000	199	7% life used
FS5-11	80	1.75	0.109	orbital	72	3000	32	26% life used
FS5-12	80	1.75	0.109	orbital	72	3000	229	26% life used
FS5-13	80	1.75	0.109	orbital	72	3000	233	26% life used
FS5-14	80	1.75	0.125	none	72	3000	285	0% life used
FS5-15	80	1.75	0.125	none	72	3000	456	6% life used
FS5-16	80	1.75	0 125	none	72	3000	480	6% life used
FS5-17	80	1.75	0.125	none	72	3000	347	12% life used
FS5-18	80	1.75	0.125	none	72	3000	366	
FS5-19	80	1.75	0.125	manual	72	3000	93	0% life used
FS5-20	80	1.75	0.125	manual	72	3000	265	6% life used
FS5-21	80	1.75	0.125	manual	72	3000	305	6% life used
FS5-22	80	1.75	0.125	manual	72	3000	162	
FS5-23	80	1.75	0.125	orbital	72	3000	292	0% life used
FS5-24	80	1.75	0 125	orbital	72	3000	281	0% life used
FS5-25	80	1.75	0 125	orbital	72	3000	306	12% life used
FS5-26	80	1.75	0 125	orbital	72	3000	392	12% life used
FS5-27	80	1.75	0 134	none	72	3000	453	14% life used
FS5-28	80	1.75	0 134	manual	72	3000	245	12% life used
FS5-29	80	1.75	0 134	manual	72	3000	359	14% life used
FS5-30	80	1.75	0.134	orbital	72	3000	289	12% life used
FS5-31	80	1.75	0 134	orbital	72	3000	346	14% life used

Table 22

Field Data Set "6" Fatigue Test Data

Identity	Grade (KSI)	Diameter	Wall (nom)	Weld type	Radius	Pressure	N (fm	Comments
FS6-1	80	2.00	0 134	none	72	3000	218	28% life used
FS6-2	80	2.00	0.134	orbital	72	3000	201	8% life used
FS6-3	80	2.00	0.134	orbital	72	3000	212	8% life used
FS6-4	80	2.00	0.134	orbital	72	3000	228	8% life used
FS6-5	80	2.00	0.134	orbital	72	3000	110	28% life used.
FS6-6	80	2.00	0.134	orbital	72	3000	189	28% life used

Table 23

Data Set "A" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
A-1	1.75	0.109	none	0.114	1.859	1.791	---	In Seam	3/32	Straight
A-2	1.75	0.109	none	0.115	2.033	1.976	---	In Seam	1/4	Straight
A-3	1.75	0.109	none	0.114	2.039	2.005	---	In Seam	5/16	Horse shoe
A-4	1.75	0.109	none	0.115	2.079	2.012	---	In Seam	1/8	Straight
A-5	1.75	0.109	none	0.113	2.105	1.994	---		1 1/4	Straight
A-6	1.75	0.109	bias	0.112	1.783	1.766	Toe of Bias	In Seam	1/8	Straight
A-7	1.75	0.109	bias	0.109	1.83	1.798	Toe of Bias	In Seam	1/8	Straight
A-8	1.75	0.109	bias	0.111	1.874	1.842	Toe of Bias	In Seam	1/8	Straight
A-9	1.75	0.109	bias	0.112	1.829	1.811	Toe of Bias	In Seam	1/16	Straight
A-10	1.75	0.109	bias	0.113	1.879	1.848	Fusion Line of Bias Weld		1/8	Straight
A-11	1.75	0.109	bias	0.112	1.858	1.833	Toe of Bias	In Seam	1/8	Straight
A-12	1.75	0.109	bias	0.112	1.838	1.811	Toe of Bias	In Seam	1/8	Straight
A-13	1.75	0.109	bias	0.112	1.882	1.841	Toe of Bias	In Seam	3/16	Straight
A-14	1.75	0.109	bias	0.11	1.91	1.875	Toe & HAZ of Bias	In Seam	1/8	Straight
A-15	1.75	0.109	bias	0.11	1.925	1.896	Toe & HAZ of Bias	In Seam	3/16	Straight
A-16	1.75	0.109	manual	0.115	1.764	1.726	HAZ	Just Off Seam	3/16	Straight
A-17	1.75	0.109	manual	0.114	1.808	1.781	HAZ	In Seam	3/8	Straight
A-18	1.75	0.109	manual	0.114	1.81	1.763				
A-19	1.75	0.109	manual	0.115	1.784	1.744	HAZ		5/32	Horseshoe
A-20	1.75	0.109	manual	0.114	1.929	1.854	HAZ	In Seam	3/32	Straight
A-21	1.75	0.109	manual	0.113	1.941	1.868	HAZ	In Seam	5/32	Straight
A-22	1.75	0.109	manual	0.114	1.952	1.88				
A-23	1.75	0.109	manual	0.113	1.842	1.819	HAZ	In Seam	1/16	Straight
A-24	1.75	0.109	manual	0.114	1.879	1.822	HAZ		1/4	Straight
A-25	1.75	0.109	manual	0.113	1.885	1.858	HAZ	In Seam	5/8	Straight
A-26	1.75	0.109	orbital	0.111	1.763	1.76	HAZ	In Seam	7/32	Straight
A-27	1.75	0.109	orbital	0.114	1.811	1.781	HAZ		1/8	Straight
A-28	1.75	0.109	orbital	0.113	1.845	1.785	HAZ	In Seam	3/4	Jagged
A-29	1.75	0.109	orbital	0.115	1.837	1.772				
A-30	1.75	0.109	orbital	0.11	1.835	1.793	HAZ	In Seam	1/16	Slight Curve
A-31	1.75	0.109	orbital	0.112	1.97	1.884	HAZ	In Seam	5/16	Straight

Table 24

Data Set "A" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
A-32	1.75	0 125	none	0 128	1 805	1.764	---	In Seam	3/32	Straight
A-33	1.75	0.125	none	0 126	1.89	1.835				
A-34	1 75	0 125	none	0 126	1.906	1.826				
A-35	1 75	0 125	none	0 126	1.882	1.812	---	In Seam	1/8	Straight
A-36	1 75	0 125	none	0 125	2 094	2.056	---	In Seam	1/4	Straight
A-37	1.75	0 125	bias	0.128	1.882	1.829	ween Bias Weld Contact	In Seam	1/8	Straight
A-38	1.75	0.125	bias	0.127	1.863	1.826				
A-39	1.75	0 125	bias	0.128	1 9	1.844				
A-40	1.75	0.125	manual	0 129	1.812	1.806				
A-41	1 75	0.125	manual	0 126	1 795	1.793				
A-42	1.75	0.125	manual	0 125	1.88	1.838	In Weld	In Seam	5/32	Straight
A-43	1.75	0 125	manual	0 125	1.828	1.772	4" from Weld		5/16	Jagged
A-44	1.75	0 125	orbital	0.127	1.8	1.785	Fusion Line		1/16	Discontinuous
A-45	1 75	0 125	orbital	0 126	1.857	1.796	HAZ		3/16	Straight
A-46	1.75	0.125	orbital	0.125	1.848	1.789	HAZ	In Seam	3/32	Straight
A-47	1 75	0 125	orbital	0 131	1.853	1.827	HAZ	In Seam	3/8	Straight

Table 25

Data Set "A" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
A-48	1.75	0.134	none	0.139	1.782	1.755	---	In Seam	5/32	Straight
A-49	1.75	0.134	none	0.141	1.844	1.842	---		3/16	Straight
A-50	1.75	0.134	none	0.14	1.817	1.783	---	In Seam	1/16	Straight
A-51	1.75	0.134	none	0.14	1.852	1.784	---	In Seam	5/32	Curved
A-52	1.75	0.134	none	0.14	1.96	1.882	---	In Seam	3/16	Straight
A-53	1.75	0.134	bias	0.138	1.783	1.76	Toe of Bias	In Seam	1/16	Straight
A-54	1.75	0.134	bias	0.14	1.799	1.779	Toe of Bias	In Seam	1/8	Straight
A-55	1.75	0.134	bias	0.14	1.818	1.795	Toe of Bias	In Seam	1/8	Straight
A-56	1.75	0.134	bias	0.14	1.833	1.796	Toe of Bias	In Seam	1/16	Straight
A-57	1.75	0.134	bias	0.139	1.881	1.843	Fusion Line of Bias Weld	Just Off Seam	1/8	Straight
A-58	1.75	0.134	manual	0.139	1.762	1.747				
A-59	1.75	0.134	manual	0.139	1.791	1.776	---	In Seam	1/8	Straight
A-60	1.75	0.134	manual	0.141	1.821	1.796				
A-61	1.75	0.134	manual	0.14	1.825	1.792				
A-62	1.75	0.134	manual	0.14	1.808	1.787	HAZ	In Seam	1/4	Straight
A-63	1.75	0.134	manual	0.139	1.811	1.8	---	In Seam	1/16	Straight
A-64	1.75	0.134	manual	0.141	1.912	1.835	Weld Center		5/16	Straight
A-65	1.75	0.134	orbital	0.14	1.772	1.769	HAZ	In Seam	3/32	Straight
A-66	1.75	0.134	orbital	0.141	1.82	1.787	HAZ		3/16	Straight
A-67	1.75	0.134	orbital	0.14	1.809	1.805	HAZ	In Seam	1/4	Straight
A-68	1.75	0.134	orbital	0.14	1.786	1.785	Fusion Line	In Seam	7/8	Straight
A-69	1.75	0.134	orbital	0.141	1.905	1.888	HAZ	In Seam	1/4	Straight

Data Set "A" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
A-70	1.75	0.156	none	0.16	1.779	1.752	---	In Seam	1/8	Straight
A-71	1.75	0.156	none	0.161	1.836	1.787	---	In Seam	1/16	Straight
A-72	1.75	0.156	none	0.162	1.833	1.782	---	In Seam	3/16	Straight
A-73	1.75	0.156	none	0.164	1.824	1.78	---	In Seam	1/8	Straight
A-74	1.75	0.156	none	0.16	2.051	1.927	---	In Seam	5/32	Curve
A-75	1.75	0.156	bias	0.16	1.785	1.756	Toe of Bias	In Seam	1/8	Straight
A-76	1.75	0.156	bias	0.162	1.826	1.78	Toe of Weld	In Seam	1/8	Straight
A-77	1.75	0.156	bias	0.16	1.823	1.79	Toe of Weld	In Seam	1/8	Straight
A-78	1.75	0.156	bias	0.161	1.826	1.794	Toe of Weld	In Seam	1/16	Straight
A-79	1.75	0.156	bias	0.16	1.94	1.884	Toe of Bias	In Seam	1/8	Straight
A-80	1.75	0.156	manual	0.161	1.753	1.756	Fusion Line	In Seam	1/2	Straight
A-81	1.75	0.156	manual	0.161	1.797	1.744	HAZ		1/2	Straight
A-82	1.75	0.156	manual	0.161	1.782	1.778				
A-83	1.75	0.156	manual	0.16	1.802	1.782				
A-84	1.75	0.156	manual	0.159	1.892	1.888	HAZ	In Seam	1/8	Straight
A-85	1.75	0.156	orbital	0.164	1.78	1.775	HAZ	In Seam	5/32	Straight
A-86	1.75	0.156	orbital	0.161	1.819	1.811	HAZ	In Seam	5/32	Straight
A-87	1.75	0.156	orbital	0.16	1.839	1.827	HAZ	In Seam	1/8	Straight
A-88	1.75	0.156	orbital	0.161	1.795	1.787	HAZ	In Seam	7/32	Straight
A-89	1.75	0.156	orbital	0.161	1.877	1.875	HAZ	In Seam	1/4	Straight

Data Set "A" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
A-90	1.75	0 175	none	0 181	1 765	1 754	---	In Seam	3/16	Straight
A-91	1 75	0 175	none	0 183	1 792	1.763				
A-92	1 75	0 175	none	0 183	1 81	1.765	---	In Seam	3/32	Straight
A-93	1 75	0.175	none	0.181	1 798	1 766				
A-94	1 75	0.175	none	0 182	1 819	1 76	—	In Seam	5/32	Straight
A-95	1 75	0.175	none	0 181	1 912	1 818	---	In Seam	1/8	Straight
A-96	1 75	0 175	bias	0 182	1.794	1.767	Between Bias Welds	In Seam	1/8	Straight
A-97	1 75	0 175	bias	0 18	1.78	1.757				
A-98	1 75	0 175	bias	0 182	1.795	1.762				
A-99	1 75	0 175	manual	0 179	1 764	1.754	Fusion Line	In Seam	5/8	Straight
A-100	1.75	0 175	manual	0 183	1 765	1 75	In Weld		1/4	Straight
A-101	1 75	0 175	manual	0 183	1 761	1 752				
A-102	1 75	0 175	manual	0 184	1.771	1.752				
A-103	1 75	0 175	manual	0 181	1.783	1.775	Fusion Line		3/4	Straight
A-104	1 75	0.175	orbital	0 181	1.78	1.776	HAZ		7/32	Straight
A-105	1 75	0.175	orbital	0 182	1 795	1.777	HAZ		5/16	Straight
A-106	1 75	0 175	orbital	0 182	1 789	1.771	HAZ		1/8	Straight

Table 28

Data Set "A" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
A-107	1 75	0 188	none	0 193	1 769	1.75	---	In Seam	1/16	Straight
A-108	1 75	0 188	none	0 194	1.804	1.762	---	In Seam	1/8	Straight
A-109	1 75	0 188	none	0 195	1.795	1.753	---	In Seam	1/8	Straight
A-110	1 75	0 188	none	0 196	1 796	1.756	---	In Seam	1/8	Straight
A-111	1.75	0 188	none	0 191	1 873	1 803	---	In Seam	5/32	Straight

Data Set "A" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
A-112	1.75	0.125	bias	0 129	1 812	1 785				
A-113	1 75	0 125	bias	0.128	1.853	1.806				
A-114	1 75	0.125	manual	0 125	1 814	1.806				
A-115	1 75	0 125	manual	0 139	1 79	1 789				
A-116	1 75	0 125	orbital	0 128						
A-117	1 75	0 125	orbital	0 126						
A-118	1 75	0.156-0.175	bias taper	0 162-0 182	1.767	1.757				
A-119	1.75	0 156-0 175	bias taper	0.161-0.182	1.855	1 804				
A-120	1 75	0 175	bias	0 182	1 774	1.75				
A-121	1.75	0.175	bias	0 183	1.781	1.759				
A-122	1 75	0 175	orbital	0 184	1.774	1.762				
A-123	1 75	0 175	orbital	0 183	1.771	1.762				

Table 30

Data Set "A" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
A-124	1.75	0.109-0.125	bias taper	0.111-0.130	1.794	1.76	Toe of Bias	In Seam	1/8	Straight
A-125	1.75	0.109-0.125	bias taper	0.111-0.129	1.859	1.836	Toe of Bias	In Seam	1/8	Straight
A-126	1.75	0.109-0.125	bias taper	0.115-0.129	1.848	1.827	Toe of Bias	In Seam	1/8	Straight
A-127	1.75	0.109-0.125	bias taper	0.115-0.129	1.85	1.839	Toe of Bias	In Seam	1/8	Straight
A-128	1.75	0.109-0.125	bias taper	0.112-0.130	1.934	1.884	Fusion Line of Bias Weld		1/8	Straight
A-129	1.75	0.109-0.125	manual	0.111-0.127	1.801	1.798	Fusion Line		1/4	Straight
A-130	1.75	0.109-0.125	manual	0.113-0.126	1.879	1.839	Fusion Line	In Seam	1/2	Straight
A-131	1.75	0.109-0.125	manual	0.113-0.127	1.936	1.874	Fusion Line	In Seam	3/4	Straight
A-132	1.75	0.109-0.125	manual	0.112-0.126	1.931	1.871	Fusion Line	In Seam	5/16	Straight
A-133	1.75	0.109-0.125	manual	0.112-0.127	1.812	1.808	Fusion Line	In Seam	3/4	Straight
A-134	1.75	0.109-0.125	orbital	0.113-0.125	1.847	1.835	HAZ		3/8	Jagged
A-135	1.75	0.109-0.125	orbital	0.113-0.125	1.91	1.88	HAZ		1/2	Straight
A-136	1.75	0.109-0.125	orbital	0.112-0.125	1.92	1.894	HAZ		3/8	Curve
A-137	1.75	0.109-0.125	orbital	0.113-0.127	1.912	1.876	HAZ		7/8	Jagged
A-138	1.75	0.109-0.125	orbital	0.112-0.127	1.897	1.873	HAZ	In Seam	1	Straight
A-139	1.75	0.125-0.134	bias taper	0.126-0.138	1.801	1.798	Toe of Bias	In Seam	1/16	Straight
A-140	1.75	0.125-0.134	bias taper	0.125-0.138	1.85	1.809	Toe of Bias	In Seam	1/16	Straight
A-141	1.75	0.125-0.134	bias taper	0.127-0.139	1.87	1.828	Toe of Bias	In Seam	1/8	Straight
A-142	1.75	0.125-0.134	bias taper	0.126-0.139	1.851	1.794	Toe of Bias	In Seam	3/32	Straight
A-143	1.75	0.125-0.134	bias taper	0.127-0.138	1.934	1.933	Toe of Bias	In Seam	3/8	Straight
A-144	1.75	0.134-0.156	bias taper	0.139-0.161	1.783	1.776	Toe of Bias	In Seam	1/8	Straight
A-145	1.75	0.134-0.156	bias taper	0.135-0.162	1.826	1.811	Toe of Bias	In Seam	1/8	Straight
A-146	1.75	0.134-0.156	bias taper	0.137-0.160	1.837	1.808	Toe of Bias	In Seam	1/4	Straight
A-147	1.75	0.134-0.156	bias taper	0.138-0.160	1.845	1.785	Toe of Bias	In Seam	3/32	Straight
A-148	1.75	0.134-0.156	bias taper	0.137-0.160	1.859	1.81	Toe of Bias	In Seam	1/8	Straight

Data Set "A" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
A-149	1 75	0.156-0 175	bias taper	0.162-0.82	1 831	1 794	Toe of Bias	In Seam	7/32	Straight
A-150	1 75	0.156-0 175	bias taper	0.160-0 181	1 825	1 806	Toe of Bias	In Seam	3/16	Straight
A-151	1 75	0 156-0.175	bias taper	0.161-0 182	1.818	1 806	Toe of Bias	In Seam	1/16 - 1/4	Straight
A-152	1 75	0 156-0 175	manual	0 160-0 183	1 79	1.786	HAZ		1/4	Straight
A-153	1 75	0 156-0.175	manual	0 161-0 182	1 842	1 831	Fusion Line	In Seam	3/4	Straight
A-154	1 75	0 156-0 175	manual	0 163-0 182	1 864	1 827	HAZ		3/32	Straight
A-155	1 75	0 156-0 175	manual	0 161-0 183	1 868	1 837	HAZ	In Seam	1/4	Straight
A-156	1 75	0 156-0 175	manual	0 160-0 183	1 889	1.873	HAZ	In Seam	3/32	Straight
A-157	1 75	0.156-0 175	orbital	0 163-0.184	1.8	1.782	HAZ	On Seam Edge	1/4	Straight
A-158	1 75	0.156-0 175	orbital	0 163-0 183	1 859	1 853	HAZ		3/16	Straight
A-159	1.75	0 156-0.175	orbital	0 162-0 183	1 861	1 834	HAZ	In Seam	5/32	Straight
A-160	1 75	0 156-0 175	orbital	0 163-0 185	1 857	1 823	HAZ		1/4	Straight
A-161	1 75	0 156-0 175	orbital	0 163-0 185	1 923	1 892	HAZ	In Seam	3/16	Straight
A-162	1 75	0 175-0 188	bias taper	0 184-0 199	1 775	1 762	Toe of Bias	In Seam	3/8	Straight
A-163	1 75	0 175-0 188	bias taper	0 181-0 195	1 802	1 777	Toe of Bias	In Seam	1/16	Straight
A-164	1.75	0 175-0.188	bias taper	0 183-0 193	1 811	1 78	Toe of Bias	In Seam	5/32	Straight
A-165	1 75	0 175-0 188	bias taper	0 183-0 195	1 811	1 777	Toe of Bias	In Seam	1/8	Straight
A-166	1 75	0 175-0 188	bias taper	0 180-0 195	1 861	1.83	Toe of Bias	In Seam	1/8	Straight

