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HOMOPOLAR PIPELINE WELDING RESEARCH PROGRAM

Final Report

March 30, 1998
Austin, Texas

Presented to:

JOINT INDUSTRY SPONSORS

AMOCO Corporation
BP Exploration
Exxon Production Research
Mobil Technology Company
Shell Development Company
Texaco, Inc.
CRC-Evans Automatic Welding
Parker Kinetic Designs
Minerals Management Services
Department of Transportation

RO 130

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PREFACE

The Homopolar Offshore Pipeline Research Welding Project is a joint industry program between the Center for Electromechanics at the University of Texas at Austin, eight companies of the offshore oil industry and two government agencies. The company representatives, both past and present, made valuable contributions to the program over the five year program. The current company representatives are

Jim Ibarra, Amoco
Mike Vandenbossche, BP
Richard L. Jones, CRC-Evans
Calvin Crossley, Exxon
Steve LeBlanc, Mobil
Jim Weldon, PKD
Carl Langner, Shell
Fred Levert, Texaco
Charles Smith, DOT/DOI

The UT-CEM people involved during the five years of the program were:

Current staff

Bob Carnes, Co-Principal Investigator and Program Manager
Steve Nichols, Co-Principal Investigator and Director of CEM
Bobby Hudson, Engineer
Ben Rech, 12-inch Fixture Design Engineer
Alber Walther, Technician
Chek Ming Queck, Graduate student

Former staff

John Gully, Original Principal Investigator
Dr. Mike Harville, Engineer
Dr. Paul Haase, Engineer
Jui-Fai Kuo, Graduate student
Many undergraduate students

This final report is based on the quarterly reports presented to the sponsors during the program, and the primary objective of this report is to review the program objectives and accomplishments. Detailed reporting and specific test results are found in the past quarterly reports.

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EXECUTIVE SUMMARY

Objective

The original objective for the Homopolar Offshore Pipeline Welding Research Program (HOPWRP) was to ascertain if homopolar welding (HPW) was a suitable means for the welding of offshore pipelines in deep water, J-Lay situations. Inherent in that question were the component ones of what strength and toughness could be expected, what would the finished profile be; and, if these were found acceptable, would the method scale up to pipe sizes larger than three inches in diameter. At the first quarterly meeting the sponsors proposed the additional task of determining if there were a method of NDE suitable for HPW welds.

Experimental Procedure

The first task was to determine and define the test values in each of the areas of interest which together constituted an acceptable weld. Once those definitions were agreed upon, each of the characteristics in question was addressed with series of welds, appropriate destructive testing, and assessment and re-evaluation of welding parameters. The experimental welding program was designed to establish the bounds of the various welding parameters that would produce acceptable welds consistently, i.e., the welding parameter tolerance box. A concurrent study of nondestructive evaluation methods was undertaken to designate the ones most apt to detect the zero-volume defects resistance forge welding methods are thought to be prey to.

Significant Results

The most significant result was the agreement by all parties that HPW was eminently suitable for the J-Lay of pipe, particularly the higher strength, cleaner grades of pipe currently being run offshore. Early in the program, criteria for the acceptance were developed. Target tensile and ultimate strengths were achieved relatively early in the program. Toughness was harder to achieve, but by the end of the third year Charpy V-notch toughness approaching that of parent metal was being repeatably produced. A certain amount of weld metal displacement was determined to be crucial to weld quality, so work was done to shape the as welded profile to facilitate removal of the weld reinforcement. In the fourth year a machine was designed and built for the welding of twelve-inch pipe. In the fifth year the first twelve-inch, one-half inch wall pipe welds were made, proving that high quality welds could be made in any size pipe in the same time as required for three-inch welds. The NDE study determined that ultrasonic inspection was the method most likely, and further study was done on existing apparatus, companies, and their capabilities.

INTRODUCTION

This is the final report to the sponsors of the Homopolar Offshore Pipeline Welding Research Program. The Joint Industry Program, which began in February 1993, was initially supported by a team of six oil companies and one welding contractor. The five-year program's ultimate goal was to produce a prototype system suitable for installation on a J-lay barge. This was to be achieved by building and demonstrating operation of a full scale vertical HPW system capable of producing industry acceptable homopolar welds in 12 in. schedule 60 (0.562 in. wall) carbon steel pipe. The research effort is being performed by the Center for Electromechanics at The University of Texas at Austin.

The current sponsors include six oil companies, two industrial sponsors, and two government agencies. All six of the oil companies participated for the full five years, at a total investment of $200,000 each. PKD and CRC donated similar amounts in in-kind support, and the government agencies invested $100,000 each in the last three years of the program. Sponsors are listed below:

Oil Companies

AMOCO Corporation
BP Exploration
Exxon Production Research
Mobil Research and Development Corporation
Shell Development Company
Texaco, Inc.

Industrial Sponsors

CRC-Evans Automatic Welding (in-kind)
Parker Kinetic Designs (in-kind)

Government Agencies

Office of Pipeline Safety of the Department of Transportation
Mineral Management Services of the Department of Transportation

Quarterly review meetings have served to brief sponsor representatives on program status and solicit sponsor input. These meeting locations alternated between Austin and Houston. The preliminary work necessary to initiate this program was supported by the National Science Foundation through the Offshore Technology and Research Center (OTRC).

Motivation

Typically, offshore pipelines are constructed using the S-lay method, which permits the pipe to be welded and inspected in the horizontal position. Multiple welding and inspection stations are possible with this method, being limited only by the deck length of the welding barge. Due to increased buckling stresses, deep water pipelines require the steeper angle of entry into the water presented by the J-lay method. The vertical or near-vertical welding position inherent in J-lay necessitates a single welding station, presenting great economic incentive to minimize pipe handling and welding cycle times.

Homopolar Welding and the Pipe Welding Research Program

Homopolar welding (HPW) is a one-shot resistance welding process being investigated as a method to join API 5L carbon steel linepipe. Homopolar welding utilizes the high current, low voltage electrical pulse produced by a homopolar generator to rapidly resistance heat the interface between abutting pipe ends, producing a full circumference resistance forge weld in under 3 seconds.

A five year joint industry program sponsored HPW research with the goal of developing the process for deep water offshore pipeline construction utilizing the J-lay method. The program concentrated on weld parameter optimization by producing, testing and evaluating welds in various grades, wall thicknesses, types and compositions of four 3 in. nominal (3.5 in. OD) diameter API 5L carbon steel pipe and one 12 in. nominal diameter pipe. Mechanical properties of the welds and parent metal were evaluated by tensile testing, impact testing and hardness traverse testing according to guidelines and criteria established by the industrial sponsors.

Homopolar welding has demonstrated the capability of producing industrially acceptable full circumference welds in carbon steel linepipe via a rapid, one-shot process. The 12-inch welding fixture demonstrated the scalability of the homopolar welding process, serving as a proof of the principal of homopolar welding.

BACKGROUND

The first experiments with Homopolar welding at the University of Texas were conducted in 1976, and its potential as a high speed automatic welding system stimulated significant interest in the welding community. In the period from 1976 to 1989, twenty-four programs were carried out, sponsored by fifteen government agencies and contractors and five industrial concerns, at an average cost of about $100,000 each. HPW's failing to become a commercialized process from these programs suggested that HPW lacked the perceived potential as a high speed welding process. This oilfield-sponsored JIP was funded for a sufficiently long research program to study each material, optimize the process, and reliably produce high quality welds.

HPW Process Description

Homopolar welding is properly classified as a resistance-forge welding process. The primary components of a HPW system are the homopolar generator and the hydraulic welding fixture. The homopolar generator stores energy kinetically in a rotating flywheel and converts it to electrical energy in a discharge circuit via electromechanical energy conversion.

The HPW process begins by accelerating the homopolar generator's rotor to a predetermined discharge speed. Then the generator is energized by exciting the field and engaging the sliding electric contacts, or brushes, onto the slip ring of the spinning rotor. Discharge is initiated by closing switches in the circuit near the generator terminals. The resultant current pulse is directed through the pipes, where weld joint electrical resistance produces extensive localized heating. After a preset time delay, upset pressure is applied to the pipes, displacing metal at the original interface and creating a full circumferential butt weld.

Postweld cooling rate is determined by the pipe and electrode physical dimensions, with the copper electrodes acting as a heat sink during cooling. Increasing the distance between the electrodes heats a larger bulk of the pipe on either side of the weld joint and increases the thermal conduction path from the weld zone, slowing the cooling rate. In combination with electrode location, generator discharge speed and field current, pipe end preparation, upset pressure, time between generator discharge and application of upset pressure, and duration of the upset pressure are all controllable process parameters affecting weld quality.

The method is similar to other resistance welding methods, with the exception that the energy is delivered in the form of a single high current dc pulse. The process is therefore fast, and does not produce the localized skin heating effects present in ac resistance welding methods. Flash Butt Welding can be used on the same pipe diameters that are being targeted for J-lay, but flash butt welding takes from one to two minutes per joint and produces extensive melting and a large heat affected zone (HAZ). Homopolar welding requires only a few seconds and is considered a solid state welding process.