Table 32

Data Set "B" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)
B-1	1.75	0.109	bias	0.114	1.89	1.833	Toe of Bias	In Seam	3/16
B-2	1.75	0.109	bias	0.114	1.905	1.859	Toe of Bias	In Seam	1/8
B-3	1.75	0.109	bias	0.116	1.897	1.832	Toe of Bias	In Seam	1/8
B-4	1.75	0.109	bias	0.117	1.902	1.877	Toe of Bias	In Seam	1/8
B-5	1.75	0.109	bias	0.112	1.932	1.897	Toe of Bias	In Seam	1/8
B-6	1.75	0.125	none	0.129	1.946	1.833	---	In Seam	3/16
B-7	1.75	0.125	none	0.129	1.945	1.849	---	In Seam	1/8
B-8	1.75	0.125	none	0.131	1.988	1.92	---	In Seam	1/8
B-9	1.75	0.125	bias	0.13	1.954	1.834	Outside HAZ	In Seam	1/8
B-10	1.75	0.125	bias	0.129	1.911	1.834	Toe of Bias	In Seam	1/8
B-11	1.75	0.125	bias	0.129	1.919	1.837	HAZ	Edge of Seam	1/8
B-12	1.75	0.125	bias	0.13	1.928	1.822	HAZ	In Seam	3/16
B-13	1.75	0.134	bias	0.14	1.85	1.797	Toe of Bias	In Seam	1/16
B-14	1.75	0.134	bias	0.145	1.85	1.8	Both Welds	In Seam	3/16
B-15	1.75	0.134	bias	0.139	1.873	1.83	Toe of Bias	In Seam	1/8
B-16	1.75	0.134	bias	0.138	1.911	1.823	3 3/4" from Bias Weld	In Seam	1/8
B-17	1.75	0.156	bias	0.159	1.825	1.771	In Bias Weld	Edge of Seam	1/16
B-18	1.75	0.156	bias	0.16	1.836	1.775	3" from Bias Weld	In Seam	1/8
B-19	1.75	0.156	bias	0.16	1.839	1.796	Outside HAZ of Bias	In Seam	3/16
B-20	1.75	0.156	bias	0.16	1.834	1.78	6 3/8" from Bias Weld	In Seam	1/16
B-21	1.75	0.175	none	0.18	1.819	1.768	—	In Seam	1/8
B-22	1.75	0.175	none	0.181	1.825	1.786	—	In Seam	1/8
B-23	1.75	0.175	none	0.182	1.841	1.78	—	In Seam	1/8
B-24	1.75	0.175	bias	0.18	1.818	1.771	HAZ?	Edge of Seam	1/8
B-25	1.75	0.175	bias	0.181	1.831	1.776	8" from Bias Weld	In Seam	1/8
B-26	1.75	0.175	bias	0.181	1.84	1.772	HAZ of Bias Weld	In Seam	1/8
B-27	1.75	0.175	bias	0.183	1.851	1.793	6 3/4" from Weld	In Seam	1/16

Table 33

Data Set "C" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Side of Weld	Length (in)
C-1	1.25	0.087	none	0.082	1.275	1.243	---	In Seam	---	1/16
C-2	1.25	0.087	none	0.085	1.411	1.375	---	In Seam	---	1/8
C-3	1.25	0.087	none	0.09	1.404	1.365	---	In Seam	---	1/16
C-4	1.25	0.087	none	0.095	1.409	1.353	---	In Seam	---	1/8
C-5	1.25	0.087	none	0.082	1.541	1.461	---	In Seam	---	5/16
C-6	1.25	0.087	manual	0.085	1.345	1.318	HAZ	In Seam	?	1/4
C-7	1.25	0.087	manual	0.088	1.319	1.291	Fusion line		Up	1/8
C-8	1.25	0.087	manual	0.088	1.342	1.327	Fusion Line		Up	1/8
C-9	1.25	0.087	manual	0.085	1.351	1.3	Fusion Line	In Seam	Down	1/2
C-10	1.25	0.087	manual	0.087	1.374	1.346	Fusion Line		Up	1/2
C-11	1.25	0.087	manual	0.087	1.41	1.351	Fusion Line		Up	3/4 - 1/8
C-12	1.25	0.087	manual	0.09	1.357	1.335	Fusion Line		Down	1/8
C-13	1.25	0.087	manual	0.085	1.448	1.383	HAZ		?	3/4
C-14	1.25	0.087	manual	0.089	1.405	1.388	HAZ		Down	1/16
C-15	1.25	0.087	manual	0.096	1.448	1.39	Base Metal	In Seam	Down	1/16
C-16	1.25	0.087	orbital	0.089	1.365	1.323	Fusion Line	In Seam	Up	3/16
C-17	1.25	0.087	orbital	0.083	1.394	1.348	Fusion Line	In Seam	Down	9/16
C-18	1.25	0.109	orbital	0.112						
C-19	1.25	0.109	orbital	0.096	1.392	1.335	Fusion line		Down	9/16
C-20	1.25	0.156	bias	0.164	1.31	1.272	Base Metal	In Seam	Down	1/8
C-21	1.25	0.156	bias	0.168	1.301	1.267	1 1/2" from Weld		Down	1/16
C-22	1.25	0.156	bias	0.168	1.299	1.262	---		---	3/16

Data Set "D" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
D-1	1.75	0.109-0.116	bias taper	0.113-0.123	1.847	1.805	1 7/8" from Bias Weld	In Seam	1/16	Straight
D-2	1.75	0.109-0.116	bias taper	0.113-0.122	1.946	1.9	HAZ of Bias	In Seam	1/16	Straight
D-3	1.75	0.109-0.116	bias taper	0.113-0.124	1.947	1.899	HAZ of Bias	Just Off Seam	1/4	Straight
D-4	1.75	0.109-0.116	bias taper	0.115-0.121	1.942	1.911	Toe of Bias	In Seam	5/32	Straight
D-5	1.75	0.109-0.116	bias taper	0.113-0.121	2.046	1.968	Toe of Bias	In Seam	1/8	Straight
D-6	1.75	0.109-0.125	bias taper	0.113-0.122	1.85	1.81	Toe of Bias	In Seam	3/32	Straight
D-7	1.75	0.109-0.125	bias taper	0.113-0.125	1.942	1.898	HAZ of Bias		7/16	Straight
D-8	1.75	0.109-0.125	bias taper	0.115-0.123	1.998	1.955	HAZ		3/8	Straight
D-9	1.75	0.109-0.125	bias taper	0.115-0.123	1.987	1.916	HAZ		1/4	Straight
D-10	1.75	0.109-0.125	bias taper	0.113-0.125	1.981	1.937	HAZ of Bias		3/8	Straight
D-11	1.75	0.109-0.125	bias taper	0.113-0.122	2.008	1.992	Transversing HAZ		5/8	Discontinuous
D-12	1.75	0.116-0.125	bias taper	0.119-0.122	1.844	1.82	HAZ of Bias Weld	In Seam	1/16	Straight
D-13	1.75	0.116-0.125	bias taper	0.119-0.123	1.996	1.931	Toe of Bias	In Seam	1/8	Straight
D-14	1.75	0.116-0.125	bias taper	0.120-0.123	1.95	1.902	Toe of Bias	In Seam	5/32	Straight
D-15	1.75	0.116-0.125	bias taper	0.118-0.124	1.98	1.952	HAZ of Bias		5/32	Straight
D-16	1.75	0.116-0.125	bias taper	0.120-0.124	2.061	2.01	Fusion Line		15/16	Discontinuous
D-17	1.75	0.125-0.134	bias taper	0.123-0.136	1.879	1.828	7" from Bias Weld	In Seam	1/8	Straight
D-18	1.75	0.125-0.134	bias taper	0.124-0.138	2.002	1.926	Toe of Bias	In Seam	1/2	Straight
D-19	1.75	0.125-0.134	bias taper	0.122-0.137	1.989	1.939	Toe of Bias	In Seam	3/32	Straight
D-20	1.75	0.125-0.134	bias taper	0.125-0.138	2.008	1.963	Toe of Bias	In Seam	1/8	Straight
D-21	1.75	0.125-0.134	bias taper	0.121-0.137	2.051	1.994	HAZ of Seam	Parralels Seam	6	Discontinuous

Table 35

Data Set "E" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)
E-1	1.25	0.087	none	0.090					
E-2	1.25	0.087	none	0.093					
E-3	1.25	0.087	none	0.092					
E-4	1.25	0.087	none	0.092					
E-5	1.25	0.087	none	0.091					
E-6	1.25	0.087	bias						
E-7	1.25	0.087	bias	0.090					
E-8	1.25	0.087	bias	0.090					
E-9	1.25	0.087	bias	0.098					
E-10	1.25	0.087	bias	0.092					
E-11	1.25	0.087	manual						
E-12	1.25	0.087	manual	0.092					
E-13	1.25	0.087	manual	0.092					
E-14	1.25	0.087	manual	0.092					
E-15	1.25	0.087	manual	0.091					
E-16	1.25	0.087	none	0.089					
E-17	1.25	0.087	none	0.088					
E-18	1.25	0.087	none	0.090					
E-19	1.25	0.087	none	0.090					
E-20	1.25	0.087	none	0.090					
E-21	1.25	0.087	bias	0.089					
E-22	1.25	0.087	bias	0.090					
E-23	1.25	0.087	bias	0.090					
E-24	1.25	0.087	bias	0.090					
E-25	1.25	0.087	bias	0.089					
E-26	1.25	0.087	manual	0.089					
E-27	1.25	0.087	manual	0.089					
E-28	1.25	0.087	manual	0.090					
E-29	1.25	0.087	manual	0.093					

Data Set "F" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
F-1	2.00	0.190	none	0.191	2.109	2.031	—		1/4	Straight
F-2	2.00	0.190	none	0.190	2.077	2.012	—		1/4	Straight
F-3	2.00	0.190	none	0.188	2.255	2.12	—		1/8	Straight
F-4	2.00	0.190	none	0.188	2.185	2.089	—		1/4	Straight
F-5	2.00	0.190	none	0.187	2.45	2.15	—		9/16	Straight
F-6	2.00	0.190	none	0.187	2.325	2.21	—		1 1/4	Curved
F-7	2.00	0.190	manual	0.191	2.11	2.05	HAZ		3/16	Straight
F-8	2.00	0.190	manual	0.191	2.144	2.14	HAZ		1/4	Straight

Table 37

Data Set "G" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
G-1	1.75	0.109	none	0.11	1.994	1.796	---	In Seam	1/8	Straight
G-2	1.75	0.109	none	0.113	1.996	1.816	---	In Seam	1/8	Straight
G-3	1.75	0.109	none	0.112	2.049	1.796	---	In Seam	1/8	Straight
G-4	1.75	0.109	none	0.113	2.027	1.819	---	In Seam	1/4	Curve
G-5	1.75	0.109	none	0.113	2.062	1.771	---	In Seam	7/8	Discontinuous
G-6	1.75	0.125	none	0.125	1.994	1.865	---	In Seam	3/16	Chicken Foot
G-7	1.75	0.125	none	0.126	2.109	1.885	---	In Seam	1/8	Straight
G-8	1.75	0.125	none	0.127	2.005	1.859	---	In Seam	1/8	Straight
G-9	1.75	0.125	none	0.126	1.997	1.877	---	In Seam	5/16	Straight
G-10	1.75	0.125	none	0.126	2.224	1.896	---	Edge of Seam	1/8	Wavy
G-11	1.75	0.134	none	0.141	1.94	1.82	---	In Seam	3/8	Straight
G-12	1.75	0.134	none	0.139	1.978	1.856	---	In Seam	1/8	Straight
G-13	1.75	0.134	none	0.137	2.03	1.857	---	In Seam	1/4	Straight
G-14	1.75	0.134	none	0.138	2.055	1.956	---		3/8	Straight
G-15	1.75	0.156	none	0.16	1.796	1.745	---	In Seam	1/8	Curve
G-16	1.75	0.156	none	0.159	1.78	1.76	---	In Seam	3/16	Straight
G-17	1.75	0.156	none	0.158	1.929	1.823	---	In Seam	1/8	Straight
G-18	1.75	0.156	none	0.161	1.933	1.821	---	In Seam	1/8	Straight
G-19	1.75	0.156	none	0.161	1.941	1.815	---	In Seam	1/8	Straight
G-20	1.75	0.156	none	0.16	1.954	1.834	---	In Seam	3/16	Straight
G-21	1.75	0.156	none	0.157	1.941	1.833	---	In Seam	1/8	Straight
G-22	1.75	0.156	none	0.16	1.972	1.842	---	In Seam	3/16	Straight
G-23	1.75	0.156	none	0.157	2.135	1.993	---		9/16	Straight
G-24	1.75	0.175	none	0.18	1.89	1.795	---	In Seam	1/8	Straight
G-25	1.75	0.175	none	0.183	1.883	1.797	---	In Seam	1/8	Straight
G-26	1.75	0.175	none	0.179	1.899	1.795	---	In Seam	3/16	Straight
G-27	1.75	0.175	none	0.18	1.931	1.81	---	In Seam	3/16	Straight
G-28	1.75	0.175	none	0.179	1.956	1.809	---	In Seam	3/16	Straight

Table 38

Data Set "H" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
H-1	2 375	0 19	none	0 191	2 681	2.484	—		1/4	Straight
H-2	2 375	0 19	none	0 190	2.558	2 433	—		3/32	Straight
H-3	2 375	0 19	none	0 190	2.655	2.475	—	In Seam	1/16	Straight
H-4	2 375	0 19	none	0 190	3.051	2.81	—	In Seam	3/8	Straight
H-5	2 375	0 19	manual	0 195	2.483	2 395	Fusion Line	In Seam	3/8	Straight
H-6	2 375	0 19	manual	0 194	2 51	2.421	Fusion Line	Adjacent to	5/8	Straight
H-7	2 375	0 19	manual	0 195	2.491	2 424	Center of Weld	In Seam	1/16	Straight
H-8	2 375	0.19	manual	0 195	2.67	2 545	HAZ		1/4	Straight
H-9	2 375	0 19	orbital	0 193	2.45	2.402	Fusion Line		7/8	Straight
H-10	2 375	0 19	orbital	0 195	2 49	2.423	HAZ		3/8	Straight
H-11	2 375	0 19	orbital	0 190	2.479	2.436	Fusion Line	Intersects	1 5/16	Straight
H-12	2 375	0 19	orbital	0 193	2 558	2.528	Fusion Line	Intersects	1 1/4	Straight

Field Data Set "1" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
FS1-1	2 00	0 134	none	0 138	2.326	2 22	—		1/4	Straight
FS1-2	2 00	0 134	none	0 139	2 321	2.001	—		1/4	Straight
FS1-3	2 00	0 134	none	0 137	2 381	2.237	—		1/4	Straight
FS1-4	2 00	0 134	none	0 137	2.395	2.303	—		7/8	Straight
FS1-5	2.00	0 134	manual	0 135	2 184	2.115	Fusion Line	In Seam	1 3/4	Jagged
FS1-6	2 00	0 134	manual	0 14	2.13	2 054	Fusion Line		3/4	Discontinuous
FS1-7	2 00	0 134	manual	0 139	2.19	2.09	Fusion Line		3/4	Jagged
FS1-8	2 00	0 134	manual	0 137	2.298	2.102	Fusion Line		5/16	Jagged
FS1-9	2 00	0 134	manual	0 138	2.16	2.067	Fusion Line		1 1/2	Jagged

Table 40

Field Data Set "2" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
FS2-1	2 875	0 190	none		3 268	3.003	—		1/4	Discontinuous
FS2-2	2.875	0 190	none		3 493	3 184	—		3/16	Wavy & Broken
FS2-3	2 875	0 190	none	0 195	3.2	2 97	—		3/8, 1/8, 1/8,	
FS2-4	2 875	0 190	none		3.41	3.118	—		1/4	Straight
FS2-5	2 875	0 190	none	0 196	3 453	3 106	—		1/4, 3/16, 1/8	Straight,
FS2-6	2 875	0 190	none	0 195	3 4	3 193	—		5/16	Straight
FS2-7	2 875	0 190	none	0 196	3.504	3 313	—		2 1/8	Straight
FS2-8	2 875	0 190	none	0 195	3.52	3 46	—		3/4	Straight
FS2-9	2.875	0.190	manual	0 195	2 951	2 877	Fusion Line		2	Straight
FS2-10	2 875	0 190	manual		2.952	2.875	Weld		1/8	Straight
FS2-11	2 875	0 190	manual	0.193	2.973	2.863	Fusion line		1 1/8	Discontinuous
FS2-12	2 875	0 190	manual	0 196	2.989	2.878	Fusion Line		1 2/8	Straight
FS2-13	2 875	0 190	manual	0 192	2 982	2.897	Fusion Line		5/8	Straight
FS2-14	2 875	0 190	manual	0 189	3 021	2.934	Fusion Line		1 1/8	Straight
FS2-15	2 875	0.190	manual	0 186	3 055	2 945	Fusion Line		1 3/8	Straight
FS2-16	2 875	0.190	manual	0 191	3 104	3 018	Fusion Line		1 7/8	Straight

Table 41

Field Data Set "3" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
FS3-1	1 75	0 109	none	0 114	1 9	1.823	—		3/8	Straight
FS3-2	1 75	0 109	none	0 115	2 059	2 032	—		3/8	Straight
FS3-3	1.75	0 109	none	0 113	2.113	1 996	—		1/16	Straight
FS3-4	1 75	0 109	none	0 115	2.161	2.061	—		1/16	Straight
FS3-5	1 75	0 109	none	0 115	2.115	2 045	—		7/8	Straight
FS3-6	1 75	0 109	manual	0 112	1 79	1.778	HAZ		5/32	Straight
FS3-7	1 75	0 109	manual	0 113	1 877	1.867	HAZ		1/4	Straight
FS3-8	1 75	0 109	manual	0 112	1.879	1.875	HAZ		1/4	Curved
FS3-9	1 75	0 109	manual	0 113	1 972	1 9	HAZ		5/8	Straight
FS3-10	1 75	0 109	manual	0 112	1 879	1.869	HAZ		3/4	Straight

Table 42

Field Data Set "3" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
FS3-11	3.50	0.190	none							
FS3-12	3 50	0 190	none							
FS3-13	3 50	0 190	manual	0.195	3 644	3.486	HAZ		1/4	Straight
FS3-14	3 50	0 190	manual	0 195	3.742	3.555	Fusion Line	In Seam	1 9/16	Straight
FS3-15	3 50	0 190	manual	0 194	3 747	3.554	Fusion Line		7/8	Straight
FS3-16	3.50	0 190	manual	0 194	3.775	3.608	Fusion Line		1 3/8	Jagged
FS3-17	3.50	0 190	manual	0 196	3 796	3 704	HAZ		3 1/8	Discontinouos

Table 43

Field Data Set "4" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
FS4-1	2 375	0 190	manual	0 205	2 409	2.372	Fusion Line		1/4	Straight
FS4-2	2 375	0.190	manual	0 209	2 455	2 397	Fusion Line	Adjacent to Seam	1	Straight
FS4-3	2 375	0 190	manual	0 207	2 458	2 397	Fusion Line		1	Jagged
FS4-4	2.375	0.190	manual	0 208	2 437	2 393	Fusion Line		3/4	Slight Curve
FS4-5	2 375	0 190	manual	0 208	2.49	2.439	Fusion Line		1 1/4	Straight