The same generator and fixturing used to produce a homopolar weld may be utilized to heat treat the weld and HAZ. After the weld zone has cooled below the transformation temperature, an additional HPG pulse may be used to reheat the weld zone. Electrode location and generator parameters can be preselected to control the amount of heating, width of heated zone, and the subsequent cooling rate.

HOPWRP Program Objectives

At the first regular quarterly meeting held in June of 1993, the sponsors reviewed the program objectives as described in the prospectus and expanded the scope of the program. This sponsor input signified a change in the program organization by increasing the sponsors influence of the program direction and emphasis. This set a precedent for the relationship between the sponsors and the research team at the Center for Electromechanics for the remainder of the program.

Over the course of the five year program, the specific objectives changed yearly, but the main objective of developing homopolar welding for J-Lay pipelaying applications remained in tact. The following is a listing of the major objectives of the research program by the fifth and final year:

- Optimize weld parameters for homopolar welding 3 in. HSLA API 5L line pipe
- Investigate a range of materials with varying strength, wall thickness, composition, heat treatment and manufacturing method
- Produce 3 in. welds with acceptable mechanical properties
- Improve the finished weld profile
- Design and build a laboratory welding fixture for joining 12 in. Schedule 80 line pipe
- Demonstrate homopolar weldability of 12 in. pipe
- Transfer technology in preparation for commercialization of HPW
- Develop an NDE program

Property and Defect Acceptance Criteria (Hammond Criteria)

One of the first requirements of the research program was to develop acceptance criteria for the program. The criteria needed to be compatible with the existing pipeline welding codes, although these relate principally to fusion welding techniques and did not adequately address the different nature of solid-phase welding processes and the different characteristic of defect that these processes might produce. John Hammond, of BP Exploration Ltd, London UK, developed suitable criteria based on study and adaptation of two widely used pipeline welding codes, API 1104 and BS 4515. The resultant document, which became known in the program as the "Hammond Criteria", served to guide the research through the development of this new welding process. The Hammond Criteria document was included in the first annual report.

Synopsis of research program

The five year research program made progress toward developing homopolar welding for J-Lay applications, investigating four 3 in. material and one 12 in. material. The following is a synopsis of the program developments by year.

Year One. The program started with the reworking of the 10 MJ HPG control system to improve the control of the generator performance and overall safety of operation. The data acquisition system was upgraded at this time also. The initial research was a continuation of the NSF-OTRC program researching the homopolar weldability of material A, a 3 in., schedule 160, X52 seamless linepipe. Material B, a 3 in., schedule 80, X60 ERW linepipe, was added to the materials researched during the second half of the first year. By year's end, material A was determined to be unsuited for homopolar welding due to consistently low toughness. Material B was determined to be more weldable, but the impact toughness, while acceptable, was highly variable, especially in the as-welded condition. The NDE research accomplishments for the year included identification of possible HPW flaws and the best method for flaw detection in similar welding processes.

Year Two. During the second year, the only equipment modification was the installation of a spherical bearing in the three inch hydraulic welding press to improve the uniformity of the initial interface contact. The weld parameters were expanded on material B to include joint profiling and increased initial load settings to improve impact toughness and reduce the variability. Two additional 3 in. materials were included in the research program: material C, a schedule 160, X52 ERW normalized linepipe and material D, a schedule 80, X65 quenched and tempered seamless pipe. Comparative studies were started to characterize base metal properties and how the welding process changed each. The NDE research located a local NDT company to perform ultrasonic inspection of welds prior to mechanical testing. Also a round robin study was initiated with three automatic ultrasonic inspection contractors to evaluate the detectability of the possible HPW flaws.

Year Three. The parameter modifications, profiled joint and higher initial load, were started in the second year and completed during the third. The homopolar welding process had been transformed from a process controlled by contact resistance heating to one controlled by "geometric" I^2R heating[1]. The transformed process was capable of repeatably producing near base metal properties in the as-welded condition of both higher strength materials. The final modification to the process, machining a radius on the bevel shoulder where it meets the pipe wall, improved the weld profile without affecting other properties. Postweld pulsed heat treatments produced no significant improvements in either of the higher strength materials. Metallurgical studies were initiated under the supervision of Dr. D. Olson, of Colorado School of Mines, to determine the cause of the occasional low toughness in homopolar welds. The NDE research produced "calibration" welds with intentionally placed flaws to mimic the possible, typical HPW flaws.

Year Four. During the fourth year, the 3-inch welding program determined the tolerances of the process and demonstrated process robustness. Studies were conducted to determine optimum setting, like step geometry, and minimum system requirements, like discharge speed. Metallurgical studies continued on the cause of occasional low toughness, and the NDE research completed the round robin series and purchased a compact mechanized ultrasonic inspection system for in-house testing. The major emphasis of the year was completing the design of the 12-inch fixture and starting its fabrication. An electrode study was conducted to evaluate the electrode performance on 12 in. material.

Year Five. During the fifth year, the 12-inch fixture was completed, and seven 12 in. welds were produced. These welds were performed at similar weld parameters to the 3 in. material, achieving full tensile strength and acceptable weld profile with the first full section weld. Achieving acceptable impact toughness remains to be completed. Substantial effort was made to

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[1] The homopolar technique used during the first year was the standard method from previous welding programs. This traditional method used machined-flat pipe ends and carefully aligned the interface to insure uniform contact over the entire interface surface. A light initial load produced intense interface heating that diffused to adjacent material and softened it. A higher "upset" load was applied after sufficient material was softened to forge the joint. The modified approach replaced the flat pipe end with a profiled end and used a high constant load. The shaped end heats differentially with the square of the current density and begins deforming at the interface where the heating rate and stress are highest. These changes are covered in more detail in a recent paper on the welding program included in Appendix B.

produce papers, posters, and conference presentation to inform the welding community of the accomplishments of the five year welding program.

Publications and Presentations

Over the course of the research program, homopolar welding research was presented at several conferences, two PhD dissertations and one Master's thesis were submitted, and multiple patents were submitted. These are presented in Appendix A.

Related Welding Projects

During the five years of the HOPWRP, other research projects were conducted using the 10 MJ homopolar generator. These included pulsed compaction of zirconium sponge, homopolar pulsed brazing of copper, pinch and roll forging of Ti 6-4 and Inconel 718, and homopolar welding of coil tubing, low carbon steel linepipe, bars of rail steel, and titanium alloys. The pipe welding projects incorporated advances from the HOPWRP and demonstrated the applicability of the improved welding technique on other materials and shapes.

Mechanical Testing Procedures

Standard mechanical testing of the completed welds included impact toughness testing, tensile testing, hardness testing, and metallurgical examination. Other tests performed on a limited number of welds included bend testing, CTOD, and low cycle fatigue. The standard tests, as specified in the Hammond Criteria, are described in the remainder of this section.

Impact test specimens are full size (10 mm x 10 mm x 55 mm) for welds in which the pipe is schedule 160 (0.438 in.) wall, half size (5 mm x 10 mm x 55 mm) for schedule 80 (0.300 in.) wall pipe welds. In other words, full size specimens are tested for material A and C welds, half size specimens are tested for material B and D welds. Specimens are cut to length with the weld line centered in the specimen, and standard Charpy V-notches are cut in the specimens at the weld line on a specimen side corresponding to the through wall thickness of the weld joint (for example, the 5 mm wide face is notched on the half size specimens). Testing is performed at 0°C by immersion of test specimens in an ice water bath at least five minutes prior to testing. The test values reported are actual test values, no adjustments are made for non-standard specimen sizes.

Tensile tests are performed on strip specimens with 0.50 in. specimen width in the two in. gage length, with the weld line centered in the gage section. Specimen thickness can vary from full thickness specimens (no machining on ID and OD) to less than 0.200 in. for flat specimens from welds requiring extensive cleanup due to non-symmetrical weld line deformation. Typically, flat specimens are nominally 0.25 in. in thickness. Cross sectional area of the specimens is obtained by measuring the width and thickness of each specimen to the nearest 0.005 in.

Tensile testing is performed on an Instron Model 1125 test frame with a 100 kN load cell at a constant crosshead speed of 2 mm/minute. The load-displacement curve is plotted on chart paper during testing, this plot is then used to determine peak load and yield point load in cases where a yield point phenomena is observed. After testing to failure, the specimen halves are placed together and the final gage length, along with width and thickness at necked location, is measured and recorded. These values are used to calculate percent elongation after failure and percent reduction in area after testing.

Hardness traverses are performed using a Vickers macrohardness tester with a load of 10 kg. applied for 15 s. A typical traverse covers 50 mm, 25 mm on each side of weld line, with indentations spaced 1 mm apart.

RESULTS

The results are presented by material, chronologically, starting with Material A, then B, C, D, and N. Material compositions for all materials are presented in Table 1. The last topic presented in this section reviews some of the metallurgical and related studies conducted during the program. As indicated in the summary of results, during the second year, the traditional approach to homopolar welding underwent a transformation from a contact resistance heating controlled process to a geometric heating controlled process. The new technique successfully joined the two higher strength materials (B & D), producing acceptable strength[2], impact toughness, hardness, and microstructure as required by the Hammond Criteria. In the lower strength materials (A & C), acceptable strength and hardness were easily achieved, but acceptable impact toughness was not achieved with any consistency. When a new material was introduced to the program, the most current welding technique was applied. Consequently, no attempts were made to join materials C and D with the traditional HPW method.

Material A

Material A , a hot-rolled, nominal 3 in. schedule 160, X52 seamless pipe, had the highest carbon content and IIC_{EQ} of the materials joined during the HOPWRP and was judged the metallurgically "dirtiest" of the materials joined. It was the only material joined in the preceding NSF-OTRC program and the first material joined in the HOPWRP. Over the course of the five year program, 27 welds were completed in the first year using the traditional approach, and 8 additional welds were completed over the remaining 4 years investigating postweld pulsed heat treatments, and other miscellaneous parameters using traditional and modified weld parameters.

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[2] Material B, a controlled-rolled material, consistently failed the strength requirements when tested with flat specimens. In service, the typical weld bulge would improve the tensile properties of a material B. Controlled-rolled materials typically soften in response to high heat inputs and the short thermal cycle of HPW limited the softening ± 5mm of the weldline.

Summary of experiments and findings

The majority of the welds performed in material A used the traditional welding approach. The A1 series consisted of eighteen welds investigating the effect of discharge speed, upset duration, and electrode gap. The nine weld A2 series investigated upset pressure and upset delay. Full strength was easily achieved when the upset force was applied while the weld metal was sufficiently hot to forge the joint. Approximately 50% passed the tensile test requirements, all having similar weld parameters with peak current densities between 77 and 85 kA/in^2. All specimens had unacceptably low impact toughness, failing both the minimum average and individual acceptance criteria.

Series A3 consisted of two welds joined using the traditional weld parameters followed by a postweld pulsed heat treatment (weld bulge removed). This welding procedure improved the impact toughness to acceptable levels (minimum individual and average of 27 and 36 ft-lb., respectively).

Series A4 and A5 consisted of two welds each, performed with a bevel joint prep and a step and bevel joint prep, respectively. One weld from each of the series was postweld pulse heat treated, and a single simulated weld[3] in material A (AS1.1) was performed at the A4 weld parameters. Tensile properties remained acceptable and were unaffected by the different thermal cycles and joint geometries. Impact toughness remained unacceptable. Impact toughness between the simulated weld and the weld were similar while the impact toughness increased with the post weld pulsing for both A4 and A5 series welds.

The last weld performed in material A, MA1.1 used the fully modified weld parameters on "schedule 80" equivalent material. The inside was machined to 0.3" wall and performed at weld parameters used to successfully join materials B and D. Peak current and temperature were similar to B and D material, but this weld had typically acceptable tensile properties and low toughness.

Material A Summary

In general, material A did not achieve acceptable impact toughness in the as-welded condition, regardless of weld parameters. Post-weld pulsed heat treatments increased the impact toughness to acceptable levels in traditional HPW. While a limited number of material A welds performed with the modified HPW, weld parameters may exist that could successfully join this material. No welds were performed to adjust the heating or cooling rate or the deformation.

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[3] Simulated welds were performed by machining an equivalent profile in the middle of a solid pipe of equal length to the pair of single pipes. Simulated welds have similar responses to the welding imputs, current and load, including peak current, temperature, and deformation. Since no interface in present in simulate welds, properties of simulated welds reflect the effect of the thermal-deformation cycle on the base metal.

Material B

Material B, a controlled rolled, nominal 3 in., schedule 80 X60 ERW pipe, had the lowest IIC_{EQ} of the materials welded and was the only controlled-rolled material tested. It was micro-alloyed with Niobium. and, as a result of its calcium treatment during steelmaking, was considered one of the cleaner materials studied in the HOPWRP.

Summary of experiments and findings

Material B was the first new material welded in the HOPWRP, beginning late in the first year. Early weld series used the traditional approach, but during the second year, the joint geometry was modified and the loading sequence was adjusted. The welding program of material B ended early in the third year.

The first eight weld series totaled 45 welds and were joined using the traditional approach with variables including discharge speed, field current, upset delay and duration, initial load, and electrode gap. Series B2 used a 1" electrode gap and varied upset delay and duration over a nine weld test matrix. Five of the nine welds had acceptable impact toughness, but the variability of the toughness results was unexpected. Unexplained through-wall microstructural variation was also observed with this series. The next series, B3, attacked the lack of uniformity by substantially lowering the field to allow increased for uniformity of heating. The variables were discharge speed and upset delay. No improvements to the impact toughness resulted from these parameter variations.

The next four weld series consisted of 9 welds to further investigate possible causes of low toughness. B4 and B5 were one-weld series using a ramped field and a constant load, while the two welds in the B6 series were postweld pulse normalized. The four welds in the B7 series varied the initial load and discharge speed. The B8 series consisted of 11 welds with weld variables of initial load and upset delay. From this group of 20 welds, the two pulse-normalized satisfied the toughness requirement and had lower than usual variability . Six of the B8 welds had acceptable impact toughness, but all welds from this series demonstrated highly variable impact toughness with the ratio of minimum to maximum ranging from 4% to 62%. The toughness and variability had no correlation to the weld variables.

The B9 series was performed during the first month of the second year and initiated the transformation of the welding process. This series consisted of fourteen welds with weld parameters designed to investigate the effect of five parameters on weld quality. These welds used higher initial loads and beveled end geometry on several of the welds. Only four welds achieved acceptable impact toughness with minimum to maximum ratios from 26% to 73%. The weld with the best toughness and lowest variability used a beveled joint and a constant high load, and displayed no weldline hardening, typical of other welds in the series.

The ten-weld B10 series built on the successes of the B9 series, focusing on end geometry and initial loading. These parameters improved the impact toughness and reduced the variability.

Only one weld, a flat end geometry, failed to satisfy the impact toughness criteria. Again, a weld with a steeper bevel and a constant high load had the best overall toughness.

The nine-weld B11 series investigated the effect of end geometry, high initial load duration, electrode gap, and energy on weld quality. The four welds meeting the toughness criteria had greater upset displacement as dictated by the weld parameters. The shorter electrode gap used on three of the welds reduced the degree of weld line softening, generally smoothing out the hardness profile through the weld zone.

The B12 series was an eight-weld, seven-parameter series investigating the effect of these weld variables on weld quality. The parameters include bevel angle and contact width, upset delay and duration, initial and upset load, and discharge speed. The results of this series were fairly complicated and unsuited for summarization since so many of the parameters were aliased with others. The only variables that correlated with impact toughness were discharge speed and upset delay, both directly affecting the volume of material heated. Only two welds failed the impact toughness criteria.

The B13 series was an eight-weld, three-parameter, two-level test matrix, investigating upset delay, discharge speed, and bevel angle. 50% of these welds exceeded the impact toughness criteria, and the remaining four had a single test , failing the individual minimum criteria. No correlation was found between the weld parameters and welds with single low values. These were the first welds where the occasional low impact toughness was observed. Initially the cause was attributed to localized "brittle zones."

The B14 series was a six-weld confirmation series using a bevel end geometry and a pulsed load, with initial load set at 50% of the upset load. All welds had exceptional impact toughness, exceeding the parent metal toughness.

The B15 series was a six-weld series investigating the effects of the interface surface finish on weld quality and process parameters. Weld parameters were identical to those of the B14 series. Mechanical testing consisted of cutting alternating metallurgical and impact toughness specimens from the circumference of the welds. Overall impact toughness was slightly lower than the B14 series, with only two of the 72 specimens having unacceptably low impact toughness. The metallurgical specimens revealed no microstructural features associated with toughness variation.

The B16 and B17 weld series were part of the postweld pulse heat treatment studies similar to A4 and A5 and weld BS1.1 was part of the simulated weld study. Full mechanical testing was performed on these specimens. The B16 series and BS1.1 had a bevel end geometry while B17 welds used the step and bevel end geometry. All were welded with an initial load set at 50% of the upset load. For the B16 series and BS1.1, the impact toughness exceeded base metal properties, with a slight reduction in toughness with postweld heating. One specimen in the BS1.1 had low impact toughness. For the B17 series, post weld heating slightly increased the impact toughness. Post weld heating slightly reduced the tensile properties in the B17 weld only.

The B18 series was a four-weld confirmation series using weld parameters from the D5 confirmation weld series. This series used the transformed weld parameters of the modified homopolar welding technique: constant high load and step and bevel end geometry. Mechanical properties were typical for this material, with slight reduction in tensile properties and better than base metal impact toughness.