Table 44

Field Data Set "5" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
FS5-1	1.75	0.109	none	0.112	1.883	1.834				
FS5-2	1.75	0.109	none	0.110	1.924	1.882				
FS5-3	1.75	0.109	none	0.112	1.985	1.918				
FS5-4	1.75	0.109	manual	0.112	1.77	1.754				
FS5-5	1.75	0.109	manual	0.108	1.785	1.259	Fusion Line		3/32	Straight
FS5-6	1.75	0.109	manual	0.130	1.858	1.808				
FS5-7	1.75	0.109	manual	0.114	1.822	1.785				
FS5-8	1.75	0.109	manual	0.113	1.878	1.833	HAZ		5/8	Jagged
FS5-9	1.75	0.109	orbital	0.116	1.879	1.876	HAZ		5/32	Straight
FS5-10	1.75	0.109	orbital	0.108	1.873	1.861	HAZ	In Seam	7/8	Straight
FS5-11	1.75	0.109	orbital	0.110	1.784	1.756	Weld		5/8	Straight
FS5-12	1.75	0.109	orbital	0.111	1.891	1.862	HAZ		1/8	Straight
FS5-13	1.75	0.109	orbital	0.112	1.923	1.871	HAZ	In Seam	7/8	Jagged
FS5-14	1.75	0.125	none	0.116	1.912	1.896	—		7/8	Jagged
FS5-15	1.75	0.125	none	0.126	1.948	1.855				
FS5-16	1.75	0.125	none	0.127	2.027	1.916				
FS5-17	1.75	0.125	none	0.123	1.948	1.87	—		3/16	Straight
FS5-18	1.75	0.125	none	0.125	1.973	1.882	—		3/4	Jagged, Bias
FS5-19	1.75	0.125	manual	0.121	1.901	1.868	HAZ		5/32	Curved
FS5-20	1.75	0.125	manual	0.128	1.945	1.838				
FS5-21	1.75	0.125	manual	0.130	1.909	1.891				
FS5-22	1.75	0.125	manual	0.119	1.844	1.839	Bias Break From HAZ	In Seam	5/32	Jagged
FS5-23	1.75	0.125	orbital	0.117	1.966	1.908	1 1/4, 4 1/2, 4 1/4" from		1/8, 5/16, 1/2	Jagged
FS5-24	1.75	0.125	orbital	0.118	1.908	1.848	Fusion Line		1/8	Straight
FS5-25	1.75	0.125	orbital	0.123	1.971	1.833	5 1/2" from weld	In Seam	3/32	Straight
FS5-26	1.75	0.125	orbital	0.122	1.962	1.888	6" from Weld		7/16	Jagged
FS5-27	1.75	0.134	none	0.139	1.998	1.905	—	In Seam	1/16	Straight
FS5-28	1.75	0.134	manual	0.139	?	?				
FS5-29	1.75	0.134	manual	0.135	1.871	1.8	HAZ		3/16	Straight
FS5-30	1.75	0.134	orbital	0.121	1.871	1.828	HAZ		1/4	Straight
FS5-31	1.75	0.134	orbital	0.135	1.879	1.835	HAZ	In Seam	3/4	Jagged

Table 45

Field Data Set "6" Visual Observations

Identity	Diameter	Wall (nom)	Weld type	Wall (meas)	DIA major	DIA minor	Fracture Location	Relation to Seam	Length (in)	Appearance
FS6-1	2 00	0 134	none	0 136	2 305	2 216	—		3/8	Straight
FS6-2	2 00	0 134	orbital	0 138	2 325	2 198	3" from Weld		1/8	Straight
FS6-3	2 00	0 134	orbital	0 138	2 298	2.218	3" from Weld		1/8	Straight
FS6-4	2 00	0 134	orbital	0 136	2 331	2 221	4 1/2" from weld		3/16	Straight
FS6-5	2 00	0 134	orbital	0 138	2 147	2 038	Fusion Line		5/16	Straight
FS6-6	2 00	0 134	orbital	0 139	2 32	2 184	In Weld		1/2	Straight

Table 46

Data Set "A" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld Type	X-Ray	Inspection	Comments
A-1	1.75	0.109	none			
A-2	1.75	0.109	none			
A-3	1.75	0.109	none			
A-4	1.75	0.109	none			
A-5	1.75	0.109	none			
A-6	1.75	0.109	bias			
A-7	1.75	0.109	bias			
A-8	1.75	0.109	bias			
A-9	1.75	0.109	bias			
A-10	1.75	0.109	bias			
A-11	1.75	0.109	bias			
A-12	1.75	0.109	bias			
A-13	1.75	0.109	bias			
A-14	1.75	0.109	bias			
A-15	1.75	0.109	bias			
A-16	1.75	0.109	manual	R	porosity	small circ crack on weld/HAZ interface, near seam
A-17	1.75	0.109	manual	A		circ crack at weld/HAZ interface, near seam
A-18	1.75	0.109	manual	A		long circ crack at weld/HAZ interface, large bubble deformations, at seam
A-19	1.75	0.109	manual	R	lack of fusion	no visible crack, opposite seam, big bump one side
A-20	1.75	0.109	manual	R	porosity	small circ crack in HAZ, near seam
A-21	1.75	0.109	manual	R	pinhole	circ crack in HAZ, on seam
A-22	1.75	0.109	manual	A		circ crack in HAZ, on seam
A-23	1.75	0.109	manual	R	insuff filler	circ crack in HAZ, near seam
A-24	1.75	0.109	manual	R	porosity	
A-25	1.75	0.109	manual	R	pinhole	extensive circ crack in HAZ, near seam
A-26	1.75	0.109	orbital	A		
A-27	1.75	0.109	orbital	R	scattered porosity	circ crack in HAZ opposite seam
A-28	1.75	0.109	orbital	R	aligned porosity	long circ crack in HAZ, on seam
A-29	1.75	0.109	orbital	R	aligned porosity	circ crack in HAZ, on seam
A-30	1.75	0.109	orbital	R	aligned porosity	circ crack in HAZ close to weld, on seam
A-31	1.75	0.109	orbital	R	porosity	circ crack in HAZ, on seam

Table 47

Data Set "A" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld Type	X-Ray	Inspection	Comments
A-32	1.75	0.125	none			
A-33	1.75	0.125	none			
A-34	1.75	0.125	none			
A-35	1.75	0.125	none			
A-36	1.75	0.125	none			
A-37	1.75	0.125	bias			
A-38	1.75	0.125	bias			
A-39	1.75	0.125	bias			
A-40	1.75	0.125	manual	R	pinhole	circ crack in HAZ, opposite seam
A-41	1.75	0.125	manual	A		2 circ cracks in HAZ, opposite seam
A-42	1.75	0.125	manual	R	porosity	
A-43	1.75	0.125	manual	R	porosity	
A-44	1.75	0.125	orbital	R	pinhole	
A-45	1.75	0.125	orbital	R	porosity	
A-46	1.75	0.125	orbital	R	porosity	circ crack in HAZ, on seam
A-47	1.75	0.125	orbital	R	porosity	

Table 48

Data Set "A" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld Type	X-Ray	Inspection	Comments
A-48	1.75	0.134	none			
A-49	1.75	0.134	none			
A-50	1.75	0.134	none			
A-51	1.75	0.134	none			
A-52	1.75	0.134	none			
A-53	1.75	0.134	bias			
A-54	1.75	0.134	bias			
A-55	1.75	0.134	bias			
A-56	1.75	0.134	bias			
A-57	1.75	0.134	bias			
A-58	1.75	0.134	manual	R	insuff filler	circ crack weld or HAZ, near seam, no bumps
A-59	1.75	0.134	manual			
A-60	1.75	0.134	manual	A		circ crack at weld/HAZ interface, on seam
A-61	1.75	0.134	manual	R	internal concavity	circ crack at weld/HAZ interface, on seam
A-62	1.75	0.134	manual	R	pinhole	circ crack at fusion line, no bumps, near seam
A-63	1.75	0.134	manual			
A-64	1.75	0.134	manual	R	pinhole	circ crack at weld centerline, opposite seam
A-65	1.75	0.134	orbital	A		
A-66	1.75	0.134	orbital	R	porosity	
A-67	1.75	0.134	orbital	A		
A-68	1.75	0.134	orbital	R		
A-69	1.75	0.134	orbital	A		

Table 49

Data Set "A" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld Type	X-Ray	Inspection	Comments
A-70	1.75	0.156	none			
A-71	1.75	0.156	none			
A-72	1.75	0.156	none			
A-73	1.75	0.156	none			
A-74	1.75	0.156	none			
A-75	1.75	0.156	bias			
A-76	1.75	0.156	bias			
A-77	1.75	0.156	bias			
A-78	1.75	0.156	bias			
A-79	1.75	0.156	bias			
A-80	1.75	0.156	manual	A		
A-81	1.75	0.156	manual	A		small circ crack at weld/HAZ interface, near seam
A-82	1.75	0.156	manual	R	pinhole + insuff filler	extensive cracking at toe of weld cap, opposite seam
A-83	1.75	0.156	manual	A		circ crack in HAZ, on seam
A-84	1.75	0.156	manual	R	porosity	
A-85	1.75	0.156	orbital	R	porosity + lack of fusion + suckback	
A-86	1.75	0.156	orbital	A		
A-87	1.75	0.156	orbital	A		
A-88	1.75	0.156	orbital	A		
A-89	1.75	0.156	orbital	A		

Table 50

Data Set "A" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld Type	X-Ray	Inspection	Comments
A-90	1.75	0.175	none			
A-91	1.75	0.175	none			
A-92	1.75	0.175	none			
A-93	1.75	0.175	none			
A-94	1.75	0.175	none			
A-95	1.75	0.175	none			
A-96	1.75	0.175	bias			
A-97	1.75	0.175	bias			
A-98	1.75	0.175	bias			
A-99	1.75	0.175	manual	R	pinhole	
A-100	1.75	0.175	manual	R	pinhole + insuff filler	circ crack at toe of weld cap, near seam
A-101	1.75	0.175	manual	R	insuff penetration + undercut	circ crack in weld, opposite seam
A-102	1.75	0.175	manual	R	insuff penetration	circ crack in weld, opposite seam
A-103	1.75	0.175	manual	R		
A-104	1.75	0.175	orbital	R	suck back	
A-105	1.75	0.175	orbital	R	porosity	
A-106	1.75	0.175	orbital	R	porosity	

Table 51

Data Set "A" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld Type	X-Ray	Inspection	Comments
A-107	1.75	0.188	none			
A-108	1.75	0.188	none			
A-109	1.75	0.188	none			
A-110	1.75	0.188	none			
A-111	1.75	0.188	none			

Data Set "A" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld Type	X-Ray	Inspection	Comments
A-112	1.75	0.125	bias			stopped at 50%
A-113	1.75	0.125	bias			stopped at 75%
A-114	1.75	0.125	manual			stopped at 50% of test 252
A-115	1.75	0.125	manual			stopped at 75% of test 252
A-116	1.75	0.125	orbital	R	porosity	Stopped at 50% of test
A-117	1.75	0.125	orbital	R	porosity	Stopped at 75% of test
A-118	1.75	0.156-0.175	bias taper			
A-119	1.75	0.156-0.175	bias taper			
A-120	1.75	0.175	bias			stopped at 50%
A-121	1.75	0.175	bias			stopped at 75%
A-122	1.75	0.175	orbital	A		stopped at 50%
A-123	1.75	0.175	orbital			stopped at 75%

Table 53

Data Set "A" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld Type	X-Ray	Inspection	Comments
A-124	1 75	0 109-0 125	bias taper			
A-125	1 75	0 109-0.125	bias taper			
A-126	1 75	0 109-0 125	bias taper			
A-127	1 75	0 109-0 125	bias taper			
A-128	1 75	0 109-0 125	bias taper			
A-129	1 75	0.109-0.125	manual	A		
A-130	1.75	0 109-0 125	manual	A		
A-131	1.75	0 109-0 125	manual	R		
A-132	1 75	0 109-0 125	manual	R		
A-133	1 75	0 109-0.125	manual	A		
A-134	1 75	0 109-0.125	orbital	A		
A-135	1 75	0 109-0.125	orbital	A		
A-136	1.75	0 109-0 125	orbital	A		
A-137	1 75	0.109-0 125	orbital	A		
A-138	1 75	0 109-0.125	orbital	A		
A-139	1 75	0 125-0.134	bias taper			
A-140	1 75	0 125-0.134	bias taper			
A-141	1 75	0 125-0 134	bias taper			
A-142	1 75	0.125-0 134	bias taper			
	1.75	0 125-0.134	bias taper			
A-143						
A-144	1 75	0 134-0.156	bias taper			
A-145	1 75	0 134-0.156	bias taper			
A-146	1.75	0.134-0 156	bias taper			
A-147	1 75	0.134-0 156	bias taper			
A-148	1 75	0 134-0 156	bias taper			

Table 54

Data Set "A" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld Type	X-Ray	Inspection	Comments
A-149	1 75	0.156-0 175	bias taper			
A-150	1 75	0 156-0 175	bias taper			
A-151	1.75	0 156-0 175	bias taper			
A-152	1 75	0 156-0 175	manual	R		
A-153	1 75	0 156-0 175	manual	A		
A-154	1 75	0 156-0 175	manual	R		
A-155	1.75	0 156-0 175	manual	R		
A-156	1 75	0.156-0 175	manual	R		
A-157	1 75	0.156-0.175	orbital	R	porosity + lack of fusion	
A-158	1 75	0 156-0 175	orbital	A		
A-159	1 75	0 156-0 175	orbital	R	porosity	
A-160	1 75	0.156-0 175	orbital	R	porosity + suck back	
A-161	1.75	0 156-0 175	orbital	R	porosity + suck back	
A-162	1.75	0 175-0.188	bias taper			
A-163	1.75	0.175-0.188	bias taper			
A-164	1.75	0.175-0.188	bias taper			
A-165	1.75	0 175-0.188	bias taper			
A-166	1.75	0 175-0.188	bias taper			

Table 55

Data Set "B" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld type	X-Ray	Inspection	Comments
B-1	1.75	0.109	bias			weld/seam junction (top)
B-2	1.75	0.109	bias			weld/seam junction (top)
B-3	1.75	0.109	bias			weld/seam junction (bottom)
B-4	1.75	0.109	bias			weld/seam junction (top)
B-5	1.75	0.109	bias			weld/seam junction (top)
B-6	1.75	0.125	none			
B-7	1.75	0.125	none			
B-8	1.75	0.125	none			
B-9	1.75	0.125	bias			weld/seam junction (bottom)
B-10	1.75	0.125	bias			weld/seam junction (bottom)
B-11	1.75	0.125	bias			weld/seam junction (bottom)
B-12	1.75	0.125	bias			weld/seam junction (bottom)
B-13	1.75	0.134	bias			weld/seam junction (bottom)
B-14	1.75	0.134	bias			weld/seam junction (bottom)
B-15	1.75	0.134	bias			weld/seam junction (bottom)
B-16	1.75	0.134	bias			3.75" below weld
B-17	1.75	0.156	bias			weld/seam junction (bottom)
B-18	1.75	0.156	bias			weld/seam junction (bottom)
B-19	1.75	0.156	bias			weld/seam junction (top)
B-20	1.75	0.156	bias			8" below weld
B-21	1.75	0.175	none			
B-22	1.75	0.175	none			
B-23	1.75	0.175	none			
B-24	1.75	0.175	bias			weld/seam junction (bottom)
B-25	1.75	0.175	bias			8.5" below weld
B-26	1.75	0.175	bias			weld/seam junction (bottom)
B-27	1.75	0.175	bias			8" below weld

Data Set "C" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld type	X-Ray	Inspection	Comments
C-1	1.25	0.087	none			
C-2	1.25	0.087	none			
C-3	1.25	0.087	none			
C-4	1.25	0.087	none			
C-5	1.25	0.087	none			
C-6	1.25	0.087	manual	R	lack of fusion	
C-7	1.25	0.087	manual	R	lack of penetration	
C-8	1.25	0.087	manual	R	tungsten inclusion	
C-9	1.25	0.087	manual	R	bad undercut	
C-10	1.25	0.087	manual	A		
C-11	1.25	0.087	manual	R	2 pinholes + inclusion	
C-12	1.25	0.087	manual	R	pinhole + tungsten inclusion	
C-13	1.25	0.087	manual	A		
C-14	1.25	0.087	manual	R	pinhole + undercut	
C-15	1.25	0.087	manual	R	undercut	
C-16	1.25	0.087	orbital			suspect - high flash, not ground
C-17	1.25	0.087	orbital	R	pinholes + undercut	
C-18	1.25	0.109	orbital	R	no penetration - LEAKED	
C-19	1.25	0.109	orbital	R	pinholes	
C-20	1.25	0.156	bias			
C-21	1.25	0.156	bias			
C-22	1.25	0.156	bias			

Table 57

Data Set "D" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld type	X-Ray	Inspection	Comments
D-1	1.75	0.109-0.116	bias taper			
D-2	1.75	0.109-0.116	bias taper			
D-3	1.75	0.109-0.116	bias taper			
D-4	1.75	0.109-0.116	bias taper			
D-5	1.75	0.109-0.116	bias taper			
D-6	1.75	0.109-0.125	bias taper			
D-7	1.75	0.109-0.125	bias taper			
D-8	1.75	0.109-0.125	bias taper			
D-9	1.75	0.109-0.125	bias taper			
D-10	1.75	0.109-0.125	bias taper			
D-11	1.75	0.109-0.125	bias taper			
D-12	1.75	0.116-0.125	bias taper			
D-13	1.75	0.116-0.125	bias taper			
D-14	1.75	0.116-0.125	bias taper			
D-15	1.75	0.116-0.125	bias taper			
D-16	1.75	0.116-0.125	bias taper			
D-17	1.75	0.125-0.134	bias taper			
D-18	1.75	0.125-0.134	bias taper			
D-19	1.75	0.125-0.134	bias taper			
D-20	1.75	0.125-0.134	bias taper			
D-21	1.75	0.125-0.134	bias taper			

Data Set "E" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld type	X-Ray	Inspection	Comments
E-1	1 25	0 087	none			
E-2	1 25	0.087	none			
E-3	1.25	0 087	none			
E-4	1 25	0 087	none			
E-5	1 25	0.087	none			
E-6	1 25	0 087	bias			
E-7	1 25	0 087	bias			
E-8	1.25	0 087	bias			
E-9	1 25	0 087	bias			
E-10	1 25	0 087	bias			
E-11	1 25	0 087	manual			
E-12	1 25	0 087	manual			
E-13	1.25	0 087	manual			
E-14	1 25	0 087	manual			
E-15	1 25	0 087	manual			
E-16	1 25	0 087	none			
E-17	1 25	0 087	none			
E-18	1 25	0 087	none			
E-19	1 25	0 087	none			
E-20	1 25	0 087	none			
E-21	1 25	0 087	bias			
E-22	1.25	0 087	bias			
E-23	1.25	0 087	bias			
E-24	1 25	0.087	bias			
E-25	1 25	0.087	bias			
E-26	1 25	0.087	manual			
E-27	1 25	0 087	manual			
E-28	1 25	0 087	manual			
E-29	1 25	0 087	manual			

Data Set "F" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld type	X-Ray	Inspection	Comments
F-1	2 00	0 190	none			distorted pipe
F-2	2 00	0 190	none			distorted pipe
F-3	2 00	0 190	none			distorted pipe
F-4	2.00	0 190	none			distorted pipe
F-5	2.00	0.190	none			distorted pipe
F-6	2 00	0.190	none			distorted pipe
F-7	2.00	0 190	manual			on weld - distorted pipe
F-8	2 00	0.190	manual			on weld - distorted pipe

Table 60

Data Set "G" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld type	X-Ray	Inspection	Comments
G-1	1.75	0.109	none			
G-2	1.75	0.109	none			
G-3	1.75	0.109	none			
G-4	1.75	0.109	none			
G-5	1.75	0.109	none			
G-6	1.75	0.125	none			
G-7	1.75	0.125	none			
G-8	1.75	0.125	none			
G-9	1.75	0.125	none			
G-10	1.75	0.125	none			
G-11	1.75	0.134	none			
G-12	1.75	0.134	none			
G-13	1.75	0.134	none			
G-14	1.75	0.134	none			
G-15	1.75	0.156	none			
G-16	1.75	0.156	none			
G-17	1.75	0.156	none			
G-18	1.75	0.156	none			
G-19	1.75	0.156	none			
G-20	1.75	0.156	none			
G-21	1.75	0.156	none			
G-22	1.75	0.156	none			
G-23	1.75	0.156	none			
G-24	1.75	0.175	none			
G-25	1.75	0.175	none			
G-26	1.75	0.175	none			
G-27	1.75	0.175	none			
G-28	1.75	0.175	none			