The four-weld B20 series was similar to the B18 series, using material D weld parameters, D7.2. The D7.2 weld was the first weld using the radiused bevel shoulder to produce a smoothly transitioning weld bulge on the OD and ID of the pipe wall with a thin extrusion, referred to as the "fin", containing the original step and interface material. Two of the welds were CTOD tested by Omni Engineering, one was mechanical tested in house and one was held for display. The CTOD results, included in the 13th Quarterly Report, were good with CTOD values ranging from 0.0226 to 0.0263 in. over six tests. Mechanical properties for the remaining weld were typical.

The last weld series consisted of two welds using material B which had been normalized prior to welding to produce a coarser microstructure, possibly similar to that of the X52 materials. These welds were indistinguishable from the unquenched base material welds having similar process characteristics and excellent toughness. The normalizing process produced a coarser microstructure as it softened the base metal. The welding process refined the weld zone microstructure, resulting in weld zone hardening only, and increasing to 50% of the original (prior to normalizing) base metal hardness. This response was similar to the X52 hardness.

The B19 weld series was a four-weld series with each weld containing intentionally placed flaws possibly occurring in HPW welds. These were produced for the nondestructive testing program. These are discussed in detail in the NDE section of the report. No mechanical testing has been performed on these welds.

Material B Summary

In general, material B was a homopolar weldable material, achieving acceptable properties within the band of all welding approaches attempted. With the flat end, pulsed load technique, acceptable properties in the as-welded condition were achieved, but the impact toughness variability was excessive. Postweld pulsed heat treatment reduced the variability while maintaining toughness. Use of a profiled joint preparation, either a bevel or a step and bevel, combined with a higher initial load, improved the impact toughness and reduced the variability. Tensile properties were less than parent metal values despite weld parameters, and post weld heating further softened this material despite previous thermo-mechanical history.

Material C

Material C, a normalized, nominal 3 in., schedule 160, X52 ERW pipe, had a low carbon content (0.11) and IIC_{EQ} (0.34). Despite the improved chemistry compared with material A, this material had similar homopolar weldability. Material C welding began during the second year with 16 welds being completed during the remainder of the program.

Summary of experiments and findings

All of the material C welds were performed with either bevel or step and bevel end geometry. The C1 series consisted of three welds to establish the welding parameters for the new material. Weld variables included electrode gap, discharge speed, and end geometry (bevel angle), with peak current densities between 77 and 79 kA/in^2. All exceeded parent metal yield and tensile properties but displayed 50 to 65% reduction in % elongation. All toughness specimens had unacceptably low impact toughness, displaying 100% cleavage fracture.

The C2 series consisted of eight welds with weld variables of discharge speed, field current, and initial load. The end geometry was a 30° double bevel with the contact width one third of the wall thickness. Peak current density ranged from 73 to 84 kA/in^2, and impact toughness was low for all welds.

The C3 and C4 series and the CS1.1 weld were similar to A4, A5, and AS1.1, investigating postweld pulsed heat treatment and the effect of the weld interface on properties. Postweld pulse heating improved mean impact toughness in C3 series by a factor of five, but also increased the range by nearly the same factor, with a single unacceptably low test results. The C4 welds were performed at a lower discharge speed and postweld pulsing had no significant effect on toughness. The simulated weld, CS1.1, had low toughness similar to the weld.

The last C weld performed, MC1.1, was similar to MA1.1, with the wall machined to 0.3" thick and welded at parameters successfully joining materials B and D. As with MA1.1, the tensile properties were similar to the parent metal, but the toughness remained low. The weld metal was finer grained than base metal, with a grain size more similar to the B and D materials.

Material C Summary

Only a limited number of welds were performed in the C material, and overall it was not found to be homopolar weldable. Future studies might investigate adjusting the cooling rate (electrode gap), heating rate (field), and load to improve the toughness.

Material D

Material D, a quenched and tempered, seamless, nominal 3 in., schedule 80, X65 pipe, had the lowest carbon content of materials welded in the HOPWRP. This Niobium micro-alloyed material was calcium treated and was among the cleanest in the test program.

Summary of experiments and findings

This material was the last three inch material studied in the HOPWRP and the primary material used to define the modified welding technique and determine the tolerance band for weld parameters. Better than 95% of the material D welds used the step and bevel end geometry and the constant load

The D1 and D4 weld series were part of the postweld pulse heat treatment studies similar to A4 and A5 series and weld DS1.1 was part of the simulated weld study. All were welded with an initial load set at 50% of the upset load. Series D1 and weld DS1.1 used bevel end geometry, and Series D4 used step and bevel geometry but at 8% lower discharge speed. Full mechanical testing was performed on theses specimens. With these parameters, material D displayed variable impact toughness for all welds, and unacceptably low average impact toughness for all but the simulated weld and the as-welded step and bevel end weld. Tensile strength was similar to parent metal for all welds, but yield strength was at parent metal only for the simulated weld and the as-welded bevel end weld.

The D2 series consisted of six welds using six different profiled end geometries, identical initial and upset load, and three discharge speeds. Tensile properties were similar to base metal while impact toughness was low or variable. Only the weld with the beveled interface had acceptable impact toughness, with one exceptionally high test.

The D3 series was eight-weld, three-parameter, two-level test matrix, investigating weld energy (discharge speed) and two features of the end geometry, step length and bevel angle. All used a constant high load. Five of the eight welds had acceptable impact toughness without excessive variability. The welds with low impact toughness had longer narrow step geometry which increased weldzone temperatures and allowed substantially more deformation. Tensile properties were similar to parent metal for all welds. Welds had HAZ softening on either side of harder weld centerline. This series was the first step and bevel series with the high constant load and provided baseline parameters for the D5 and D6 weld series. It demonstrated a set of weld parameters that produced excellent mechanical properties.

The six-weld D5 confirmation series was based on weld D3.2 and produced consistent high impact toughness and base metal tensile properties, similar to D3.2 This series demonstrated the repeatability of these weld parameters.

The D6 weld series was an eight weld, three-parameter, two-level test matrix investigating field current, load, and step width. All welds had acceptable impact toughness with the exception of a single low value (1 of 40). Tensile properties were all at parent metal values. This series identified the interaction between field current level and contact width: increasing the field and contact width produced better impact toughness than increasing only one. Matching generator parameters to end geometry parameters can improve properties.

The D7 series was a nine-weld series consisting of three welds to improve the weld profile, five additional confirmation welds, and a final weld to investigate the field current-discharge speed interaction. The first three welds identified the radiused bevel shoulder parameter that produced a smooth transition between the pipe wall and the weld bulge with a thin extrusion, the fin, extending from the center of the weld bulge. The five confirmation welds were based on D7.2, with the radiused bevel shoulder. Two were CTOD tested by Omni Engineering, one was saved for display, and the remainder mechanical tested in house. The CTOD results, included in the 13th Quarterly Report, were good for four of the six specimens with CTOD values ranging from 0.0201 to 0.0253 in., and one low test from each weld at 0.00424 and 0.0100 in.. Mechanical properties for the remaining weld were typical. D7.7, the field current-discharge speed weld, is discussed with the D8 weld series.

The D8 series consisted of eleven welds, an eight weld, three-parameter, two-level test matrix, with the remaining welds confirmation welds or welds with a single parameter changed. The D7.7 weld became part of the D8 test matrix. The test matrix investigated the three primary end geometry parameters, step length, step width, and bevel angle. The two welds with the long narrow steps had exceptionally low toughness, as expected, but typical tensile properties. The remaining welds from the series had excellent toughness and strength, now typical of these weld parameters. This series concluded the transformation of the welding process to one where the heating and deformation response was substantially controlled by the joint profile, with no reliance on interface heat generation. The shaped end controls the temperature profiles by controlling the local current density. With the high load, the shaped end forges as it reaches a forging temperature. This limits the peak temperature and decreased the time at temperature, producing a fine weldline microstructure similar to the parent metal.

The D9 series was an eight weld series designed to evaluate end geometry sensitivity. Mismatched upper and lower end geometries were used, many taken for the D8 series. Overall this series demonstrated the robustness of the step and bevel end geometry, with six of the welds satisfying the toughness criteria. One failed the minimum individual criteria, probably attributed to the occasional low toughness. The other failed the minimum average toughness criteria, and was probably due to insufficient heating and deformation.

The D10 series consisted of 16 welds designed to determine the sensitivity of the welding method to real world conditions like misalignments of the welds and coarser surface finishes. The misalignments included radial and tilt. Joints were prepared with portions of the step machined away (segments). Four of the welds were baseline specimens, two of which were submitted for fatigue testing. The welds with the radial misalignment heated uniformly but could not be impact tested due to excessive lateral displacement during welding. Two of the welds with tilt misalignment had a single low impact toughness test, probably occasional low toughness. The other that failed had portions of the step removed to produce circumferentially non-uniform heating and had a single high toughness value with the other two specimens having no toughness. The cause was attributed to uneven heating and the delayed collapse of the step. The degree of misalignment, mismachining, and surface finish exceeded the achievable tolerances currently in practice, demonstrating the robustness of the process.