Table 61

Dat Set "H" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld type	X-Ray	Inspection	Comments
H-1	2 375	0.190	none			
H-2	2 375	0 190	none			
H-3	2 375	0 190	none			
H-4	2 375	0 190	none			
H-5	2.375	0 190	manual	R	Pinhole	
H-6	2 375	0 190	manual	A		
H-7	2 375	0 190	manual	A		
H-8	2 375	0 190	manual	A		
H-9	2 375	0 190	orbital	A		
H-10	2 375	0.190	orbital	A		
H-11	2 375	0 190	orbital	A		
H-12	2 375	0 190	orbital	A		

Table 62

Field Data Set "1" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld type	X-Ray	Inspection
FS1-1	2 00	0 134	none		
FS1-2	2 00	0 134	none		
FS1-3	2 00	0 134	none		
FS1-4	2 00	0 134	none		
FS1-5	2 00	0 134	manual		
FS1-6	2 00	0 134	manual		
FS1-7	2 00	0 134	manual		
FS1-8	2 00	0.134	manual		
FS1-9	2 00	0 134	manual		

Field Data Set "2" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld type	X-Ray	Inspection	Comments
FS2-1	2.875	0.190	none			
FS2-2	2.875	0.190	none			
FS2-3	2.875	0.190	none			
FS2-4	2.875	0.190	none			
FS2-5	2.875	0.190	none			
FS2-6	2.875	0.190	none			
FS2-7	2.875	0.190	none			
FS2-8	2.875	0.190	none			gross ripples
FS2-9	2.875	0.190	manual	R	Tungsten Inclusion	
FS2-10	2.875	0.190	manual	R	melt through	
FS2-11	2.875	0.190	manual	R	pinholes	
FS2-12	2.875	0.190	manual	A		
FS2-13	2.875	0.190	manual	R	Internal Undercut	
FS2-14	2.875	0.190	manual	A		
FS2-15	2.875	0.190	manual	A		
FS2-16	2.875	0.190	manual	A		

Field Data Set "3" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld type	X-Ray	Inspection	Comments
FS3-1	1 75	0.109	none			
FS3-2	1 75	0 109	none			
FS3-3	1 75	0 109	none			
FS3-4	1 75	0 109	none			
FS3-5	1 75	0 109	none			
FS3-6	1 75	0 109	manual	A		
FS3-7	1 75	0 109	manual	A		
FS3-8	1 75	0 109	manual	A		
FS3-9	1 75	0 109	manual	A		
FS3-10	1 75	0 109	manual	A		

Field Data Set "3" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld type	X-Ray	Inspection	Comments
FS3-11	3.50	0 190	none			
FS3-12	3.50	0 190	none			
FS3-13	3.50	0 190	manual	A		
FS3-14	3 50	0 190	manual	A		
FS3-15	3 50	0 190	manual	R	Gouge	
FS3-16	3 50	0 190	manual	A		
FS3-17	3.50	0 190	manual	A		

Table 66

Field Data Set "4" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld type	X-Ray	Inspection	Comments
FS4-1	2.375	0 190	manual	A		
FS4-2	2 375	0 190	manual	A		
FS4-3	2.375	0 190	manual	A		
FS4-4	2 375	0 190	manual	A		
FS4-5	2 375	0 190	manual	A		

Field Data Set "5" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld type	X-Ray	Inspection	Comments
FS5-1	1.75	0.109	none			7% life used
FS5-2	1.75	0.109	none			7% life used
FS5-3	1.75	0.109	none			26% life used
FS5-4	1.75	0.109	manual	R	porosity	7% life used
FS5-5	1.75	0.109	manual			7% life used
FS5-6	1.75	0.109	manual	R	root concavity	7% life used
FS5-7	1.75	0.109	manual	R	root concavity + porosity	26% life used
FS5-8	1.75	0.109	manual			26% life used
FS5-9	1.75	0.109	orbital			0% life used
FS5-10	1.75	0.109	orbital			7% life used
FS5-11	1.75	0.109	orbital			26% life used
FS5-12	1.75	0.109	orbital			26% life used
FS5-13	1.75	0.109	orbital			26% life used
FS5-14	1.75	0.125	none			0% life used
FS5-15	1.75	0.125	none			6% life used
FS5-16	1.75	0.125	none			6% life used
FS5-17	1.75	0.125	none			12% life used
FS5-18	1.75	0.125	none			
FS5-19	1.75	0.125	manual			0% life used
FS5-20	1.75	0.125	manual	R	inclusions	6% life used
FS5-21	1.75	0.125	manual	R	lack of penetration + cavities	6% life used
FS5-22	1.75	0.125	manual			
FS5-23	1.75	0.125	orbital			0% life used
FS5-24	1.75	0.125	orbital			0% life used
FS5-25	1.75	0.125	orbital			12% life used
FS5-26	1.75	0.125	orbital			12% life used
FS5-27	1.75	0.134	none			14% life used
FS5-28	1.75	0.134	manual			12% life used
FS5-29	1.75	0.134	manual			14% life used
FS5-30	1.75	0.134	orbital			12% life used
FS5-31	1.75	0.134	orbital			14% life used

Table 68

Field Data Set "6" Radiographic Results and Comments

Identity	Diameter	Wall (nom)	Weld type	X-Ray	Inspection	Comments
FS6-1	2.00	0 134	none			28% life used
FS6-2	2 00	0 134	orbital			8% life used
FS6-3	2 00	0 134	orbital			8% life used
FS6-4	2 00	0 134	orbital			28% life used
FS6-5	2 00	0 134	orbital			28% life used
FS6-6	2 00	0 134	orbital			28% life used

Table 69

5 DATA ANALYSIS

The following sections discuss each of the primary variables known to influence the fatigue life of plain pipe. It is reasonable to suppose that these variables will have a very similar effect on the weld cycle life. However, it is quite possible that the mechanical properties of the welds can cause these variables to have a greater or lesser impact on the cycle life. To this end, much use is made of graphs where the observed weld life is plotted as a percentage of the equivalent plain pipe life. This allows broad comparisons to be made between different sets of data for which one variable changes. Care must be taken, however, because there are so many variables in play that a definitive comparison is rarely possible.

The following types of welds are identified in this report:

Plain Pipe	Sections of unwelded coiled tubing.
Manual welds	Butt welds perpendicular to the longitudinal axis of the CT, performed by hand by a welder.
Orbital welds	Butt welds perpendicular to the longitudinal axis of the CT, performed by semi-automatic machines, which control most variables of the welding process while being operated by a welder or welding operator.
Bias welds	Welds made at the factory in the flat steel strip prior to milling the tubing. The strip is cut and welded typically at 45° to the longitudinal axis, such that when the tubing is formed the bias weld is distributed helically along the axis. The weld is performed by semi-automatic machines, which control most variables of the welding process while being operated by a welder or welding operator.

The following is also discussed as an important special case:

Tapered welds	Manual, orbital or bias welds made between tubing of different wall thickness either side of the weld.

The distribution of specimens tested in the study was as follows.

Weld Type	Number Tested
Plain Pipe (no weld)	117
Manual	98
Manual Tapered	10
Orbital	50
Orbital Tapered	10
Bias	64
Bias Tapered	46

5.1 Observed Effect of Weld Type

5.1.1 Plain Pipe (Graphs 186-196)

Results for unwelded pipe samples are displayed for each Data Set grouped by diameter and wall thickness. Data for unwelded pipe was required to provide a reference for the expected cycle life for every weld from the same batch of tubing.

In accordance with the well-known fatigue behavior of coiled tubing, all results for plain pipe show a clear tendency for the number of cycles to failure (N_{FTM}) to decline significantly with increasing test pressure.

The results for 1.25" diameter plain pipe from Data Sets **C**, **E** and **G**, which were tested over a 48" radius, show a trend at 2500 psi for cycles to failure to increase with increasing wall thickness. The trend can be clearly observed comparing the data at 2500 psi test pressure.

The 1.75" diameter results from Data Sets **A** and **B**, along with Field Data Sets **3** and **5**, have very good agreement for the same wall size (Graphs **187-193**). Here again the trend is for cycles to failure to increase with increasing wall thickness.

The 2.0" diameter median values (Graph **194**) show excellent correlation between similar points from Field Data Sets **1** and **6**. The number of cycles to failure also increase as the wall thickness increases from 0.134" to 0.190".

One unexpected anomaly in this plain pipe data is the tendency for some thick-wall CT to fail earlier than expected at low pressure (1500 psi), based on the apparent trend at higher pressures (3000 psi and above) and model predictions (see Graphs **192**, **193**, **194**). The pipe sizes are 1.75"/0.175" and 0.188" (D/t = 10 and 9.3)., 2.00"/0.134" (D/t = 14.9) and 2.375"/0.190" (D/t = 12.5). There appears to be no obvious correlation between the D/t ratios and the shortfall at low pressure, since other sizes which did not show this tendency had the same D/t.

5.1.2 Bias Welds (Graphs 197-204)

Bias weld data, sorted by CT diameter and wall thickness, generally display cycle lives relatively close to the plain pipe data, and show less scatter and consistently higher lives than the corresponding manual and orbital welds. It is widely considered that the strength of the bias weld lies in the fact that the axis of the weld and the HAZ are not aligned perpendicular to the principal stress. This allows stress cycles to be distributed to different sections of the weld, HAZ or base metal around the circumference of the tubing.

However, the observed lives are still measurably lower than for plain pipe, and CTES is proposing a conservative 80% derating factor for untapered bias welds. It is certainly not correct to consider such welds as having effectively the same life expectancy as parent tube, as is sometimes claimed within the industry.

The 1.75" diameter median value data shows excellent correlation between similar wall thickness CT from different Data Sets **A** and **B** (Graph **199**). The relationship is shown in Graphs **81**, **82**, **91** and **232**. This confirms the consistency of bias welds and suggests they should have good field reliability. Graphs **92** and **238** are a little misleading due to the high plain pipe results in Data Set **A** which can be seen in Graph **192**.

There is a very strong relationship between the increasing cycles to failure and wall thickness. This trend is very similar to that observed in the plain pipe data.

The vast majority of the fractures in the bias welded samples are at the intersection of the longitudinal and bias weld, or toe of the bias weld. This area is brought to welding temperature twice and subjected to modified stress distribution resulting from the junction of the two weld beads. If further improvements are to be made in performance of bias welds, the fatigue properties of this junction should be addressed.

5.1.3 Bias Tapered Welds (Graphs 205-206)

The 1.75" diameter bias tapered welds in Data Set **A** in material with 80,000 psi minimum specified yield strength exhibited close data grouping. The cycles to failure were lower than regular bias welded CT made from the same base materials. This relationship can be observed by comparing Graph **199** with Graph **205**. This significant drop in fatigue life may be associated with the stress intensification created by the different wall thicknesses.

The 1.75" diameter bias tapered welds in Data Set **D** in material with 70,000 psi minimum specified yield strength exhibited extremely close data grouping. Results are displayed on Graph **206**. Unfortunately, no plain pipe from this batch of pipe was available to test for comparison. There is no obvious trend toward increasing cycles to failure with increasing wall thickness since all the data for differing wall sizes are clustered together and the wall sizes are also close.

5.1.4 Manual Butt Welds (Graphs 207-217)

It is clear from the Graphs that there is a great deal of scatter in the manual weld results, across all Data Sets, regardless of diameter or wall size. This is further reinforced by the manual weld graphs, numbers **207-217**. To a large extent this is to be expected, given the overall difficulty of the technique and the large number of potential variables from weld to weld.

There are some curious results at 1500 psi which, from simple observation, are clearly below the number of cycles which might be expected based on the corresponding 3000 psi results. A closer examination of these apparent low points was performed.

> In Data Set **A** the manual welds with 0.109" and 0.125" wall thickness resulting in low cycle lives had fractures in the HAZ. Low cycle failures in the HAZ cannot normally be attributed to poor welding, though they may be associated with excessive heat input in thin walled pipe. The low result samples in the same Data Set with 0.134" and 0.156" wall thicknesses had fractures in the fusion zone. The location of these fractures were

observed from the outside diameter. Most fracture initiation points are on the inside diameter, so these cracks may have followed the fusion line or started in the HAZ and propagated to the fusion zone. It is conceivable the low results for these samples could have been due to poor welding.

Data Set **C** has a number of manual welds tested at a single pressure, showing extremely wide variation in observed cycles to failure. The samples with the low lives are divided approximately equally between fractures located in the fusion zone and fractures in the HAZ. It is interesting that none of these samples showed fractures in the weld, where common centerline defects associated with poor welding technique might be located.

The 1.25" diameter manual weld median values compare very well between Data Sets **C** and **E**. Both were tested on 48" bend mandrels, but have different mechanical properties.

The 1.75" diameter data from Data Set **A** and Field Data Sets **3** and **5** show reasonable correlation. There is not as strong a relationship between increasing cycles to failure and wall thickness as was observed for the plain pipe.

Reflecting the overall scatter in the manual weld data, there were also occasionally high cycle lives observed. In a number of cases, manual welds had cycles to failure both above and below those of similar orbital welds. Manual welds clearly have more potential for variation than orbital welds.

Based on median values expressed as a percentage of plain pipe lives, manual welds perform the worst of the weld types tested, though not very different to orbital welds.

5.1.5 Manual Tapered Butt Welds (Graphs 212, 213)

Current field practice is often to avoid joining two different walls sizes with a manual weld. Two such configurations were tested in Data Set **A**, 0.109"/0.125" and 0.156"/0.175". The results (Graphs **212** and **213**) indicate that such a weld has approximately half the life of the equivalent untapered weld where the wall size is the smaller of the two walls in the taper.

5.1.6 Orbital Butt Welds (Graphs 218-226)

The graphs of orbital weld data are displayed by Data Set, CT diameter and wall thickness. Orbital weld data is also summarized in Graphs **218-227**. Orbital weld results exhibit some scatter, but not as much as the corresponding manual welds. Hence, orbital welding cycle life results appear to be more reproducible than those for manual welds and any derating factor based on these results is likely to be rather more reliable.

The majority of the fractures for orbital welds are located in the HAZ, indicating the weld metal is not contributing to premature fracture. The median cycles to failure are generally better than those of manual welds in thin wall sections and clearly higher for those with thicker sections, but not close to those of bias welds. *It is clear that to improve the fatigue performance of orbital welds, the thermal effect of the welding process on the base metal in the HAZ must be addressed.*

The 1.75" orbital welds show reasonable correlation between the data from Data Set **A** and Field Data Set **5**, as observed in Graphs **230**, **234** and **237**. There is no clear relationship between increasing cycles to failure and wall thickness as was observed for plain pipe. This implies increased variability in fatigue performance of orbital welded joints when compared with plain pipe.

5.1.7 Orbital Tapered Butt Welds (Graphs 220, 223)

The same observations made above for manual tapered welds also apply here, namely it is common practice to try and avoid joining two different walls with an orbital butt weld. Two such configurations were tested in Data Set **A**, 0.109"/0.125" and 0.156"/0.175". The results (Graphs **220** and **223**) indicate that such a weld, like the equivalent manual butt welds, has approximately half the life of the equivalent untapered weld where the wall size is the smaller of the two walls in the taper.

5.1.8 Performance of Welds Compared with Plain Pipe

The median value for each series of plain pipe samples from the same data set with the same CT diameter, wall thickness, weld type and test pressure were determined and used as the basis to determine percentage of plain pipe values for each welded sample separately. Median values were preferred in lieu of other statistical methods to minimize the effect of single errant data points. Where plain pipe and welds were tested from material with the same heat and coil history, the percentage of plain pipe value was calculated. Percentage of plain pipe is calculated through dividing the cycles to failure value of the welded CT by the median cycles to failure value for the plain pipe and subsequently multiplying by 100. This percentage minimizes the influence of base material physical and mechanical property variations, allowing some level of comparison between data sets. The percentage of plain pipe average values, along with standard deviations and number of samples used for each type of welded CT joint are displayed in the following table. More detailed breakdowns by data set, diameter, wall thickness and bend radius are in the tables which follow.

Summary:

- The number of cycles to failure increases with increasing wall thickness for a given diameter. The rate of increase does not appear to be related to the D/t ratio.

- Bias welds have significantly higher cycles to failure values than manual or orbital welds for the same conditions.

- Further improvement in the number of cycles to failure as a percentage of plain pipe for bias welds might be achieved if the fatigue properties of the junction between the longitudinal and bias weld seam are improved.

- Orbital welding produces median values of cycles to failure which are slightly higher than manual welds. However, manual welds cycles to failure results are more variable than orbital welds.

- Automation of the welding process produces more consistent results but currently does not always produce better results.
- To improve the fatigue performance of manual and orbital welds, the thermal effect of the welding process on the base metal in the HAZ must be addressed.

Percentage of Plain Pipe Life for Various Weld Types

Weld Type	Pressure	1500	2500	3000	5000	Average
Manual	Avg	30%	59%	48%	76%	47%
	Std Dev	13%	31%	30%	61%	32%
	No.	20	10	54	7	91
Manual Taper	Avg	13%		22%	15%	19%
	Std Dev	6%		2%	6%	6%
	No.	2		6	2	10
Orbital	Avg	41%	29%	68%	43%	62%
	Std Dev	12%	23%	43%	21%	40%
	No.	6	2	36	3	47
Orbital Taper	Avg	16%		22%	22%	21%
	Std Dev	3%		3%	3%	3%
	No.	2		6	2	10
Bias	Avg	71%		79%	91%	80%
	Std Dev	14%		21%	28%	21%
	No.	3		30	4	37
Bias Taper	Avg	36%		52%	54%	49%
	Std Dev	12%		22%	25%	22%
	No.	5		15	5	25

STATISTICAL DISTRIBUTION OF PLAIN PIPE CYCLES TO FAILURE

			1500			3000			5000		
Data Set	Dia - Wall	R	Avg.	Med	Std. Dev.	Avg.	Med	Std. Dev	Avg.	Med	Std. Dev
C	1 25-.087	48"							76	76	•
E	1 25-.087	48"	312	312	8	316	313	87	223	223	87
G-	1 75-.109	48"									
G-	1 75-.125	48"									
G-	1 75-.134	48"									
G-	1 75-.156	48"							146	146	•
G-	1 75-.175	48"									

			250			2500		
Data Set	Dia - Wall	R	Avg	Med	Std. Dev.	Avg.	Med	Std. Dev.
C	1 25-.087	48"	423	423	•	347	324	118
E-	1 25-.087	48"						
G-	1 75-.109	48"				188	176	12
G-	1 75-.125	48"				219	219	9
G-	1 75-.134	48"				283	283	60
G-	1 75-.156	48"	338	338	4	320	312	32
G-	1 75-.175	48"				332	302	59

3-	1 75-.109	72"	859	859	•	331	326	13	94	94	•
5-	1 75-.109	72"				176	134	88			
A-	1 75-.109	72"	705	705	•	288	284	21	85	85	•
5-	1 75-.125	72"				387	386	80			
A-	1 75-.125	72"	552	552	•	346	348	5	163	163	•
B-	1 75-.125	72"				448	441	47			
5-	1 75-.134	72"				453	453	•			
A-	1 75-.134	72"	667	667	•	496	523	87	299	299	•
A-	1 75-.156	72"	788	788	•	586	606	65	420	420	•
A-	1 75-.175	72"	787	787	•	934	889	206	617	617	•
B-	1 75-.175	72"				630	611	58			
A-	1 75-.188	72"	845	845	•	811	903	32	703	703	•

1	2 00-.134	72"				202	197	23			
B-	2 00-.134	72"				218	218	•			
F-	2 00-.190	72"	466	466	87	525	525	101	142	142	3
H	2 375-.190	72"	605	668	149	260	260	•			
2-	2.875-.190	72"	289	277	55	109	109	17			