The next four weld series, D11-D14, consisted of 35 welds, including several small studies on single parameter effects of the end geometry and load response. Five additional real world welds were included. These items will be reviewed according to the specific study. Weld quality was based on impact toughness for these welds.

Wavy interface. One weld was prepared with an intentionally wavy interface to continue the real world condition study. This weld had a discretized wave machined into the end of one pipe with an amplitude of 0.005 in. peak to peak, and a period of one fourth of the circumference.

The points of first contact heated first, but the entire step rapidly heated to a red glow then forged. The impact toughness was substantially reduced, but the still acceptable.

Commercial end preps. These large geometry welds were prepared by CRC-Evans using a commercial pipe facing machine. The interface was uncleanably rough. All four welds had excellent impact toughness, with the two higher energy welds having some of the best, most consistent properties. This study demonstrated the robustness of the process and the suitability for use with commercially supplied joint preparation.

Step Length Study. This study included ten welds based on the small and large geometry end preps. For both studies, the step length was varied about the nominal geometry in 0.025 in. steps, with two on each side. The maximum step length equaled the step width for both geometries. This study showed the large geometry to be relatively insensitive to step length over the lengths studies, while the small geometry had its optimum length at the baseline setting, falling off steadily on either side. These studies were for constant generator and welding fixture settings.

Step Width Study: This study consisted of two new welds with the step width decreased by 0.025" from the baseline value for both end geometries. This study showed the small geometry to be relatively insensitive to reduced step width, but the large geometry had reduced impact toughness as the longer step approached the long narrow shape of the two low toughness D8 welds.

Radial Step Position. This four weld study shifted the radial location of the step in the pipe wall toward the outside for both baseline geometries in increments of 0.025 in. and 0.050 in. Of interest was the effect of step position on ID weld profile. Shifting the step towards the OD increased the actual weld displacement and with the 0.025 in displacement, the ID profile was improved. At 0.050 in shift, the ID fin was barely displaced past the wall. Impact toughness was exceptional for all welds.

Axial Interface Position Study. This study investigated the impact of the axial position of the step interface on weld properties. This was accomplished by comparing a base line weld, one having the interface centered between the edges of the bevel, to a welds with the entire step attached to one bevel and only a bevel on the other. An additional pair of welds replaced the attached step, with ring, of identical proportion to the step, and butted to two beveled pipe ends, effectively adding one more interface. A simulated step and bevel weld was also included in this study for comparison to a weld with no interface. The effect of these variations had little effect on the measured heating or displacement, but the off-centered steps had reduced toughness and the additional interface of the ring-insert-welds reduced the toughness further. The simulated weld had similar properties to a baseline weld. The loss of toughness in the other welds may have resulted from increased temperature and slower cooling from the unbalanced interface location or the extra interface.

Bevel Shoulder Radius Studies. The bevel shoulder radius was studied in six weld, looking at three effects. The first investigated the effect of increasing the shoulder radius on the weld profile and the weld properties. The increased bevel radius heated and forged more , even at a slightly lower discharge speed. Impact toughness was slightly lower, but still exceptional. The second study expanded the first by using a lower constant load to investigate the effect of reducing a system parameter. These welds had excellent impact toughness except for one low value, thought to be an occasional low toughness specimen. The last bevel shoulder radius study compared a shallower bevel, larger radius combination to a steeper bevel, smaller radius. The finished welds were largely indistinguishable in profile and properties. Process parameters were also similar.

Load Studies. Six welds were performed primarily to investigate the effect of various load settings on weld quality. Welds were performed in pairs using both baseline geometries. The first two welds used lower load and higher discharge speed which produced only slight reduction in toughness. The second pair investigated the effect of discontinuing the high load before the generator stops completely. Lowering the load after primary forging might reduce the degree of cold work and residual stress in the welds. These welds had lower but exceptional toughness. The last pair of welds applied an even higher load for a short duration when step collapse commenced to offset the drop in the applied load. One of these welds had lower displacement, which was attributed to premature collapse of the step and loss of that component of the thermal energy. This weld had unacceptably low impact toughness resulting from the reduced heating and deformation. The other weld had typical properties.

The last weld series consisted of two welds in material D which had been normalized prior to welding to produce a coarser microstructure, possibly similar to that of the X52 materials. These welds were indistinguishable from the unquenched base material welds having similar process characteristics and toughness. One CVN specimen even displayed low toughness. The normalizing process produced a coarser microstructure, softening the base metal. The welding process refined the weld zone microstructure and produced weld zone hardening only, reaching near original (prior to normalizing) base metal hardness. This response was similar to the X52 hardness, while the toughness was typical of the D material.

Material D Summary

In general, material D was readily homopolar weldable and served well as a material for developing and testing new weld parameters. Most welds made with the new welding technique had exceptional toughness, and those failing to meet the toughness criteria were cold or hot with insufficient or excessive displacement. Through these studies, the bounds of HPW parameters was established and knowledge of which parameters produced unacceptable welds was acquired. The studies completed to date may only scratch the surface of the control of the welding process possible through the seven to eleven available parameters. Further discussion and figures are found in Appendix B.

Material N

Material N, a quenched and tempered, seamless, nominal 12 in., 0.50 in. wall, X65 seamless pipe, is similar in chemistry and heat treatment as material D. Both were supplied by the Nippon Steel Corporation.

Summary of experiments and findings

This is the only 12 in. material welded in the HOPWRP, and only seven welds have been produced using the new 12-inch welding fixture. Prior to performing welds, solid pipe tests were performed to commission the new welding machine and to set generator parameters for welds. Initially, the 12-inch homopolar welder was configured to use two of the Balcones Homopolar Generators (BHPG) at near peak output. Due to the arrangement of the laboratory, the existing BHPG busswork and the busswork extensions and cables necessary to connect to the 12-inch welding machine increased the total circuit resistance significantly, limiting the energy available for welding. A simulated weld and one weld were performed with two BHPGs, but both welds were not full section welds. After reconfiguring the system to use three BHPGs, six additional welds were completed. Only the first three-generator weld was not a full section weld, being performed at insufficient discharge speed.

The initial material N welds were designed to identify an optimum set of baseline parameters for future welds. Figure 1 shows a defacto weld test matrix with three parameters: field current, geometry, and discharge speed. As indicated by the figure, the middle of the matrix was emphasized since the parameter combinations at the top and bottom would produce cold or hot welds, respectively. Welds in the center of the matrix received sufficient energy to form full section welds while minimizing peak temperatures.

All five full section welds (N1.3-7) had similar responses to the application of the current pulse and the continuous forging load, typical of the step and bevel end geometry. As with the 3 in. welds, base metal tensile properties were easily achieved, but impact toughness was not. All had unacceptably low weld line impact toughness at 0°C test temperature. Off-weld line impact toughness increased to base metal properties in 1 to 2 mm. Weld line tests at room temperature had higher toughness for weld N1.6, but not for N1.7, indicating that the welding process had shifted the transition temperature curve to higher temperatures. Weld parameters and test results are presented in tables 2-4. The simulated weld and the first three welds were low energy, partial welds. Two of the four, having better impact toughness, had finer weld line microstructure and were also the lower energy welds. The other two were similar to full section welds. The coarser microstructure in the higher energy welds is related to the loss in toughness. Causes of coarser microstructure include higher peak temperature, slower cooling, and less dynamic recrystallization. Adjusting the weld parameters may not be sufficient to correct these problems, necessitating modifying the welding fixture. These modifications are discussed in the section of the 12-inch welding fixture.

Material N Summary

This first set of 12 in. welds demonstrated the scalability of homopolar welding and the ability to deliver the required energy to the weld interface. Parent metal tensile properties were achieved immediately with the step and bevel parameters. High current levels were introduced through the outside of the pipe repeatably without damaging the surface of the pipe or the electrode. The inability to achieve acceptable impact toughness in these first seven welds is

Three Inch Welding Fixture

The 3-inch laboratory welding fixture consists of a load-controlled hydraulic press and the 10 MJ homopolar generator, often referred to as "Old Blue". Both have been used for welding and forging research over the past several years, with minimal modification to the basic operation. At the beginning of the HOPWRP, a new control system was installed to improve the operation and control of the generator and improve the data acquisition system. Figure 2 presents a cutaway of the 10 MJ homopolar generator. Figure 3a-d presents photographs of the hydraulic welding fixture and the workpiece before, during, and after a weld, and figure 3e shows a schematic of the thermo-mechanical cycle of the weld interface during a weld.

During the second year a spherical bearing was installed between the lower platen and the hydraulic ram to improve circumferential interface uniformity and produce more uniform heating. As the parameters were modified with use of the bevel end geometry and higher initial loads, the magnitude of the lateral shift increased due to the reduced tilt constraint of the spherical bearing. The new welding parameters lacked the high sensitivity to uniformity of initial contact of the original parameters, so the spherical bearing was removed.

Even with the removal of the spherical bearing, welds continued to have lateral displacements. Guides were installed to improve lateral stiffness of the fixture with limited success. Procedures were implemented to carefully position the weld in the center of the four shafts connecting the upper and lower platens. These two measures reduced the lateral shift substantially and are currently in use.

Twelve Inch Welding Machine

One of the major program tasks was building a new welding fixture capable of joining larger diameter pipe. The additional cost for this fixture was estimated at $289K as presented in the first annual report. A design engineer began working on development of fixture during the second year with detail drawing reported as 60% complete by middle of the third year. During the design of this fixture, the requirements changed from one that applied the loads through the outer surface of the pipe wall to an end-loaded design. This was an expedient cost cutting measure where the fixture would now only demonstrate the scalability of the welding process from 3 in. pipe to 12 in. pipe. When complete, the fixture would deliver the current pulse to the workpiece through the pipe outside surface and forge the joint. Gripping would be left for the next fixture. A discussion of the design requirements for the 12-inch fixture is found in Appendix B.

Even with the additional funding from the DOI and DOT, the fixture design required substantial design optimization to minimize the cost. Final design was completed and work finally commenced during the fourth year. CRC-Evans assisted with the final design and detail drawings. The final design incorporated available components to minimize costs.

Performing an electrode performance study was part of the research conducted to evaluate scalability of the welding process. The initial study identified limitations of the electrode design in making sufficiently uniform contact across a single 3 in. electrode. Subsequent studies used a compliant insert between the electrode and the pipe outside surface to improve the uniformity of contact. This modification was successful and implemented in the final electrode design.

The fixture was finally completed and tested during the first quarter of the final year. All available manpower was enlisted to complete the fixture during the previous two quarters. The first weld was completed on April 21,1997 using two generators operated near their maximum speed. The weld was incomplete due to insufficient energy as a result of the reduced the circuit efficiency from extended busswork and cables. A third generator was brought on line and the next weld was completed one month later, May 29, 1997. Five additional welds were completed over the remaining seven months.

The new 12-inch fixture was designed to join 12 in. schedule 60 steel linepipe, having a cross-sectional area of 21 in^2. A schematic of the 12-inch fixture is presented in figure 4. The busswork, consisting of the 36 hexapolar cables, the aluminum bussbars, and the central "turret" buss assembly, is not shown. Figure 5 presents a photograph of the "upset module" of the 12-inch welding machine with the hexapolar cables attached. The features and capabilities of the new fixture include:

- 1.5 MA peak current with 100 ms rise time.
- 430,000 lbf forging force delivered by parallel-configured hydraulic cylinders to an internal 4 in. diameter tension rod.
- Constant load enabled by a single, high-pressure, 5 gallon gas-pressured accumulator.
- 12 pairs of hydraulically actuated electrodes to conduct the current across the pipe OD and to constrain the motion of the pipes during upset to axial displacement.
- A data acquisition system designed to acquire up to 15 channels of data.

Presently, the 12-inch fixture is capable of delivering the required energy and load with acceptable circuit losses and has demonstrated full strength welds with acceptable weld profile. A remaining task is to demonstrate that acceptable impact toughness can be achieved consistently in the 12 in. welds and this may be material dependent to some extent as for the earlier 3 in. welds. Some of the features of the 3-inch welding fixture were not incorporated in the 12-inch fixture and their absence may have contributed to the low impact toughness. The lack of massive busswork adjacent to the electrodes slowed the postweld cooling rate, possibly producing a coarser microstructure. The radial bussbars mounted on the two inch thick iron platens develop high axial electromagnetic repulsive forces between the upper and lower bussbar/platen assemblies. The effect of such massive repulsive forces is still not fully quantified, and the load cell output partially conflicts with conventional understanding of the expected effect. On the next weld, modifications to the welding fixture to increase the cooling rate will be incorporated , and extra instrumentation will be attached to the fixture to monitor the load response more completely.

NONDESTRUCTIVE TESTING AND EVALUATION RESEARCH

Summary of the NDE Research

The major accomplishments of the NDE research included identifying the flaw characteristics of homopolar welds, identifying the best suited method for detecting such flaws, developing of procedures for destructively testing for verification of NDT, developing probes and calibration specimens for ultrasonic testing, and beginning in-house test procedures. The work remaining for this portion of the HOPWRP include optimizing the tandem probe test, writing procedures, and verifying test performance. Destructive inspection of the B19 series will follow final testing with optimized test procedures.

In closing out this section, much work was performed towards developing the NDE program, but as an added program, funding was never sufficient. Advancing technology requires considerable time and money. The primary goal of this project was developing a welding method, which it did. The research program did not complete the development of the nondestructive tests and procedures sufficiently to qualify the process, but this initial work was a valuable start to the process. In subsequent programs, the task of completing the development of the nondestructive test method will benefit from these accomplishments, but at this point, NDT contractors may be the best suited for this work, especially those with past experience in NDT of solid state welds.

COMMERCIALIZATION

During the five year program, Parker Kinetic Designs, Inc. invested considerable time investigating potential commercial applications for homopolar welding, including economics of J-lay, reeling applications, and coil tubing. They also designed a 15 MJ homopolar generator specifically for welding applications. A comprehensive summary of their work is included in Appendix D, covering the following:

- Commercial Applications for Pulsed Power
- Market Considerations for Near-Term Applications
- Homopolar Pulsed Welding Equipment Description
- Homopolar Pulsed Welding Advantages and Economics

This section, which was prepared by PKD, also includes a paper on the economics of homopolar welding presented at the ASME/API Energy Week Conference, Houston, Tx, 1996.

FUTURE WORK

The HOPWRP advanced homopolar welding technology towards its ultimate goal of commercialization, but additional research and testing must be completed for the welding process to gain industry wide acceptance as a commercial welding process. Sufficient welds must be produced and tested in commercially used pipe sizes to demonstrate capabilities and reliability of HPW for J-Lay applications. Lifetime performance characteristics of these pipe welds must be determined as required by the industry. QA/QC procedures and techniques must be developed capable of qualifying the acceptability of the overall process and each weld, assuring the reliability of the process and the quality of the individual weld. Finally, developing and demonstrating formal procedures for qualifying the homopolar weldability of a new material and the determining the welding parameters would prepare HPW for the commercial market.

A proposed research effort addresses these needs with a focused program, bringing in expertise from appropriate organizations to insure its success. Producing 12 in. welds with acceptable impact toughness will be the initial focus and include adjustments to the welding parameters and fixture as necessary. It will conclude with a test matrix to evaluate parameter sensitivities and subsequent confirmation welds. The fatigue study begins initially with 3 in. welds and subsequently on 12 in. weld, with fatigue testing being performed by experienced fatigue testing agencies. The nondestructive evaluation program includes a fracture mechanics analysis to determine the critical flaw size and how an isolated critical flaw affects weld performance. The NDE program also develops ultrasonic testing technology for homopolar welds. Test results will be implemented using automated or mechanized ultrasonic testing system. Development of procedures for qualifying materials and setting weld parameters is incorporated in the general welding research.

CLOSING REMARKS

The five year HOPWRP investigated four different 3 in. materials and adapted the welding process to produce acceptable welds in two of the four materials, both higher strength and considered more difficult to weld. The changes to the welding process constituted a transformation of the basic approach to homopolar welding, from a process where heat generation depended primarily on contact resistance to one where joint shape controlled heat generation. The new technique for homopolar was demonstrated to be a robust process, with a wide tolerances on multiple weld parameters, permitting optimization of a single parameter. The new approach produced excellent welds at lower generator speeds, allowing larger sections to be joined without increasing the generator size, and used a simpler load control system that decreased the complexity of the welding machine. Finally, the range of parameters producing acceptable welds was well understood, permitting production of consistently excellent welds.

The new HPW technique was incorporated in the design of the 12-inch welding fixture and full-section welds were produced when equivalent energy was used, based on peak current density, rise time, and pulse length. This demonstrated that larger cross-sections could be joined in the same time as small sections by maintaining similar current density. The welding time was independent of area joined. Full strength welds with acceptable weld profile were achieved by the third weld, but acceptable impact toughness was not in any of the remaining four welds. The causes of this deficiency have been attributed to lack of equivalency between the 3 and 12-inch fixtures. Future 12 in. welds will address these differences and should improve impact toughness.