STATISTICAL DISTRIBUTION OF BIAS WELDS PERCENTAGE OF PLAIN PIPE CYCLES TO FAILURE

			1500			3000			5000		
Data Set	Dia - Wall	R	Avg.	Med	Std. Dev.	Avg.	Med	Std. Dev.	Avg.	Med	Std. Dev.
3-	1.75-.109	72"	55%	55%	•	90%	96%	17%	114%	114%	•
A-	1 75-.125	72"				69%	72%	19%			
B-	1 75-.125	72"				86%	88%	7%			
A-	1 75-.134	72"	73%	73%	•	69%	71%	6%	62%	62%	•
A-	1 75-.156	72"	84%	84%	•	78%	74%	9%	75%	75%	•
A-	1 75-.175	72"				58%	62%	19%			
B-	1 75-.175	72"				105%	106%	24%			

STATISTICAL DISTRIBUTION OF BIAS TAPERED WELDS PERCENTAGE OF PLAIN PIPE CYCLES TO FAILURE

			1500			3000			5000		
Data Set	Dia - Wall	R	Avg.	Med	Std. Dev.	Avg.	Med	Std. Dev	Avg.	Med	Std. Dev.
A-	1 75-.109/.125	72"	45%	45%	•	44%	43%	4%	94%	94%	•
A-	1 75-.125/.134	72"	47%	47%	•	71%	67%	27%	61%	61%	•
A-	1 75-.134/.156	72"	31%	31%	•	41%	44%	7%	34%	34%	•
A-	1 75-.156/.175	72"	17%	17%	•	28%	28%	2%	31%	31%	•
A-	1 75-.175/.188	72"	38%	38%	•	75%	80%	11%	51%	51%	•

STATISTICAL DISTRIBUTION OF MANUAL WELDS PERCENTAGE OF PLAIN PIPE CYCLES TO FAILURE

			1500			3000			5000		
Data Set	Dia - Wall	R	Avg.	Med	Std. Dev.	Avg.	Med	Std. Dev.	Avg.	Med	Std. Dev.
E-	1.25-.087	48"	32%	32%	•	24%	23%	20%	38%	38%	•

			250			2500		
Data Set	Dia - Wall	R	Avg.	Med	Std. Dev.	Avg.	Med	Std. Dev.
E-	1.25-.087	48"				59%	49%	31%

3-	1.75-.109	72"	21%	21%	•	42%	47%	12%	60%	60%	•
5-	1.75-.109	72"				87%	79%	70%			
A-	1.75-.109	72"	30%	30%	3%	39%	42%	7%	126%	126%	•
5-	1.75-.125	72"				56%	58%	26%			
A-	1.75-.125	72"				43%	43%	15%			
5-	1.75-.134	72"				83%	83%	22%			
A-	1.75-.134	72"	43%	43%	30%	47%	50%	8%	68%	68%	•
A-	1.75-.156	72"	13%	13%	•	44%	50%	14%	54%	54%	•
A-	1.75-.175	72"				24%	25%	10%			

1	2.00-.134	72"				66%	67%	12%			
F-	2.00-.190	72"				39%	39%	•	58%	58%	•
4-	2.375-.190	72"				21%	22%	1%	37%	37%	•
2-	2.875-.190	72"	30%	27%	13%	45%	45%	•			

STATISTICAL DISTRIBUTION OF MANUAL TAPERED WELDS PERCENTAGE OF PLAIN PIPE CYCLES TO FAILURE

			1500			3000			5000		
Data Set	Dia - Wall	R	Avg.	Med	Std. Dev.	Avg.	Med	Std. Dev.	Avg.	Med	Std. Dev.
A-	1.75-.109/.125	72"	8%	8%	•	21%	21%	1%	11%	11%	•
A-	1.75-.156/.175	72"	18%	18%	•	24%	25%	2%	20%	20%	•

STATISTICAL DISTRIBUTION OF ORBITAL WELDS PERCENTAGE OF PLAIN PIPE CYCLES TO FAILURE

			1500			3000			5000		
Data Set	Dia - Wall	R	Avg.	Med	Std. Dev.	Avg.	Med	Std. Dev.	Avg	Med	Std. Dev.
5-	1.75-.109	72"				141%	171%	67%			
A-	1.75-.109	72"	24%	24%	•	38%	37%	4%	72%	72%	•
5-	1.75-.125	72"				87%	82%	14%			
A-	1.75-.125	72"	44%	44%	•	39%	44%	11%			
5-	1.75-.134	72"				62%	70%	38%			
A-	1.75-.134	72"	50%	50%	•	34%	34%	8%	49%	49%	•
A-	1.75-.156	72"	57%	57%	•	51%	56%	16%	50%	50%	•
A-	1.75-.175	72"				38%	40%	50%	50%	•	

6-	2.00-.134	72"				86%	92%	21%			
H-	2.375-.190	72"	35%	35%	1%	53%	53%	•			

STATISTICAL DISTRIBUTION OF ORBITAL TAPERED WELDS PERCENTAGE OF PLAIN PIPE CYCLES TO FAILURE

			1500			3000			5000		
Data Set	Dia - Wall	R	Avg.	Med	Std. Dev.	Avg.	Med	Std. Dev.	Avg.	Med	Std. Dev.
A-	1.75-.109/.125	72"	18%	18%	•	21%	21%	2%	24%	24%	•
A-	1.75-.156/.175	72"	14%	14%	•	22%	24%	4%	20%	20%	•

5.2 Observed Effect of Pressure

Pressures ranging from 250 to 5000 psi were applied internally to the samples during each test. As has already been mentioned, the majority of tests for 2" CT and smaller were performed at a pressure of 3000 psi, so the data is naturally biased in favor of this pressure. 2.375" CT and larger was tested mostly at 1500 psi, with a smaller number of tests at 3000 psi, reflecting the fact that this size of tubing is usually subject to lower pressures than smaller pipe.

As with unwelded pipe, the cycle life of pipe containing welds decreases absolutely with increasing pressure (eg Graph **2**). However, if the median observed weld life is plotted as a percentage of the equivalent plain pipe life, it appears in a number of cases that there is a trend towards a greater percentage of life realized with increasing pressure. In other words, the performance of a weld relative to plain pipe improves with increasing pressure. This is illustrated in Graph **227** (1.75" CT in various wall sizes from different sources) where at 1500 psi the weld data falls in a 20-55% band, which at 5000 psi improves to a 50-70% band. However, there are also quite a few exceptions to this trend, particularly between 1500 psi and 3000 psi, so generalizations are dangerous.

Using plain pipe as the reference, the performance of welds at 1500 psi should be substantially better than that at 3000 psi, but with much greater scatter. The latter is because pressure is a very strong driving mechanism in the fatigue process, and serves to reduce the usual stochastic scatter seen in fatigue data. However, there are quite a few examples in this project where the 1500 psi data is no better than, and in some cases rather worse than, the 3000 psi data. Since only one data point was usually recorded at the lower pressure, versus three at the higher, it is difficult to conclude that this represents a definite trend. However, it is reasonable to suppose that there are additional mechanical limits to the life of a weld over and beyond the variables which control fatigue. These might include the influence of stress risers such as grinding marks or imperfections. Hence, however favorable the pressure environment, these mechanical limits still influence the weld life. If the pressure is high, then these additional effects are not seen so clearly because the weld fails before the other mechanical considerations come into play. However, if the pressure is low, then the additional effects have time to accumulate and cause an apparently premature failure. This will be the subject of more detailed discussion in the GRI portion of this project.

Summary:

Weld life decreases with increasing internal pressure.

Weld life expressed as a percentage of plain pipe life for the same test conditions may be greater at high pressures than at low.

5.3 Observed Effect of CT Wall Size

The median cycles to failure for Data Set A are plotted against wall thickness for plain pipe, manual, orbital and bias welded samples on Graphs **45** to **48**.

As expected, the data for plain pipe show a clear trend toward increasing cycles to failure with increasing wall thickness. It is noticeable that the higher pressure tests have a more consistent trend than lower pressure tests. The same pattern of increasing cycles to failure with greater wall thickness is also evident in the bias and orbital weld data. Manual welds show a slight trend toward increasing cycles as wall thicknesses increase to about 0.134" diameter. Beyond this point the 1500 and 3000 psi tests median values flatten or decline. It may be significant that 0.134" is the wall thickness where most welding operations go from single to multipass techniques, and variability could be associated with the increased number of starts and stops. In welding CT in the fixed 5G position welding progresses uphill from the 6 o'clock position to the 12 o'clock position. In multipass welds the starts and stops must be aligned at these positions, potentially compounding the effect of imperfections in superimposed starts and stops.

Comparing the percentage of plain pipe cycles to failure to the wall thickness on Graphs **49** to **51** indicates no clear trend for any welded joint. Bias welds tested at 3000 and 5000 psi tend to decline with increasing wall thickness, while 1500 psi tests increase. Manual welds tested at 1500 and 5000 psi tend to show declines with increasing wall thickness, while tests at 3000 psi show little change. Orbital welds tested at 1500 psi increase, those at 3000 psi are variable, and those tested at 5000 psi tend to decrease. In all three graphs the percentage values tend to reduce variability with increasing wall thickness. That is to say there is the greatest variability between values of percentage of plain pipe at the 0.109" wall thickness.

Summary:

- Fatigue life of welds, like that of unwelded pipe, increases with increasing wall thickness.
- Result of thicker walled tests tend to be more consistent than thinner walled tests.
- Changing from single to multiple welding passes may influence the weld performance. This requires more investigation.

5.4 Observed Effect of CT Diameter

In order to determine the influence of tubing diameter on the cycle life of CT, a comparison should be made between tests performed using material from the same raw material batch (heat), with the same wall thickness and tested at the same pressure. In practice, it is often necessary to compare tubing of the same nominal material type (for example, 80 KSI yield) in the knowledge that this minimum specification allows for a range of actual material properties which might confuse the comparison.

For this project, it is possible to look at the general trend by taking data from multiple data sets for 0.134" and 0.190" wall sizes that are equivalent over a range of diameters. These results are shown in Graphs **265** to **270** for plain pipe, manual and orbital welds.

The observed trends agree with previously reported results that coiled tubing life decreases as the nominal diameter increases.

Diameter Growth

The sample diameter in the proximity of the weld was measured at the end of each test on two axes, major and minor.

Previous work has demonstrated an approximately linear relationship between diameter growth and cycles. Based on this assumption, an estimate of the diameter growth rate can be made for each sample tested using the following formula:

$$G = \frac{D_f - D_I}{D_I} x \frac{100}{N_{FTM}}$$

where: D_f = Final Maximum Diameter (in)
D_I = Initial Nominal Diameter (in)
N_{FTM} = Number of Cycles (Fatigue Test Machine)

AVERAGE PERCENTAGE GROWTH RATES of 1.75" CT

Wall Size	Plain Pipe	Bias Weld	Orbital	Manual	Bias Tapered
0.109"	0.0767%	0.0354%	0.0860%	0.0990%	0.0507%
0.125"	0.0335%	0.0261%	0.0361%	0.0297%	0..0453%
0.134"	0.0146%	0.0163%	0.0237%	0.0169%	0.0216%
0.156"	0.0134%	0.0107%	0.0361%	0.0310%	0.0141%
0.175"	0.0058%	0.0056%	0.0056%	0.0064%	0.0057%
0.188"	0.0030%				

The percentage growth rates remain fairly constant between the various welding processes for a given wall size, as can be seen on the Percentage Growth Rate Graphs **315-319**. There is an observed reduction in the growth rate as the wall thickness increases. As the wall thickness increases, the pipe becomes more rigid and provides greater stability to cylindrical form. The percentage diameter growth rates are measures of deformation per unit length and are essentially equivalent to strain measurements. A theoretical average plastic strain per cycle experienced on the circumference can be estimated by multiplying the percentage diameter growth by π. The 0.109" wall thickness samples experienced between 0.11% theoretical average strain per cycle for bias welds, to 0.31% for manual welds. These amounts of strain are significant when the amount of plastic deformation defining the yield strength of materials is 0.2%.

Application of pressure on the inside of the CT creates hoop stresses on the pipe, and axial tensile load due to pressure applied to the end caps. Hoop stresses generated during testing varied from 1400 psi to 40,000 psi, or approximately from 1.75% to 50% of the minimum specified yield strength. Applied tensile stresses due to hydrostatic pressure on the end caps range from 99 psi to 17,300 psi in 1.25" pipe, but are below 4800 psi in 1.75" diameter and larger pipe. These hydraulically applied tensile stresses are not considered separately in this study, because they are small in comparison with the yield stress, which is exceeded during testing.

An important limit to acceptable CT diameter growth is the clearance between the tubing and the internal diameter of the brass inserts in the stripper. This limit is about 0.050", which can be reached with as little as 6% increase in diameter.

A second noticeable effect of the internal pressure is that the diameter growth at any given number of cycles is less with decreasing pressure. Or, conversely, the number of cycles required for a fixed expansion increases as pressure decreases. The data points at failure congregate along a linear trend line, suggesting an inverse relation between diameter expansion and number of cycles to failure, related to test pressure. Higher test pressures increase diameter expansion rates per cycle and decrease total cycles to failure.

Summary:

- The percentage growth rate declines with increasing diameter
- The percentage growth rate does not vary significantly between different welding processes.

5.5 Observed Effect of Bending Radius

Two bending mandrels were available for testing, one of 48" radius and the other 72".

All tests on 1.25" CT were performed at 48" bending radius.

All tests on 1.75" CT and larger were performed at 72" bending radius, except for Data Set G (1.75" CT). It was intended to perform tests on 1.75" at two bending radii to allow a comparison of results and hence evaluate the effect of bending radius on weld life, but a predominant number of fractures in the lower section of the pipe near the mounting bracket, well below the center section of the bending mandrel, were observed. The 48" radius was determined to be too severe for testing 1.75" diameter CT for the purposes of this project and all subsequent testing was switched to the 72" radius bend fixture. This decision was taken in conjunction with Quality Tubing Inc., who were performing parallel testing on their own FTM at the same time for the same tubing configuration and had observed similar results. This decision was taken before any welds were tested, thus all results in Data Set G are for unwelded pipe.

Hence, data is not available in this project for the same weld and tubing configuration at different bending radii. The following table of results is presented for plain pipe for the sake of completeness.

MEDIAN CYCLES TO FAILURE OF PLAIN PIPE AT TWO DIFFERENT BEND RADII

CT Size	Data Set A 72"R, 1500 psi	Data Set G 48"R, 250 psi
1.75" OD 0.156" Wall	788	338

CT Size	Data Set A 72"R, 3000 psi	Data Set G 48"R, 2500 psi
1.75" OD 0.109" Wall	284	175
1.75" OD 0.125" Wall	348	219
1.75" OD 0.134" Wall	523	262.5
1.75" OD 0.156" Wall	606	311.5
1.75" OD 0.175" Wall	888.5	302

CT Size	Data Set A 72"R, 5000 psi	Data Set G 48"R, 5000 psi
1.75" OD 0.156" Wall	420	146

Summary:

- Data is not available to compare the relative effect of bending radius on welds with that on plain pipe.

5.6 Observed Effect of CT Material

5.6.1 Material Strength

Classical high endurance limit fatigue studies have shown that fatigue limits for heat treated steels are proportional to their ultimate tensile strength. Similar results have been shown with CT fatigue studies. The cycles to failure generally increase with increasing coiled tubing tensile strength, although some departures have been noted at low pressures. Higher tensile strength usually means greater difficulty in welding. The weldability or the relative ease of welding, of steel material, usually drops as tensile strength increases. Reduced weldability in higher strength steel weldments usually requires preheat, postweld heat treatment and other precautions to prevent weld bead cracking. In this study there were insufficient samples of significantly different tensile strength to seriously consider the influence of material strength on CT fatigue life. The potential interaction of anticipated increasing fatigue life with simultaneously decreasing weldability in higher strength materials is an area of potential future study.

5.6.2 Surface Condition

Nearly all recorded fatigue fractures in this study originate and propagate from surface locations, so it follows that the condition of the surface can play an important life in cycle life. The finding in Dr Tipton's report, that some of these fractures are associated with rough grinding striations on the surface, leads to consideration of surface roughness and condition. Grinding marks act as stress risers in the material surface. The deeper and courser the marks, the higher the stress riser. Whenever grinding must be employed, the direction of grinding should be in the same direction as the principal applied fatigue stress. The finished ground surface should have the smoothest finish practical to minimize stress risers.

Summary:

- Insufficient data is available to compare the effect of material type on weld performance.

5.7 X-Ray Inspection

5.7.1 Definition and Description of Weld Discontinuities

Weld discontinuities found by radiographic examination are interruptions of the typical weld or surrounding base material structure. They represent the absence of homogeneity in the mechanical, physical or metallurgical characteristics of the material. A weld defect or flaw is a discontinuity or collection of discontinuities which render the weld or finished part unsuitable for its intended purpose. Discontinuities which appear in CT welds and are detectable by radiographic methods include the following.

Burn Through (BT)	This discontinuity normally occurs in the 11 o'clock to 1 o'clock position, when excessive heat causes melt off of the root of the weld.
Crack	A linear fracture type discontinuity characterized by a sharp crack tip.
Inadequate penetration (IP)	A condition where the weld metal does not extend through the joint thickness to the joint root.
Incomplete Fusion (IF)	A discontinuity where fusion does not occur between the weld bead and the base metal fusion face or previously deposited weld metal.
Internal concavity (IC)	This discontinuity normally occurs at the 5 o'clock to 7 o'clock position, when the weight of molten metal sags downward, leaving depression on the inside diameter profile on the root section. Sometimes called suck back.
Misalignment	ID to OD mismatch occurring during weld joint alignment, normally associated with used pipe, resulting in wall thinning when the finished weld joint is ground flush.
Porosity	Cavity-type discontinuities formed by gas entrapment during solidification. Porosity can be either single pockets or clusters of associated pockets of gas.
Tungsten Inclusion	Droplets from tungsten electrodes that transfer during welding and become embedded in the weld bead.

5.7.2 Standards

The accepted standard for performing radiographic inspection of CT are the following.

- ASME Section V Article 2, Radiographic Examination.
- ASTM E94 Standard Recommended Practice for Radiographic Testing
- ASTM E142 Standard Method for Controlling Quality of Radiographic Testing
- ASTM E747 Controlling Quality of Radiographic Testing Using Wire Penetrameters
- ASTM E1032 Radiographic Examination of Weldments.

None of these specifications control the acceptance criteria for radiographic examination and there is no clear industry accepted acceptance criteria for CT. There are variations in acceptance criteria between different users. The CT manufacturers currently inspect using 2T image quality indicators or penetrameters, which define an image equal to 4% of the thickness of the CT being inspected. All identifiable imperfections which exceed this minimum size are cause for rejection of the radiographed weld.

5.7.3 Ranking of Discontinuities by Severity

Fatigue is a progressive failure mechanism due to cyclic loading. Fatigue preferentially originates at locations where notches cause stress concentrations. In CT welds, discontinuities can create such stress concentrations. Fatigue cracks and progress until failure occurs or the applied stress emanating from cyclic loading is transferred to another point. In the case of CT, it is common for several cracks to initiate, however the one carrying the greatest cyclic stress will progress to failure.

It appears reasonable to assume that a weld defect situated in the applied stress field will produce a stress concentration and hence lower fatigue life. The degree to which these discontinuities can degrade the expected fatigue life varies with the size and shape of the imperfection(s). Additionally, the basic stress concentrations defined by the weld joint geometry can be more severe than those produced by weld discontinuities.

The size and shape of welding discontinuities in the weld bead will have a major influence on the propagation of fatigue cracks. Evaluation of the relative severity of common discontinuities is simplified by grouping them into three types.

1. Embedded volumetric discontinuities, porosity, tungsten inclusions and slag inclusions.

2. Planar discontinuities, including cracks and crack like flaws such as incomplete joint penetration or incomplete fusion.

3. Shape imperfections, including undercut, misalignment and burn through.

The embedded volumetric discontinuities are the most benign. Experimental work carried out on the effect of different defects showed some porosity and slag inclusions could be tolerated in an average butt weld without giving reduction to fatigue strength. Tungsten inclusions in aluminum alloy welds were found to not effect the fatigue behavior of the weld. Scattered porosity, with its round shape, has a relatively low stress intensification and very high fatigue strength in studies. Limits established for porosity in fatigue assessment are designed to prevent masking of other more important flaws during inspection. CT welds with ground surfaces revealing porosity breaking the surface are far more serious. The fatigue strength of flush ground groove welds can be significantly reduced when embedded porosity is exposed during grinding. Aligned porosity can provide a linear path for fatigue cracks to propagate along, so is considered more serious than scattered porosity. Aligned porosity can also indicate the presence of a more serious defect like lack of penetration.

The planar defects are by far the most serious of the discontinuities. Planar discontinuities are characterized by sharp tips and high ratio of length and width to opening displacement. These types of discontinuities are assessed as cracks, often using fracture mechanics criteria. The sharper the crack tip and the larger the cross sectional area of the crack face is, the higher the stress intensification factor will be. Discontinuities with higher stress intensification factors are more potentially damaging with higher fatigue crack growth rates.

The shape imperfections can influence the fatigue life of welded joints by enhancing existing regions of stress concentration, primarily the weld root and toe undercut. They should be assessed as features which could reduce the fatigue life. They also have the capability of increasing total applied stress in weld joint through reducing bearing load area. Shape imperfections become increasing important when they occur in conjunction with planar or volumetric discontinuities, where increased stress and potential fracture plains are created between the discontinuities.

5.7.4 Correlation Between Discontinuities and Observed Performance

Radiographic examination of CT welds is performed to identify, nondestructively, these discontinuities which may be capable of reducing the functional life of the CT. Fatigue cycle life can be severely reduced by injurious weld defects. Particularly, continuous and sharp edged defect are known to reduce fatigue life in structural members. Planar defects such as cracks, incomplete penetration, and lack of fusion would be considered most detrimental to fatigue life. Random porosity is rounded and isolated in nature and offers less of a risk to fatigue life. When porosity aligns in the weld centerline, the discontinuities take on a linear aspect and become more critical. Manufacturers and service companies routinely radiographically (RT) inspect welds to identify and eliminate the potentially deleterious defects.

Welds containing radiographic discontinuities, particularly planar discontinuities, would be expected to fail at lower fatigue cycle lives than similar materials with no discontinuities in the welds. Examination of the data graphs containing radiographic results clearly indicates this is not he general case. Graphs containing radiographic results are numbers **4, 11, 18, 25, 32, 55, 66, 96, 98, 135, 143, 147, 151, 154, 158** and **163**. Repeatedly, manual and orbital welds containing radiographically acceptable welds have lower fatigue life cycles than welds containing identified discontinuities in sets of similar CT material and test conditions.

Radiography is adept at identifying internal discontinuities as variations in film density (noticeable changes in shading on the radiograph film). As joint section size decreases, radiography becomes more sensitive as an inspection method. CT tubes are thin walled sections by most radiographic methods, so it is possible to detect and evaluate quite critically. It is possible to identify and evaluate discontinuities that will not adversely effect fatigue cycle life. Radiography does not easily reveal very narrow discontinuities, such as cracks, laps, or laminations which are aligned with the axis of the ionizing radiation beam. It is conceivable that critical defects, capable of severely reducing fatigue cycle life, aligned with the beam of the radiographic source, might not be detected.

A review of the manual and orbital welds from all data sets indicated the manual welds were accepted 43% of the time and orbital welds were accepted 40% of the time. A summary of the number of accepted and rejected welds, categorized by weld type and pipe size - wall thickness combination is attached in the following tables. The overall acceptance rate is below the acceptance rate for most commercial welding establishments.

REVIEW OF RADIOGRAPHIC FINDINGS

	Manual Welds				
	Original Interpretation			B31.3 Interpretation	
	Accepted	Rejected	Original Acceptance Rate (%)	Additional Accepted to B31.1	B31.1 Acceptance Rate (%)
1.25" OD 0.087" Wall	2	8	20%		
1.25" OD 0.109" Wall					
1.75" OD 0.109" Wall	4	10	29%	6	71%
1.75" OD 0.109" Wall (Field)	5	0	100%		
1.75" OD 0.125" Wall	2	7	22%	6	89%
1.75" OD 0.134" Wall	1	6	14%	4	71%
1.75" OD 0.156" Wall	3	2	60%	1	80%
1.75" OD 0.175" Wall	0	5	0%	3	60%
1.75" OD 0.109"/0.125" Wall	3	2	60%	1	80%
1.75" OD 0.156"/0.175" Wall	1	4	20%	2	60%
2.375" OD 0.190" Wall	4	1	80%	0	80%
2.375" OD 0.190" Wall (Field)	4	0	100%		
2.875" OD 0.190" Wall (Field)	4	4	50%		
3.50" OD 0.190" Wall (Field)	4	1	80%		
COLUMN TOTALS	37	50	43%	23	69%
PROCESS TOTALS		87			
1.75" & 2.375" WELDS	20	45	31%	23	66%

	Orbital Welds				
	Original Interpretation			B31.3 Interpretation	
	Accepted	Rejected	Original Acceptance Rate (%)	Additional Accepted to B31.1	B31.1 Acceptance Rate (%)
1.25" OD 0.087" Wall	0	2	0%		0%
1.25" OD 0.109" Wall	0	2	0%		0%
1.75" OD 0.109" Wall	1	5	17%	4	83%
1.75" OD 0.109" Wall (Field)					
1.75" OD 0.125" Wall	0	6	0%	5	83%
1.75" OD 0.134" Wall	3	2	60%	2	100%
1.75" OD 0.156" Wall	4	1	80%	1	100%
1.75" OD 0.175" Wall	1	5	17%	3	67%
1.75" OD 0.109"/0.125" Wall	5	0	100%	0	100%
1.75" OD 0.156"/0.175" Wall	1	5	17%	4	83%
2.375" OD 0.190" Wall	4	0	100%	0	100%
2.375" OD 0.190" Wall (Field)					
2.875" OD 0.190" Wall (Field)					
3.50" OD 0.190" Wall (Field)					
COLUMN TOTALS	19	28	40%	19	81%
PROCESS TOTALS		47			
TOTAL MANUAL & ORBITAL		134			
1.75" & 2.375" WELDS	19	28	40%	19	81%

	Manual & Orbital Welds Combined				
	Original Interpretation			B31.3 Interpretation	
	Accepted	Rejected	Original Acceptance Rate (%)	Additional Accepted to B31.1	B31.1 Acceptance Rate (%)
COLUMN TOTALS	56	78	42%	42	73%
1.75" & 2.375" WELDS	39	73	35%	42	72%

ATS were of the opinion that the original interpretation was performed to an acceptance criteria which was excessively stringent. Available radiographs were reviewed to the radiographic requirements of ANSI B31.3, *Chemical Plant and Petroleum Refinery Piping* Specification.

Since RT interpretation is a subjective evaluation, the same radiograph may be accepted or rejected by different inspectors. Indeed, radiographs may be rejected for different reasons by different inspectors. The American Society for Nondestructive Testing (ASNT) has recognized this and developed a method of standardized training and certification of radiographers. This has made interpretation of radiographs more precise and reproducible than in the past, but variations in interpretation still exist. Care must be taken to understand the results of this investigation were taken from results obtained from several different interpreters working independently. It is possible that variations in interpretation exist within the data which are not accounted for in this discussion.

The results of the interpretation to ANSI B31.3 are also shown on the table Review of Radiographic Findings. No radiographs found acceptable originally were rejected to ANSI B31.1. Forty two (42) welds originally rejected were found acceptable to ANSI B31.3. This represents 31% of a total 134 welds with radiographs, and 44% of the 94 radiographs reviewed. The large number of changes is primarily due to differences in the acceptance criteria used. The number of radiographs remaining unacceptable to ANSI B31.3 after review to the more tolerant acceptance criteria is still high at 36 radiographs not meeting the acceptance criteria of ANSI B31.3. (27% of the total).

The results of the review to ANSI B31.3 were plotted on Graphs **5**, **12**, **19**, **26** and **33** identified by "with B31.3 Radiographic Interpretation". These graphs still contain a number of welded joints with rejected radiographs outperforming welds with acceptable radiographs. Radiographic results were not a good predictor of weld fatigue cycle life in this experiment. This is not to say radiography is not a valuable tool for CT applications - it is obviously essential to identify serious discontinuities. However, it appears that many imperfections detected by radiography do not have a significant effect on the weld performance and reliance on this technique alone may be misleading.

All welds were inspected to determine the location failure occurred. The manual and orbital welds receiving RT are identified by fracture location and pipe size - wall thickness combination in the attached two tables Original Radiographic Interpretation ad Radiographic Interpretation to ANSI B31.3. Only eight (8) welds failed in the weld metal and another forty four (44) failed in the fusion zone. The remaining 67 welds failed in the HAZ or base metal. The original interpretation divided welds with fractures in the fusion zone, HAZ and base metal approximately evenly between acceptable and rejected radiographic results. One of the eight welds with a fracture in the weld was accepted originally. After evaluation to ANSI B31.3, six of the eight fractures occurring in the weld were judged acceptable. The trend toward accepting more radiographs continues with welds containing fractures in other zones. This supports the finding that radiography is not a reliable predictor of fatigue life of welded pipe.

ORIGINAL RADIOGRAPHIC INTERPRETATION

	Acceptable Welds							
	Manual				Orbital			
	Weld	Fusion	HAZ	Base Metal	Weld	Fusion	HAZ	Base Metal
1.25" OD 0.087" Wall		1	1					
1.25" OD 0.109" Wall								
1.75" OD 0.109" Wall		1	2				1	
1.75" OD 0.109" Wall (Field)			5					
1.75" OD 0.125" Wall			1					
1.75" OD 0.134" Wall		1					3	
1.75" OD 0.156" Wall		1	2				4	
1.75" OD 0.175" Wall							1	
1.75" OD 0.109"/0.125" Wall		3					5	
1.75" OD 0.156"/0.175" Wall			1				1	
2.375" OD 0.190" Wall	1		2			3		
2.375" OD 0.190" Wall (Field)		5						
2.875" OD 0.190" Wall (Field)		4						
3.50" OD 0.190" Wall (Field)		2	2					
COLUMN TOTALS	1	18	16	0	0	3	15	0
% OF PROCESS TOTAL	3%	51%	46%	0%	0%	17%	83%	0%
PROCESS TOTALS				35				18
NOT TESTED				2				1
TOTAL				37				19

	Rejected Welds							
	Manual				Orbital			
	Weld	Fusion	HAZ	Base Metal	Weld	Fusion	HAZ	Base Metal
1.25" OD 0.087" Wall		5	2	1		2		
1.25" OD 0.109" Wall						2		
1.75" OD 0.109" Wall			7				5	
1.75" OD 0.109" Wall (Field)								
1.75" OD 0.125" Wall	1			1		1	3	
1.75" OD 0.134" Wall	2	2	2			1	1	
1.75" OD 0.156" Wall		2	1				1	
1.75" OD 0.175" Wall	3	1					3	
1.75" OD 0.109"/0.125" Wall		2						
1.75" OD 0.156"/0.175" Wall			4				4	
2.375" OD 0.190" Wall		2		1				
2.375" OD 0.190" Wall (Field)								
2.875" OD 0.190" Wall (Field)	1	2						
3.50" OD 0.190" Wall (Field)		1						
COLUMN TOTALS	7	17	16	3	0	6	17	0
% OF PROCESS TOTAL	16%	40%	37%	7%	0%	26%	74%	0%
PROCESS TOTALS				43				23
NOT TESTED				7				5
TOTAL				50				28

RADIOGRAPHIC INTERPRETATION TO ANSI B31.3

	Acceptable Welds							
	Manual				Orbital			
	Weld	Fusion	HAZ	Base Metal	Weld	Fusion	HAZ	Base Metal
1.25" OD 0.087" Wall		1	1					
1.25" OD 0.109" Wall								
1.75" OD 0.109" Wall		1	8				5	
1.75" OD 0.109" Wall (Field)			5					
1.75" OD 0.125" Wall	1		1	1		1	3	
1.75" OD 0.134" Wall	2	2	1			1	4	
1.75" OD 0.156" Wall		3	2				5	
1.75" OD 0.175" Wall	2						3	
1.75" OD 0.109"/0.125" Wall		5					5	
1.75" OD 0.156"/0.175" Wall			4				4	
2.375" OD 0.190" Wall	1		2	1		3		
2.375" OD 0.190" Wall (Field)		5						
2.875" OD 0.190" Wall (Field)		4						
3.50" OD 0.190" Wall (Field)		2	2					
COLUMN TOTALS	6	23	26	2	0	5	29	0
% OF PROCESS TOTAL	11%	40%	46%	4%	0%	15%	85%	0%
PROCESS TOTALS				57				34
NOT TESTED				4				5
TOTAL				61				39

	Rejected Welds							
	Manual				Orbital			
	Weld	Fusion	HAZ	Base Metal	Weld	Fusion	HAZ	Base Metal
1.25" OD 0.087" Wall		5	2	1		2		
1.25" OD 0.109" Wall						2		
1.75" OD 0.109" Wall			1				1	
1.75" OD 0.109" Wall (Field)								
1.75" OD 0.125" Wall								
1.75" OD 0.134" Wall		1	1					
1.75" OD 0.156" Wall			1					
1.75" OD 0.175" Wall	1	1					1	
1.75" OD 0.109"/0.125" Wall								
1.75" OD 0.156"/0.175" Wall			1				1	
2.375" OD 0.190" Wall		2						
2.375" OD 0.190" Wall (Field)								
2.875" OD 0.190" Wall (Field)	1	2						
3.50" OD 0.190" Wall (Field)		1						
COLUMN TOTALS	2	12	6	1	0	4	3	0
% OF PROCESS TOTAL	10%	57%	29%	5%	0%	57%	43%	0%
PROCESS TOTALS				21				7
NOT TESTED				5				1
TOTAL				26				8

5.8 Hardness Measurements

5.8.1 Hardness Measurement Techniques

Hardness is a measurement of a material's resistance to penetration by an indentor impressed into the metal. In coiled tubing it is used as a loose approximation of relative tensile strength and a measure of flow stress in the material. Tests on CT are normally performed by either the static indention method or rebound test method.

Static indention methods employ ball, conical or pyramid indentors, forced into the metal surface. The relationship between the applied load and the depth or area of the indention determines the hardness measurement number. Brinell, Knoop, Rockwell and Vickers test methods are static indention hardness test methods.

Rebound methods employ an impacting object of standard mass and dimensions, accelerated into the metal surface. The object rebounds from the metal surface and the height or length of the rebound is measured to determine the hardness number. Equotip and Scleroscope test methods are rebound test methods.

Conversion of harness test numbers between different scales is influenced by variations from different test methods and tested material characteristics. In spite of the number of scientific reasons that hardness conversions should be inherently inaccurate, they are surprisingly reliable and useful tools in the CT industry. Several series of data in this report use converted data. One set of data is Vickers converted to Rockwell B and the other is Equotip converted to Rockwell B. In each case the readings converted are averages of multiple indentions to reduce variation. In a third case microhardness readings on several test pieces were converted to Rockwell B. In this case the specimens tested were not of sufficient size to allow multiple indentions. Unusual readings were explored with multiple indentions where practical, and multiple specimens were employed to confirm trends observed.

When working on materials which obey Hook's law and have similar modulus of elasticity to heat treated low alloy steels, hardness indentions can be used to approximate the tensile strength of a metal tested. This must be done recognizing it is another conversion, incorporating all the potential inaccuracies of conversions between measurement scales and only a crude approximation.

The composition of the steels used in the fatigue testing are ASTM A606 Type 4, modified for application as coiled tubing. Calculating the hardenability of these materials from their chemistry, reveals they are not very responsive to heat treatment. Hardenability is the relative capability of a ferrous alloy to strengthen when quenched from a temperature above the critical temperature. Hardenability only measures an alloys response to transformation strengthening during thermal cycling and not the effects of solid solution strengthening or dispersion hardening which may also be strengthening systems for these alloys. One of the functions in calculating hardenability is determining the ideal critical diameter or the maximum diameter which can be possibly hardened to 100% martensite with an "ideal quench". The chemical ideal critical diameters (DI) for the heats used in the study are all below 1.6 inches. For comparison, AISI 4140 will produce DI's between 3.1 and 7.0 inches. The result is a calculated Jomminy hardenability of 31 HRC maximum at 1/4" distance from the end and declining from that. Since cooling from above the critical temperature around a weld is nowhere near an "ideal quench", the maximum hardnesses in the weld and HAZ area may be expected in the lower 20's on the HRC scale.

This means the base material next to a weld in coiled tubing may not experience a significant changes in hardness, even when rapidly cooled by chill blocks. The results should not be expected to reveal any areas of highly hardened material.

5.8.2 Axial Variation of Hardness

Data from Field Data Sets 2, 3 and 4:

Welded specimens submitted for fatigue testing, included in Data Sets **2**, **3** and **4**, had Equotip hardness reading submitted in addition. These data were all supplied from the same source, so can be compared between Sets on the basis of effect of welding on hardness. Three Equotip readings were taken at each of three locations around the pipe, separated by 120° on the pipe circumference. Sets of reading were performed in the weld and each HAZ. Each set of three Equotip readings at a single location were averaged and the average converted to a Rockwell B number. The converted numbers are reported in the Table on the next page to better visualize the results of these data.

The three hardness readings, taken at three circumferential locations were averaged and those averages graphically displayed as a function of the location along the length of the pipe relative to the weld to better visualize the results of these data. Separate graphs, numbers 359 to 363, display average results for each size pipe and a compilation displaying the average of all five size averages with error bars indicating the spread of the averaged data.

The hardness data for the 1.75" OD 0.109" wall pipe is low, being approximately equivalent to 64 to 66 ksi tensile in the HAZ and 69 ksi in the weld. These low numbers are least in part related to the 0.109" wall thickness being below the 0.122" minimum thickness recommended for testing unsupported with the standard "D" impact device. The data do indicate the relative hardness for the weld is higher than the HAZ, implying the weld is stronger.

The hardness data for the 2.375" OD 0.190" wall indicates the HAZ has maintained the base material strength, being approximately equivalent to 76 to 81 ksi, while the weld is approximately 82 ksi. With the exception of two HAZ high hardness values the weld is harder than the HAZ.