Table 1. Mill Test Report Data

API 5L Carbon Steel Linepipe WELD PREFIX CODE	A	B	C	D	M	N	P
SUPPLIER	Dixie Pipe	Prudential	Lone Star	Nippon	NKK	Nippon	NKK
API 5L GRADE	X52	X60	X52	X65	X52	X65	X65
SCHEDULE	160	80	160	80	60		60
OUTSIDE DIAMETER	3.5	3.5	3.5	3.5	12.75	12.75	12.75
WALL THICKNESS	0.438	0.300	0.438	0.315	0.562	0.50	0.562
TYPE	Seamless	ERW	ERW	Seamless	Seamless	Seamless	Seamless
HEAT TREATMENT (not on mill test report)	Hot rolled	Controlled rolled	Normalized	Quenched & tempered	Hot Finished	Quenched & tempered	Hot Finished
LADLE CHEMISTRY							
C	0.23	0.13	0.11	0.08	0.08-0.12	0.08	0.11
Mn	1.04	0.65	1.13	1.29	1.07-1.13	1.29	1.34
P	0.010	0.005	0.014	0.011	0.006-0.014	0.011	0.015
S	0.009	0.004	0.005	0.002	0.001	0.0017	0.002
Si		0.22	0.28	0.19	0.21-0.29	0.189	0.23
Al		0.042	0.037		0.026-0.046		
Cr		0.03	0.073		0.04-0.07		
Mo		0.01	0.028	0.22	Tr	0.215	
Ni		0.01	0.07		0.02-0.03		
Cu		0.02	0.13		0.01-0.02		
Cb		0.18	0.034	0.032	Tr	0.032	
Ca		0.0048		0.0026	0.0020-0.0028	0.0026	
Ti			0.008		0.002-0.005		
V	0.08		0.040		0.003-0.04		0.065
B			0.0003		Tr -0.0003		
				0.035 Ti-Al		0.035 Ti-Al	
IIW C_{eq}	0.42	0.23	0.34	0.34	0.28-0.33	0.34	
Yield Strength (ksi)	66.0	79.5	59.5	71.6 *	62.75*		65
Tensile Strength (ksi)	94.4	86.1	79.5	80.7 *	78.4*		83
% elong in 2"	30	22	37	26.6 *	31.37*		42.7
Vickers Hardness (kg. mm^2)	193.2	181.9	171.0	185 *	186-204	219*	

* In-house test results, not included with mill test report.

Table 2. N1 summaries

a. Weld Parameters

Weld No.	# Gen	RPM	Field	Load	Gap	Step width	Step Len.	Bevel Angle	Sh'der Rad.
			[A]	[kip]	[in.]	[in.]	[in.]	[°]	[in.]
N.S2	2	5850	280	385	2.5	0.166	0.083	30	0.150
N1.1	2	6050	280	385	2.5	0.166	0.083	30	0.150
N1.2	3	4500	350	385	2.5	0.166	0.083	30	0.150
N1.3	3	5700	265	385	2.5	0.166	0.083	30	0.150
N1.4	3	5700	270	400	2.5	0.250	0.125	45	0.15
N1.5	3	5700	270	315	2	0.250	0.125	45	2nd bevel
N1.6	3	5500	310	385	2	0.250	0.125	45	2nd bevel
N1.7	3	5500	310	385	2	.0166	0.083	30-45	2nd bevel

b. Output Data

Weld No.	TOTC	@ Time	INTV	@ time	Disp1[a]	@ time	Disp2[a]	@ time	Load actual	Actual Disp
	[kA]	[sec]	[v]	[sec]	[in.]	[sec]	[in.]	[sec]	kip	[in.]
N.S2	1302.5	0.0982	1.72	0.142	0.087	0.066	0.166	2.187	380	0.176
N1.1	1272.3	0.0982	1.678	0.108	0.082	0.055	0.173	2.188	393	0.183
N1.2	1370.	0.085	1.4[1]	0.1748[1]	0.104	0.063	0.171	2.25	379	0.186
N1.3	1415.	0.0948	1.806	0.0925	0.142	0.058	0.285	2.081	400	0.2950
N1.4	1428	0.104	1.908[2]	0.1736	NA[3]	NA[3]	NA[3]	NA[3]	393	0.346
N1.5	1479[4]	0.104	2.02[2]	0.1690	0.1314	0.108	0.3059	20.5	315	0.322
N1.6	1556	0.101	1.975[2]	0.164	0.090	0.113	0.245	2.228	385	0.322
N1.7	1.532	0.105	1.968	0.157	0.097	0.130	0.230	1.900	385	0.306

c. Calculated Results

Weld No.	Peak Current Density	Energy	Interface Volume	Average Interface Energy Density	Total Action
	[kA/in^2]	[kJ]	[in^3]	[kJ/in^3]	[E12 A^2-s]
N.S2	67.7	501	6.604	75.9	0.545
N1.1	66.1	502	6.604	76.0	0.55
N1.2	71.2	477[1]	6.604	72.2	0.522
N1.3	73.5	742	6.604	112.4	0.881
N1.4	74.2	913[2]	8.297	110.0	0.860
N1.5	76.86[4]	901[5]	8.197	109.9	0.881
N1.6	80.83	781	8.197	95.3	0.847
N1.7	79.65	757.5	8.197	92.4	0.826

1. Interface volts data and calculated energy inaccurate: slow isolation module.
2. Interface volts probes separation increased to 0.66" from 0.54" due to geometry.
3. Displacement data lost.
4. Total current from BHPG integrated Rogowski output, duration under 2 seconds. HPW fixture TOTC lost.
5. Energy calculation is low since based on 1.6 second interval, less than actual pulse length

a. Process Displacement (Disp1, Disp2) for experiments through N1.5 are estimates, based on assumption that final process displacement is 95% of actual displacement.

Table 3. N1 Series Impact Toughness Results

Specimen size noted below Weld No. Test temperature and distance from weldline given for each test.

WELD #	CVN	ft-lb	% shear	Distance from weld line [mm]	Temp [°C]
NS2.	1	246	100	0	0
3/4 Size	2	99	25	0	0
	3	60	15	0	0
	min	60			
	mean	135			
	max	246			
N1.1	1	28	5	0	0
3/4 Size	2	9	0	0	0
	3	16	0	0	0
	min	9	5		
	mean	17.7	0		
	max	28	5		
N1.2	1	243	100	0	0
3/4 Size	2	7.5	0	0	0
	3	246	100	0	0
	min	7.5			
	mean	165			
	max	243			
NPM	1	232	100	na	0
3/4 Size	2	226	100	na	0
	3	250	100	na	0
	min	232			
	mean	236			
	max	250			
N1.3	4	10	0	0	0
Full size	6	20	0	0	0
	8	2	0	0	0
	min	2			
	mean	10.67			
	max	20			
N1.4	2	7.5	0	0	0
Full size	4	14.5	0	0	0
	9	8	0	0	0
	10	59	0	-1	0
	6	264	100	-2	0
	min	2			
	mean	10			
	max	20			

WELD #	CVN	ft-lb	% shear	Distance form weld line [mm]	Temp. [°C]
N1.5	4	1.5	0	0	0
Full size	8	1.5	0	0	0
	10	1	0	0	0
	6	100	15	-1	0
	2	264	100	-2	0
	min	1			
	mean	1.33			
	max	1.5			
N1.6	2	8	0	0	0
Full size	4	5	0	0	0
	6	2	0	0	0
	8	264	100	1	0
	10	48	<5	0	25
	min	2			
	mean	5			
	max	8			
N1.7	4	2.5	0	0	0
Full size	6	0.5	0	0	0
	10	0.5	0	0	0
	7	2.5	10	0	25
	2	85	8	--1	0
	min	0.5			
	mean	1.67			
	max	2.5			
NPM	1	263*	100	na	0
Full size	2	263*	100	na	0
	3	263*	100	na	0
	min	263			
	mean	263			
	max	263			
PPM	1	264	100	na	0
Full size	2	264	100	na	0
	3	264	100	na	0

Notes

1. Parent Metal Specimens toughness exceeded Charpy V-Notch Impact Tester Maximum 263 ft-lb toughness.
2. -1 mm and -2 mm refer to specimens with off-weld line notches. Off-weld line tests not used in determination of mean, min, or max.
3. 3/4 size specimens from partial section welds.

Table 4. N1 Series Tensile Test Results

Test Conditions: 100 kN Full scale load; 2 mm/min crosshead speed

Specimen	YP (ksi)	UTS (ksi)	% elong	% RA	comments
N1.3-3	69.9	85.5	32.3	67.5	
N1.3-5	66.9	84.4	30.5	67.0	
Mean N1.3	68.4	85	31.4	67.25	
N1.4-3	72.3	84.4	na	67	
N1.4-5	72.7	84.2	33	67	
Mean N1.4	72.5	84.3	33	67	
N1.5-3	72.0	84.0	25	67	
N1.5-5	72.0	84.0	28	66	
Mean N1.5	72	84	26.5	66.5	
N1.6-3	71.3	84.4	28	65	
N1.6-5	72.0	84.0	27	64	
Mean N1.6	71.6	84.2	27.5	64.5	
N1.7-3	71.1	82.9	27	65	
N1.7-11	70.4	82.6	29	64	
Mean N1.7	70.75	82.75	28	64.5	
NPM1	71.9	83.9	na	67	
NPM2	71.9	84.1	34	67	
Mean NPM	71.9	84	34	67	
PPM1	72.9	86.9	31	65	NKK X65
PPM2	73.0	87.5	30	65	NKK X65
Mean PPM	72.95	87.2	30.5	65	

Parameters:
#Gen: 3
Load: 385 kip
Gap: 2.5 in. (2–4)
2.0 in. (5–6)
Field: 265-310A
RPM: 5,500-5,700