Hardness Values from Field Data Sets 2, 3 and 4

Specimen	Location	HAZ "A"	Weld	HAZ "B"
1.75" OD - 1	0°	76.9	80.0	79.5
	120°	70.5	78.5	76.9
	240°	78.0	80.0	79.5
WELD #1	Avg	75.1	79.5	78.6
1.75" OD - 2	0°	72.9	79.5	77.4
	120°	71.7	79.0	74.1
	240°	70.5	81.0	75.2
WELD #2	Avg	71.7	79.8	75.6
1.75" OD - 3	0°	76.3	74.1	71.7
	120°	67.9	62.4	65.2
	240°	69.2	80.0	74.1
WELD #3	Avg	71.1	72.2	70.3
1.75" OD - 4	0°	69.8	76.3	74.1
	120°	81.5	79.0	80.5
	240°	74.1	80.5	72.9
WELD #4	Avg	75.1	78.6	75.8
1.75" OD - 5	0°	74.1	76.3	74.7
	120°	75.8	79.5	78.0
	240°	71.7	72.3	74.1
WELD #5	Avg	73.9	76.0	75.6

Specimen	Location	HAZ "A"	Weld	HAZ "B"
2.375" OD - 1	0°	91.8	86.4	82.0
	120°	84.7	88.8	84.3
	240°	80.0	81.5	83.8
WELD #1	Avg	85.5	85.6	83.4
2.375" OD - 2	0°	84.7	89.6	82.4
	120°	80.5	86.4	87.2
	240°	82.0	86.0	84.7
WELD #2	Avg	82.4	87.3	84.8
2.375" OD - 3	0°	85.1	87.7	85.1
	120°	76.9	84.7	86.4
	240°	82.9	84.7	86.0
WELD #3	Avg	81.6	85.7	85.8
2.375" OD - 4	0°	85.1	87.2	85.6
	120°	82.4	86.0	86.4
	240°	84.7	87.7	85.6
WELD #4	Avg	84.1	87.0	85.9
2.375" OD - 5	0°	83.8	86.0	88.4
	120°	86.0	82.9	85.1
	240°	79.5	87.7	86.4
WELD #5	Avg	83.1	85.5	86.6

Readings are Rockwell B converted from Equotip hardness values

Each Equotip value is an average of three seperate Equotip readings

Hardness Values from Field Data Sets 2, 3 and 4

Specimen	Location	HAZ "A"	Weld	HAZ "B"
2.875" OD - 1	0°	86.0	84.3	87.2
	120°	80.0	81.0	84.3
	240°	85.1	86.4	86.0
WELD #1	Avg	83.7	83.9	85.8
2.875" OD - 2	0°	77.4	87.2	86.4
	120°	88.4	89.6	82.0
	240°	85.6	87.7	82.4
WELD #2	Avg	83.8	88.2	83.6
2.875" OD - 3	0°	86.4	83.4	84.3
	120°	80.0	87.7	82.9
	240°	84.7	85.6	86.0
WELD #3	Avg	83.7	85.6	84.4
2.875" OD - 4	0°	83.4	83.8	83.8
	120°	83.4	87.2	82.9
	240°	86.4	86.0	83.4
WELD #4	Avg	84.4	85.7	83.4

Specimen	Location	HAZ "A"	Weld	HAZ "B"
3.5" OD - 1	0°	77.4	84.7	80.5
	120°	76.3	82.4	82.4
	240°	82.0	90.0	78.5
WELD #1	Avg	78.6	85.7	80.5
3.5" OD - 2	0°	82.9	91.4	78.5
	120°	77.4	86.0	82.4
	240°	82.0	86.4	79.5
WELD #2	Avg	80.8	87.9	80.1
3.5" OD - 3	0°	80.0	85.1	78.0
	120°	82.4	85.1	81.0
	240°	79.5	85.6	79.0
WELD #3	Avg	80.6	85.3	79.3
3.5" OD - 4	0°	79.5	85.6	80.0
	120°	79.5	85.1	83.8
	240°	81.5	86.8	80.5
WELD #4	Avg	80.2	85.8	81.4

The hardness data for the 2.875" / 0.190" wall pipe has one unusual hardness in the weld of sample number 5 (test no FS2-9). The radiograph for this weld indicated it had a tungsten inclusion and it only ran 52 cycles at 250 psi in the fatigue test. With the additional exception of HAZ "B" in Weld #1, the remaining weld hardnesses are higher than the surrounding HAZ areas. The high hardness in Weld #1 HAZ is unexplained, but is not exceptionally high when compared with other HAZ areas.

The hardness data for the 3.5: OD 0.190" wall pipe shows excellent consistency through the six samples, with the weld being harder than the HAZ in all cases. The hardnesses in the HAZ areas vary from averages of 78 to 83.5 HRB. These hardness numbers convert to approximately 69 to 72 ksi tensile strength. These numbers may indicate the HAZ underwent softening due to weld heat or fatigue related phenomenon. It is difficult to draw a conclusion from this data, because it includes inaccuracies of a small hardness indention, hardness conversion, tensile approximation, and unknown pipe surface condition factors.

Comparing the data of all four sizes, the hardness of the filler metal is very consistent with the exception of the 1.75" OD 0.109" wall which may be influenced by the wall thickness. The hardness values convert to approximately 78 to 79 ksi tensile, which is consistent with expected tensile values for the E-70S-6 filler metal used.

Data from Field Data Sets 5 and 6:

Specimens submitted from Field Data Sets 5 and 6 came from the same source and were accompanied by some hardness data. The hardness data were identified by coil number. The samples were reported to have come from tapered strings so identification by wall thickness is not possible. Samples 1, 2, 3, 4, 5, and 6 were from 1.75" OD CT coils. The specimens tested were removed from tapered string coils, so identification of wall thickness in the hardness data is not possible. Sample 7 was from 2.0" OD 0.134" Wall CT. Samples 8, 9, and 10 were not identified by specific coil number.

Hardness measurements were taken at the weld centerline. 0.5 mm on each side of the centerline in the HAZ and 2 mm from the weld centerline in the base metal. Three impressions were taken at each weld and HAZ location and two taken in each base metal location. Hardness readings were performed by the Vickers microhardness measurement technique using 10g load. With this small load the thinnest wall tested, 0.109" is well above the minimum thickness or unsupported section thickness required for test accuracy. . These hardness readings are reported in the following table. The Vickers reading for each location were averaged, converted to Rockwell B and plotted on Graph 364.

Hardness Values from Field Data Sets 5 and 6.

Specimen	Location	Base "A"	HAZ "A"	Weld	HAZ "B"	Base "B"
TEST #1	1	183	170	209	181	187
	2	189	193	206	181	183
	3		209	216	178	
TEST #1	Avg HV_{10}	186.0	190.7	210.3	180.0	185.0
	HRB (HV_{10})	90.2	91.1	95.1	89.0	90.0
TEST #2	1	178	183	195	206	187
	2	183	181	224	183	187
	3		212	220	172	
TEST #2	Avg HV_{10}	180.5	192.0	213.0	187.0	187.0
	HRB (HV_{10})	89.1	91.4	95.5	90.4	90.4
TEST #3	1	187	183	220	209	193
	2	199	189	224	199	198
	3		206	237	187	
TEST #3	Avg HV_{10}	193.0	192.7	227.0	198.3	195.5
	HRB (HV_{10})	91.7	91.6	97.8	92.7	92.1
TEST #4	1	187	181	195	220	183
	2	181	187	240	189	181
	3		199	237	176	
TEST #4	Avg HV_{10}	184.0	189.0	224.0	195.0	182.0
	HRB (HV_{10})	89.8	90.8	97.3	92.0	89.4
TEST #5	1	187	183	213	199	189
	2	189	187	228	178	183
	3		193	216	170	
TEST #5	Avg HV_{10}	188.0	187.7	219.0	182.3	186.0
	HRB (HV_{10})	90.7	90.8	96.5	89.5	89.2

Hardness Values from Field Data Sets 5 and 6.

Specimen	Location	Base "A"	HAZ "A"	Weld	HAZ "B"	Base "B"
TEST #6	1	183	178	209	187	187
	2	181	181	206	199	187
	3		202	209	172	
TEST #6	Avg HV_{10}	182.0	187.0	208.0	186.0	187.0
	HRB (HV_{10})	89.4	90.4	94.7	90.2	90.4
TEST #7	1	187	189	209	189	183
	2	189	202	220	181	187
	3		202	224	172	
TEST #7	Avg HV_{10}	188.0	197.7	217.7	180.7	185.0
	HRB (HV_{10})	90.7	92.6	96.3	89.1	90.0
TEST #8	1	178	183	206	195	172
	2	181	193	209	181	176
	3		213	206	178	
TEST #8	Avg HV_{10}	179.5	196.3	207.0	184.7	174.0
	HRB (HV_{10})	88.9	92.3	94.4	89.9	87.5
TEST #9	1	181	181	209	183	181
	2	187	193	213	172	181
	3		199	213	172	
TEST #9	Avg HV_{10}	184.0	191.0	211.7	175.7	181.0
	HRB (HV_{10})	89.8	91.2	95.3	87.9	89.2
TEST #10	1	181	189	224	189	187
	2	178	206	220	178	183
	3		213	228	178	
TEST #10	Avg HV_{10}	179.5	202.7	224.0	181.7	185.0
	HRB (HV_{10})	88.8	93.5	97.3	89.3	90.0

The data show the weld metal hardness to be clearly higher than either the base metal or HAZ. There is a trend toward the HAZ hardness being slightly higher than the base metal. Converted to estimated tensile strengths, the weld could be 97 to 106 ksi tensile strength, the HAZ 88 to 92 ksi and the base metal 82 to 92 ksi. These values are consistent with numbers expected for these regions.

The graphic presentation shows one HAZ has a higher hardness than the other. This is probably due to the amount of heat introduced during welding as it was affected by the angle the welder held the welding torch or arc blow. The angle of the torch will cause the arc to preferentially strike on side of the weld more than the other, putting more heat into that side. Arc blow or the deflection of the arc from a straight path by magnetic forces often induced by location of the ground could produce a similar effect.

5.9 Visual Inspection of Samples

5.9.1 Crack Axial Location

The fracture locations relative to the weld were identified, subsequent to testing. The fracture sites were identified as being in the weld, fusion zone, heat affected zone (HAZ) or the base metal. The following table summarizes these results.

OBSERVED LOCATION OF FRACTURES

	Bias			Bias Taper		
	Location	In Seam	% in seam	Location	In Seam	% in seam
Weld	1	0	0.00%	0		
Fusion Zone	2	0	0.00%	2	2	100.00%
Heat Affected Zone	4	2	50.00%	9	2	22.22%
Base Metal	12	11	91.67%	2	2	100.00%
Toe of Bias Weld	26	26	100.00%	30	30	100.00%
Seam HAZ				1	0	0.00%
TOTAL	45	39		44	36	
Percent in Seam		86.67%			81.82%	

Not broken	4			2		
Not observed	15					
TOTAL	64			46		

	Manual			Orbital		
	Location	In Seam	% in seam	Location	In Seam	% in seam
Weld	5	2	40.00%	2	0	0.00%
Fusion Zone	38	11	28.95%	10	5	50.00%
Heat Affected Zone	32	10	31.25%	37	20	54.05%
Base Metal	5	4	80.00%	6	1	16.67%
Toe of Bias Weld						
Seam HAZ						
TOTAL	80	27		55	26	
Percent in Seam		33.75%			47.27%	

Not broken	2			4		
Not observed	25			1		
TOTAL	107			60		

The fusion zone is the line between the liquid weld metal and the unmelted base metal . It is an area often likely to contain lack of fusion from poor tie in during the welding process. The metallurgy in a sound weld contains rapidly cooled metal on the liquid side and solid grains on the other side which can be subjected to rapid austenitic grain growth..

The heat affected zone (HAZ) is the area of unmelted base metal between the fusion line and material which has not been heated high enough to result in thermally induced metallurgical changes. The HAZ contains two metallurgically distinct regions in ferrous alloys, one heated above the austenitic transformation temperature and a second region where heating is below the austenitizing temperature, but high enough to generate metallurgical changes in the base material. The austenitizing range of the HAZ, includes material heated to near the melting temperature which undergoes grain growth, increasing hardenability and material which is austenitized but is not heated high enough to generate grain growth. Both these types of austenitized HAZ materials will transform on cooling. The cooling rate will determine if the transformation product is martensitic of another, softer structure. Finally the area of the HAZ heated below the transformation temperature may undergo tempering with associated loss of hardness and strength due to the heat from welding.

Manual welds fractures occurred in the fusion zone 47% of the time suggesting the tie in technique is important. The percentage of fusion fracture locations declined to 18% in the orbital welds, indicating automating processes can improve weld tie in reliability. In both manual and orbital welds, the combined percentage of fractures located in the fusion or HAZ exceeds 80%, indicating a potential to improve these processes by controlling process variables, particularly the heat input that has a direct influence on the properties of the HAZ.

In manual and orbital welds the fracture occurred in the HAZ 40% and 67% of the time respectively. No statistics were kept as the whether these fractures were above or below the austenitic transformation temperature limit line. This is too difficult to discern from visual examination of the outside diameter only. What has been observed, is most of the fractures tend to be in region expected to be below the austenitic transformation temperature. In addition this region is the location of the greatest plastic deformation. These observations combine to suggest the region is being stress relieved or experiencing a similar phenomenon during welding making the base metal more susceptible to property reduction and fatigue life loss.

Bias and bias tapered welds have the weld and HAZ oriented so the applied bending stresses are not parallel to them. As a result the data clearly indicates movement of the fracture location to the intersection of the longitudinal and bias weld. This combined with the significant improvement in the cycles to failure reported elsewhere in the report, supports the technological breakthrough these processes have provided. The longitudinal weld seam, bias weld intersection is now considered the weakest link in this system and may be so, because the intersection between the two welds has been molten as a weld bead twice. Future areas of interest may include investigation of weld bead deoxidization or solidification stress distribution in these areas.

The number of manual and orbital joints failing in the fusion zone and HAZ clearly indicates the need to improve fatigue cycle life in these areas in future work. The challenge is to understand the interaction between the welding process thermal interaction on metallurgical properties and the subsequent potential influence on the fatigue life cycles.

The size of the HAZ is determined by the amount of heat generated by the welding process and methods used to extract heat, like chill blocks, or to impart heat, such as preheat. In general the welding heat input, a measurable function of welding amperage, voltage and welding travel speed controls the size and shape of the HAZ. Higher heat inputs generate larger heat affected zones with slower cooling rates. Heat input can have a marked influence on the properties of the material.

Visual observation suggests a significant number of fractures in this study occurred in the HAZ area below the austenitizing temperature exposure range. This tempering of the high strength material may be occurring locally. This softening may by itself not lead to major changes in the fatigue cycle life, but closely associated with two higher strength material with unaffected base metal on one side and hardened material in the austenitized HAZ on the other, may lead to concentrating plastic deformation in this softened region.

5.9.2 Crack Radial Location

During the testing sequence the orientation of the longitudinal seam and failures relative to the bending mandrel were observed and recorded. The centerline of the bending mandrel was established as 0° for recording purposes. The angles between the mandrel and the longitudinal seam and fatigue fracture, around the circumference of the tube, were recorded through 360°. The Observed Orientation of Failures Table, attached, reports the number of specimens with fracture angles grouped into quadrants from 0° to 180° with 0°and 180° reported separately.

The table of Observed Orientation of Fractures show clearly the fractures tend to orient toward the inside segment of the bending radius. This is due to the presence of the maximum stress reversal cycling in this area.

5.9.3 Crack Location wrt Seam Weld

The number of fractures intersecting the longitudinal seam weld are also shown for each reported angle of fracture with the calculated percentage of each segment. The percentage of fractures occurring in the association with the longitudinal weld seam increases as the processes changes from manual to orbital to bias. Data presented elsewhere in this report, indicate the superiority of bias weld fatigue lives over manual and orbital. These facts indicate the fatigue failure mode is being isolated to the now weakest link in the bias welded system , the intersection of the bias and longitudinal seam welds. Future development on bias welded pipes may find it beneficial to concentrate on the area of the bias and longitudinal weld interface. Development in manual and orbital welding should be conscious that a technological limit in improving fatigue resistance of these welds may become the fatigue resistance of the longitudinal weld intersection.

Though the number of tests performed with the longitudinal seam in a area of the neutral axis is limited, there is enough data to indicate orienting the longitudinal seam weld near the neutral axis reduces the percentage of failures in the seam weld for all types of welds. Investigation of the samples with longitudinal seams oriented near the neutral axis, with angles from the anvil ranging from 46° to 135° does not seem to provide superior fatigue cycle resistance. Of the thirty four (34) data points in this range, ten (10) were above their group's median, two (2) were their group's median, seventeen (17) were below their group's median and five (5) were single data point groups.

OBSERVED ORIENTATION OF LONGITUDINAL SEAMS

Angle from Anvil	Bias Location	Bias With Fracture	Bias % with seam	Bias Taper Location	Bias Taper With Fracture	Bias Taper % with seam
0	46	44	95.65%	40	34	85.00%
1 - 45	0			0		
46 - 90	0			4	1	25.00%
91 - 135	0			0		
136 - 179	0			0		
180	4	4	100.00%	0		
TOTAL	50	48		44	35	
Percent in Seam		96.00%			79.55%	

	Bias			Bias Taper		
Not broken	4		c	2		
Not observed	10					
TOTAL	64			46		

Angle from Anvil	Manual Location	Manual With Fracture	Manual % with seam	Orbital Location	Orbital With Fracture	Orbital % with seam
0	54	35	64.81%	41	27	65.85%
1 - 45	9	3	33.33%	2	2	100.00%
46 - 90	17			6		
91 - 135	2			2		
136 - 179	9	1	11.11%	3		
180	4	2	50.00%	2	1	50.00%
TOTAL	95	41		56	30	
Percent in Seam		43.16%			53.57%	

	Manual			Orbital		
Not broken	2			4		
Not observed	10					
TOTAL	107			60		

OBSERVED ORIENTATION OF FRACTURES

Angle from Anvil	Bias Location	Bias In Seam	Bias % in seam	Bias Taper Location	Bias Taper In Seam	Bias Taper % in seam
0	44	44	100.00%	36	34	94.44%
1 - 45	0					
46 - 90	0			1	1	100.00%
91 - 135	0			1		
136 - 179	0					
180	6	4	66.67%	6	0	
TOTAL	50	48		44	35	
Percent in Seam		96.00%			79.55%	

	Bias			Bias Taper		
Not broken	4			2		
Not observed	10					
TOTAL	64			46		

Angle from Anvil	Manual Location	Manual In Seam	Manual % in seam	Orbital Location	Orbital In Seam	Orbital % in seam
0	67	35	52.24%	37	27	72.97%
1 - 45	5	3	60.00%	4	2	50.00%
46 - 90	0			1		
91 - 135	0			0		
136 - 179	4	1	25.00%	0		
180	19	2	10.53%	14	1	7.14%
TOTAL	95	41		56	30	
Percent in Seam		43.16%			53.57%	

	Manual			Orbital		
Not broken	2			4		

Summary:

- Most, but not a majority of manual fractures are associated with the fusion zone.
- A majority of orbital weld fractures are associated with the heat affected zone.
- Automated processing of the weld improves the performance of the weld by moving the fracture to the HAZ.
- Manual and orbital weld failures show little preference toward the longitudinal weld seam, though the orbital fractures occur there more often.
- Bias welds fractures are highly associated with the longitudinal weld, bias weld junction
- Bias welds have solved a major problem with HAZ and fusion zone fracture locations and moved the fracture to the next weakest link.

5.10 Discussion of Seam Weld Removal

A limited number of welds were supplied with their internal longitudinal seam weld flash removed. Particularly in thinner walled coiled tubing, the internal flash must be removed in the weld preparation area to insure full penetration welds. Results in this study indicate the method of preparation can influence fatigue life through surface preparation. The rougher finish will reduce expected life. The capability exists to remove the internal flash from longitudinal welds in the manufacturing process without having a significant impact on the surface finish. This study does not have data capable of predicting the potential change in fatigue life if the internal weld flash is removed. Determination of the influence of internal flash removal on fatigue life is an area for consideration in future studies.

5.11 Discussion of Field Weld Results vs Factory Welds

The data were separated into data sets, based on the raw material source of the base tubing material. The sets were further divided to segregate welds performed in coiled tubing mills or factory setting or made by an end user or field service company in a field setting. Data Sets **A-H** are the sets made in coiled tubing manufacturing settings. Field Data Sets **1-6** are those made in field settings. Where similar CT diameter, wall thickness and welding technique have been utilized, comparisons can be attempted. These comparison are displayed in Graphs **227** to **239.** In order to minimize the influence of variables such as material property differences, the median percentage of plain pipe values were the only compared data.

1.75" Diameter, 0.109", 0.125", 0.134" and 0.175" Wall

Manual and orbital welds produced in the field had higher percentage of plain pipe than manufacturing setting prepared welded samples as a percentage of the plain pipe median values. Data for 0.109" is fairly even between sources, but heavier wall show the improved fatigue performance of field prepared welds.

2.375"/0.190" CT

Manual welds produced in manufacturing setting had higher percentage of plain pipe than field welded samples.

It is difficult to conclude from the project data that there is a clear advantage between welding in ideal shop conditions versus less ideal field conditions. Characteristics which are difficult to quantify have a strong bearing on the fatigue lives of welds. Prime among these is the skill and competence of the welder or welding operator. Welders and welding operators have good skills in certain CT diameters and wall thicknesses may have difficulty in a size range they are not familiar with.

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6 SAMPLE ANALYSIS - Acute Technological Services

Acute Technological Services, Inc (ATS) were contracted to perform a metallurgical investigation of several of the tested samples. This work was performed under the auspices of the GRI Weld Study and is presented in a separate report. It is GRI's wish that this report be made available to DEA-97 participants, once the document has been reviewed and accepted. The following is a review of the work undertaken and the main conclusions reached.

All the manual and orbital welds in Data Set A were performed by ATS. Manual welds were performed using the GTAW process with 75% Helium, 25% Argon shielding and ER 70-S2 filler metal, with chill blocks, in the 5G position. Orbital welds were produced with a semi automatic GTAW machine and similar operating parameters.

Two groups of twelve manual and twelve orbital welds were subjected to metallographic analysis. The area of final rupture was identified by visual inspection and confirmed by liquid penetrant examination. Sections of the failures were cut, polished and etched for metallographic analysis. The photomacrographs and micrographs represent the major part of this report.

The photos revealed the failures occurred predominantly outside the weld. Most failures initiated on the inside diameter of the pipe and were associated with some form of surface irregularity. These irregularities included pits, ID flash cracks, thin areas near or in the weld and sharp reentrant angles between the weld cap or root and the tube wall. The photos did not disclose any clues to explain the large differences in fatigue life performance observed during the testing.

The number of rejected radiographs was higher than expected in normal welding operations. The radiographs were reviewed using ANSI B31.3 acceptance criteria. The number of radiographs rejected to B31.3 was 30% of the number originally rejected. The majority of the discontinuities found were porosity and incomplete penetration. B31.3 allows some limited porosity and insufficient penetration, provided weld is thicker than the base metal. Six samples observed had failures associated with the weld metal. Either the radiographs did not detect a rejectable discontinuity or the failure was not associated with the detected defect. Weld defects found by radiography had little bearing on the fatigue life performance

Eight samples had microhardness traverses performed on them, including impressions in the weld, HAZ, and base metal. Between fifteen and twenty two impressions were taken on each sample. No hard or soft spots were detected.

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7 SAMPLE ANALYSIS - Tulsa University

Dr. Steve Tipton, Associate Professor at the University of Tulsa and a recognized expert on low cycle fatigue, was contracted to perform a metallurgical investigation of several of the tested samples, with a particular emphasis on the fatigue mechanism. This work was performed under the auspices of the GRI Weld Study and is presented in a separate report. It is GRI's wish that this report be made available to DEA-97 participants, once the document has been reviewed and accepted. The following is a review of the work undertaken and the main conclusions reached.

Twenty four welded samples were selected and sent to Dr Steve Tipton for analysis of primary and secondary fatigue cracking behavior. Samples included four plain, unwelded, eight bias butt welds, six orbital welds, three manual but welds and three bias tapered welds. Half of these samples (identified as A-112 through A-123) had fatigue cycle testing terminated prior to failure at 50% and 75% for the cycles required to fail three similar samples.

In plain unwelded pipes the cracks initiated in the highest point on the inner surface of the longitudinal weld bead. The cracks tended to form on the inner surface of the compressive side of the tube. No secondary cracking was observed on the unwelded samples

Bias butt weld samples primary cracks initiated at the inside surface on the compressive side of the tube. The cracks appear to initiate near the inside surface of the longitudinal seam weld, then propagate through the weld bead and into the base metal. Close examination indicated porosity in the longitudinal weld approximately 0.015 to 0.020" beneath the inside surface, which may have provided an initiation site. Untempered martensitic structures were found in the inside diameter longitudinal seam upset. This martensite may act as a stress intensification area under cyclic loading. Every bias weld showed secondary cracking, with some secondary cracking along the tubing outside diameter.

Both the inner and outer surfaces of the plain pipe and bias welded samples show numerous macroscopic slip bands oriented predominantly ±45° to the tubing long axis. These slip bands are on the side of the tubing experiencing compression during cycling.

Orbital butt welds exhibited cracking in the weld HAZ. Primary cracks had multiple origins on the tubing inside diameter. These origins were associated with grinding marks across the top of the remaining weld bead.

Manual butt welds had primary cracks emanating from grinding marks on the inside diameter, evidently dressing the longitudinal weld seam. Secondary cracking was observed in outside diameter grinding marks oriented at 45° indicating such imperfections may be as detrimental as circumferential grinding marks, since the maximum shear stresses occur on 45° planes.

A microhardness traverse taken on one orbital weld show a slight increase in hardness at the weld metal and HAZ interface area. The hardness of 285 HV (28 HRC) was confirmed with additional readings in the area.

Bias taper butt welds showed primary cracking behavior similar to the bias welds. Some secondary cracking was observed along the bias weld seam.

Recommendations:

Eliminating the use of grinding to remove longitudinal seam welds prior to welding. When grinding must be performed, use a technique which imposed longitudinal marks only. After welding, surface conditioning and grinding control severity of grinding marks and orient them parallel to the tubing axis.

Assure jigs and fixture used to prepare and align tubing for welding do not impose circumferential gouges, or scratches.

The fatigue life of bias welded tubing might be extended by removing the longitudinal seam weld. If not removed, the ERW process should be controlled to eliminate the line of porosity in the weld bead upset.

Post heat the weld bead to assure the bead does not contain untempered martensite.

8 CONCLUSIONS

Preparation for Welding

- The use of grinding to prepare weld joints in CT should be avoided. When grinding is required, grinding marks in the base should be as smooth as possible and must be parallel to the longitudinal axis of the tubing.

Bias Welds

- Bias welds have higher fatigue lives, measured in cycles to failure, than either manual or orbital welds, but lower than plain (unwelded) pipe.
- Bias weld fatigue fractures are highly associated with the longitudinal seam weld - bias weld intersection.
- The bias welding technique has solved a problem with HAZ and fusion zone fatigue fracture locations and moved the fracture to the next weakest link, the longitudinal seam weld. Further improvement will require improvement in fatigue properties of the seam weld.

Manual Welds

- Most fatigue fractures were located in the fusion zone. The secondary fracture location was the heat affected zone (HAZ).
- Manual weld fatigue fractures are not predominantly associated with the longitudinal weld seam.
- Manual tapered welds have 50% lower fatigue lives than untapered manual welds.

Orbital welds

- Orbital welding process produces cycles to failure results slightly higher than manual welds.
- Orbital weld results are more repeatable than manual welds.
- The majority of the fatigue fractures were located in the heat affected zone (HAZ).
- Automated processing successfully improved orbital performance over manual welds by improving tie in and moving the major fracture location to the HAZ.

- Orbital weld fatigue fractures are not predominantly associated with the longitudinal seam.

- Orbital tapered welds have 50% lower fatigue lives than untapered orbital welds.

Interpretation

- Fatigue life of welds, like that of unwelded pipe, increases with increasing wall thickness. The rate of increase does not appear to correlate with the D/t ratio

- Fatigue lives of thicker walled tests tend to be more consistent than thinner walled tests.

- Diameter growth increases with increasing internal pressure.

- Diameter growth rates decrease with increasing wall thickness and remain essentially constant between welding processes.

- Radiographic examination of CT is not a reliable predictor of fatigue life.

9 RECOMMENDATIONS FOR FURTHER WORK

- The thermal effect of the welding process on the base metal in the HAZ should be investigated.
- The effect of single vs multiple welding passes should be investigated.
- It should be determined if removal of the internal longitudinal flash significantly improves the cycle life for both butt and bias welds.
- Methods to improve the fatigue properties of the bias weld / seam weld junction should be investigated.
- A comparison of tapered bias welds made with and without prior strip preparation (tapering the larger wall down to that of the smaller wall) should be made and the technical issues investigated.
- The influence of material yield strength on the weld performance should be investigated more thoroughly.
- Alternative welding techniques, such as amorphous welding, should be considered.

Some of these topics are being addressed within the scope of the GRI Weld Study and the results will be distributed to DEA-97 participants when they are available and subject to GRI approval.

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Acknowledgments

CTES wishes to thank all the participants who contributed to this project; the Gas Research Institute (GRI) for providing substantial additional funding to allow the scope of work to be greatly widened; Quality Tubing Inc. for providing samples and technical support beyond the call of duty; the personnel of Acute Technological Services (ATS); Steve Tipton of Tulsa University; Schlumberger-Dowell, for use of the fatigue test machine well beyond the six months initially scheduled; the field locations which provided test samples; Eldreage Boaz and Ray Brown, technicians, for performing the tests; Drexel Oilfield Services, for use of their facilities; Linda, for administrative support including assembling these reports.

References

[1] **Tipton, Steve, & Newburn, D. A.,** "Plasticity and Fatigue Damage Modeling of Severely Loaded Tubing", Advances in Fatigue Lifetime Prediction Techniques, ASTM STP 1122, M. R. Mitchell and R. W. Langraf, Eds., American Society for Testing and Materials, Philadelphia, 1992 pp. 369-382.

[2] **Newman, K. R, & Brown, P. A.,** "Development of a Standard Coiled Tubing Fatigue Test", SPE 26539, Proceedings, Fall Meeting, Society of Petroleum Engineers, 1993, pp. 303-309.

[3] **Tipton, S. M. & Brown, P. A.**, "Monitoring Coiled Tubing Fatigue Life", Second International Conference on Coiled Tubing, World Oil, Houston TX, March 1994.

[4] **Brown, P. A.,** "Use of Fatigue Test Machine to Investigate Coiled Tubing Diameter Growth", Second International Conference and Exhibition on Coiled Tubing, Amsterdam, June 1994.

[5] **Sisak, W. J. & Crawford, D. J.**, "The Fatigue Life of Coiled Tubing", SPE 27437, Proceedings, IADC/SPE Drilling Conference, 1994, pp. 65-75.

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July 26, 1994

CT Weld Fatigue JIP

Description

CTES has been requested to form a Joint Industry Project (JIP) to quantify the fatigue performance of coiled tubing (CT) welds compared with virgin CT. Previous studies have been limited in scope due to the expense and logistics of full-scale testing, or lack of a standard test machine. As a consequence, very little published work has been done to investigate the performance of biased welds, taper welds, welds in high yield strength materials or large diameter pipe. Dowell had agreed to make available the fatigue test fixture developed as part of the 1993 CoilLIFE JIP. This will enable a significant amount of weld performance data to be acquired quickly and at a reasonable cost. Tests will be performed with variations in CT diameter, wall thicknesses, bending radius, weld types, material yields, and internal pressure. The attached table is a suggested list of tests for discussion purposes. This example uses 1.5", 0.095", 80Kpsi, with a 48" bending radius as the base case. Some have suggested that 1.75" be used for the base case. Tests will have to be repeated several times (in this example, a minimum of 3 times) to determine the statistical scatter. Tests of the virgin pipe will be run for a basis of comparison. Current plans call for about 200 tests to be performed. The specific samples to be tested will be decided upon by the participants at the initial JIP meeting. Lab analysis will be performed on some samples (depending on available funds) before and after failure to investigate the failure mechanism.

Project Costs

The cost of participating in this JIP will be $12,000 for each participant. Quality Tubing and Precision Tube Technology will supply the welded pipe and virgin pipe samples, split evenly between the two companies, as their cost of participation in the project. Dowell will provide and maintain the fatigue test machine as their cost of participation.

CTES will account for all project costs at the following rates:

- $400 / technician man-day - to setup and run the test machine
- $700 / engineer man-day - to manage project, analyze data and write final report
- $100 / day facility rental for test days only (includes fork lifts, utilities, etc.)
- Cost plus 20% for other expenses (lab analysis, etc.)

The project will finish when the total of the participation fees paid to CTES has been used as per the above accounting.

An estimated budget for 200 tests assuming an average of 2 tests per day is:

100 Technical man-days $40,000

40 Engineer man-days	$28,000
100 Facility rental days	$10,000
Lab analysis and other expenses + 20%	$18,000
Total	$96,000

Thus to reach the target of 200 samples tested, 8 participants will be needed in addition to Quality Tubing, Precision Tube Technology and Dowell. If there are less participants, testing will be reduced. If there are more participants, testing will be increased. Every effort will be made to perform as much testing as possible. JIP members may decide to increase or decrease the amount of lab analysis done, which would affect the number of tests performed.

Deliverable

The deliverable from this JIP to the participants will be a detailed report including all data collected from the testing, analysis and summary of this data and all lab analysis reports. This data will remain the confidential property of CTES and the participants for two years after the completion of the project.

Schedule

The initial meeting will be held at Drexel's facilities in Conroe on Thursday, September 29, immediately after the SPE conference in New Orleans. Testing is scheduled to begin in October. The project will be completed in February 1995.

Dia. (in)	Walls (in)	Yield (Kpsi)	Radius (in)	Press. (Kpsi)	Number of Tests
Each of the following series would be done for virgin, butt weld and biased weld samples					
1.5	0.095	80	48	0.25	3
1.5	0.095	80	48	2.5	3
1.5	0.095	80	48	5.0	3
1.5	0.125	80	48	0.25	3
1.5	0.125	80	48	2.5	3
1.5	0.125	80	48	5.0	3
1.5	0.095	70	48	0.25	3
1.5	0.095	70	48	2.5	3
1.5	0.095	70	48	5.0	3
1.5	0.095	80	72	0.25	3
1.5	0.095	80	72	2.5	3
1.5	0.095	80	72	5.0	3
2.375	0.125	80	72	0.25	3
2.375	0.125	80	72	2.5	3
2.375	0.125	80	72	5.0	3
3.5	0.156	80	72	0.25	3
3.5	0.156	80	72	2.5	3
Each of the following series would be done for butt weld and biased weld samples					
1.5	0.095/.109	80	48	0.25	3
1.5	0.095/.109	80	48	2.5	3
1.5	0.095/.109	80	48	5.0	3
1.5	0.095	80/70	48	0.25	3
1.5	0.095	80/70	48	2.5	3
1.5	0.095	80/70	48	5.0	3
3.5	0.156/.175	80	72	0.25	3
3.5	0.156/.175	80	72	2.5	3
Total tests for this example = 201					

CTES, L.C.

Coiled Tubing Weld Fatigue
Joint Industry Project Agreement

This Agreement, effective as of the _______ day of ___________, 1994, is by and between CTES, L.C., having a principal office at PO Box 2178, 2800 North Fraizer, Conroe, Texas, 77305-2178, U.S.A., (hereinafter "CTES"), and other parties who execute this Agreement (hereinafter "Participants").

1 PURPOSE OF AGREEMENT

This Joint Industry Project (JIP) Agreement provides a means whereby CTES will perform fatigue testing of coiled tubing (CT) welds. Data from this testing and an analysis of the data will be given to the Participants. The purpose of this JIP is to improve the understanding of the fatigue characteristics and failure mechanisims of the current CT weld technology.

2 SCOPE OF PROJECT

The "Project" carried out under this Agreement shall comprise the three (3) tasks described below:

2.1 The fatigue test fixture described in SPE paper 26539 will be used to test butt welded, biased strip welded and virgin samples of CT until they fail. These samples will be of different diameters, wall thicknesses and yield stresses and will be tested with different internal pressures and bending radii. These parameters and the number of cycles to failure, diametral growth and any visual observations (hereinafter "Data) will be recorded for each test. The number of tests performed will depend on the project funding explained in section 6.

2.2 Lab testing of some of the failed samples will be performed to determine the type and location of the failure.

2.3 A report will be written in which the results of the Data and lab tests are analyzed.

3 DELIVERABLES

The following will be sent by CTES to the Participants:

3.1 A report of all experimental Data
3.2 Copies of all lab test reports
3.3 Report containing the analysis of the Data and the lab tests
3.4 Accounting report of the project costs

4 TECHNICAL REVIEW MEETINGS

4.1 CTES will organize two technical review meetings. The first meeting will be held September 29, 1994 in the Conroe/Houston area. The sizes of CT samples tested will be determined by the Participants at this meeting. The number of samples to be analyzed by a lab will also be determined at this meeting.

4.2 The final technical review meeting will be held when the Project is completed.

4.3 Each Participant shall have the right to send up to two representatives to each technical review meeting.

5 RESPONSIBILITIES

5.1 Schlumberger-Dowell (Dowell) will provide the fatigue test fixture as their cost of participation in the Project. Dowell will pay for any repair/maintenance costs for the fixture up to $3,000. If the repair/maintenance costs should exceed $3,000 these costs will be charged to the Project.

5.2 Quality Tubing Inc. (QT) and Precision Tube Technology (PTT) will provide the CT samples for testing as their cost of participation in the Project, with approximately 50% of the samples coming from QT and 50% from PTT. No distinction will be made between tests of QT samples and tests of PTT samples in the Data, unless otherwise agreed upon by PTT and QT.

5.3 CTES shall carry out all work necessary to perform the Project and provide to each Participant the documentation listed in section 3 entitled "Deliverables" of this Agreement.

5.4 Participants, excluding Dowell, QT and PTT, shall be charged a flat fee for participation in the Project in accordance with section 6.

6 PROJECT PARTICIPATION COSTS

6.1 Participant Cost

6.1.1 The participation cost to each Participant hereunder shall be $12,000, excluding Dowell, QT and PTT.

6.1.2 CTES will submit invoices to all Participants who execute the Agreement. All payments shall be made in U.S. dollars to CTES within 30 days of the invoice date unless otherwise agreed to by CTES.

6.1.3 The foregoing shall not cover costs of attendance of meetings, which shall be for each participants account.

6.2 Project Cost

6.2.1 CTES shall account for all project costs. Manpower costs shall be accounted for at the contract rates of $700 per day for an engineer and $400 per day for a technician. Sub-contracted, purchased and manufactured items or services shall be accounted for at cost plus 20%. A $100 per day facility rental will be charged to the Project for each day testing is performed on the fatigue test machine.

6.2.2 Testing will continue until the sum of the participation costs are used according to the above accounting method. A preliminary estimate indicates that about 200 tests could be performed if there are 8 participants excluding Dowell, QT and PTT.

7 USE OF INFORMATION

7.1 Use of Information

9.1 Liability of Parties

9.1.1 Each party hereto assumes and shall be responsible for all losses, claims, damages, judgments, costs, expenses, and liabilities for injuries to or death of its personnel or third parties, or for damage to or destruction of its or third-party property arising out of its operations under this Agreement and in connection with the subject matter of this Agreement, and shall indemnify and hold all the other parties hereto harmless from such losses, claims, damages, judgments, costs, expenses, and liabilities, regardless of the negligence or strict liability of the parties to be indemnified.

9.1.2 Nothing herein shall be construed to create a partnership or impose a partnership obligation or liabilities or an association for profit on CTES or any Participant. If, for Federal Income Tax purposes, this Agreement or any performance hereunder is regarded as a partnership, each of the parties hereto hereby elects under the authority of Section 761(a) of the Internal Revenue Code of 1954 to be excluded from the application of all the provisions of Subchapter K of Chapter 1 of Subtitle A of the Internal Revenue Code of 1954.

9.2 Patent Rights

Any patents arising from inventions of CTES shall be CTES's property. Participants are hereby granted a worldwide, royalty-free, nonexclusive, irrevocable, license to make, have made, have used, and use any invention under any patent arising from the Project of this Agreement. The licenses herein granted are nondivisible, nontransferable, nonassignable, (except as provided in Section 9.5 hereof) and without the right to grant sublicenses except to the extent necessary to allow full use of the data as provided for in Section 7 hereof. These rights shall only apply to those patents which cover inventions conceived during the period in which the Participant is a member of the Project. The provisions of this paragraph shall survive any termination of this Agreement.

9.3 Independent contractor

In performing under this Agreement, CTES shall at all times act as an independent contractor. Nothing herein shall be construed or applied so as to create the relationship of principal and agent, partnership, or employee between CTES and participants. CTES shall not make any commitment or incur any charge or expense in the name of any participant.

9.4 Agreement interpretation

This Agreement shall be deemed to be made under and shall be governed by the laws of the State of Texas in all respects, including matters of construction, validity, and performance.

9.5 Assignment of Interests

The participants shall not assign nor transfer their interest in this Agreement nor any part thereof without the written consent of CTES, which will not be unreasonably withheld, and any such assignment or transfer made without such consent shall be void, and in order to be valid must be affirmatively recognized by CTES, provided, however, such interest can be assigned or transferred to a successor of all or substantially all of the Participants' business to which this Agreement pertains.

9.6 Counterparts

This Agreement may be executed in counterparts and all such counterparts shall be construed together and shall constitute one instrument.