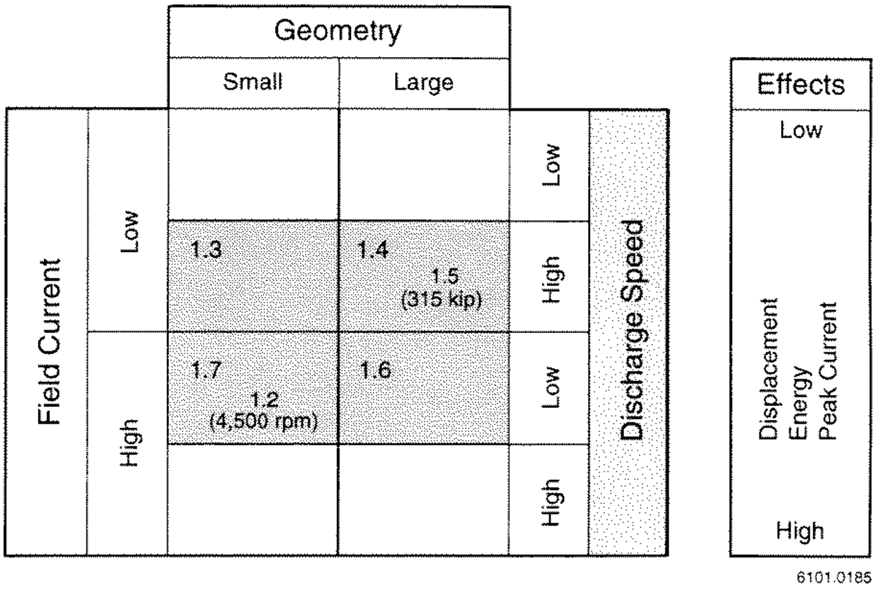


Figure 1. N1 series weld test matrix

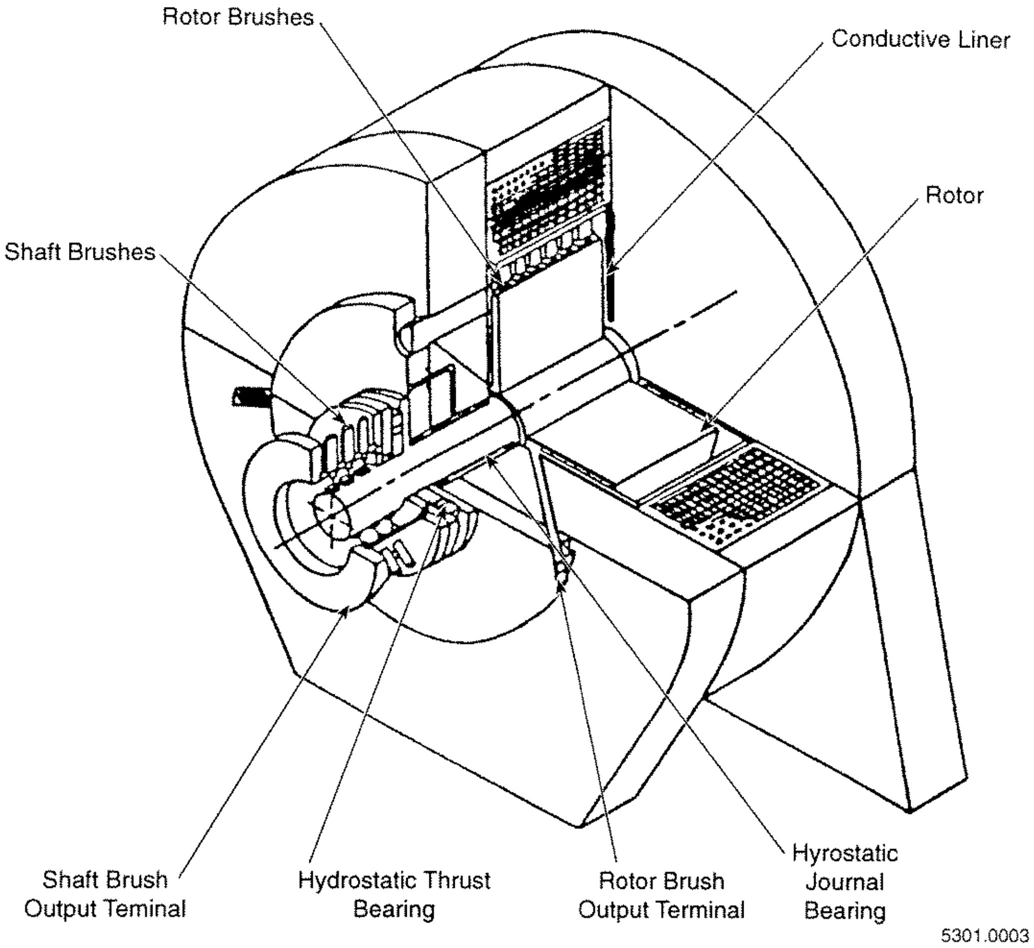


Figure 2. Cutaway sketch of the 10 MJ disk-type homopolar generator

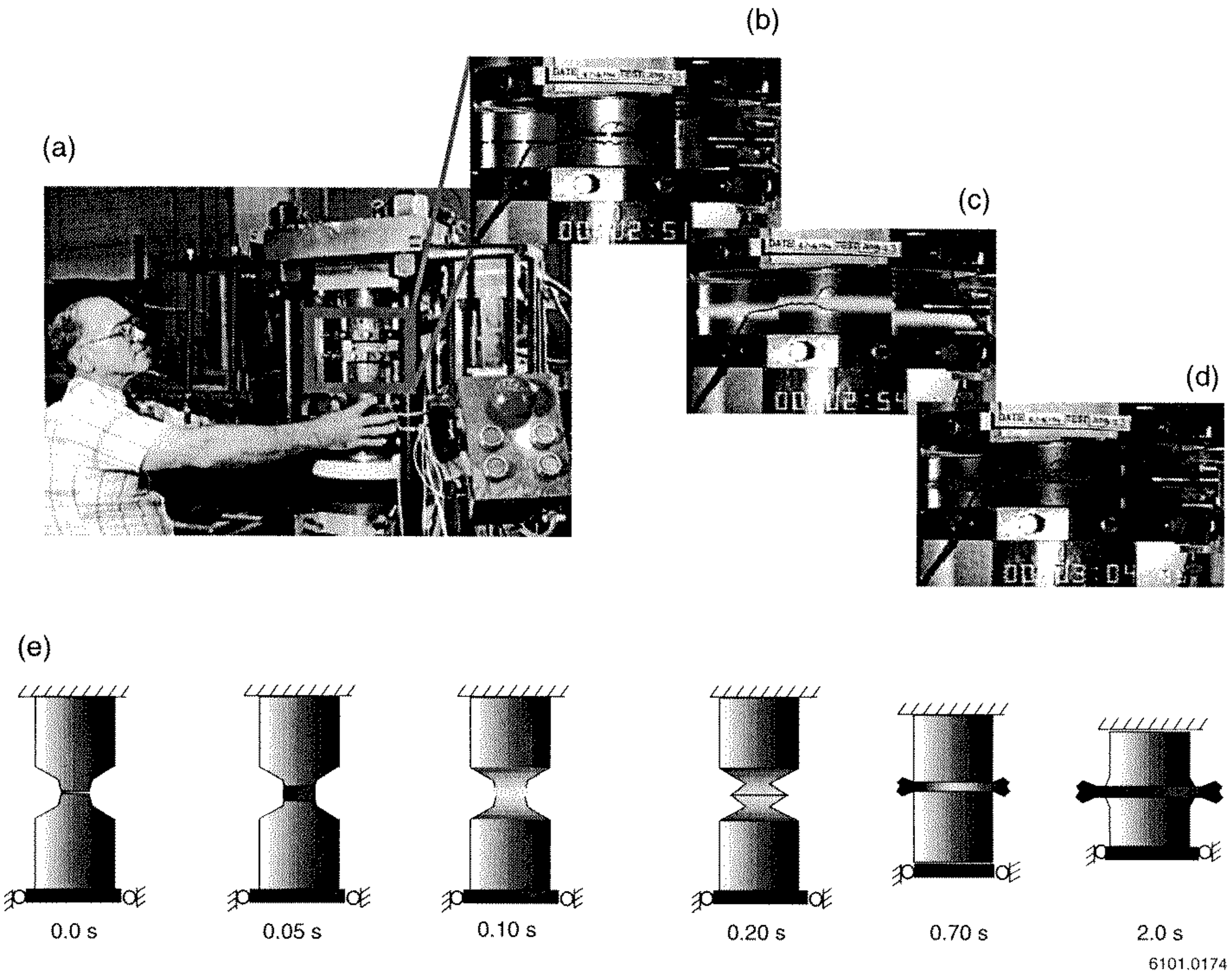


Figure 3. (a)-(d) Photographs of the hydraulic welding fixture and the pipe being homopolar welded. (e) Schematic of the thermo-mechanical cycle of the step-bevel weld interface during a homopolar weld.

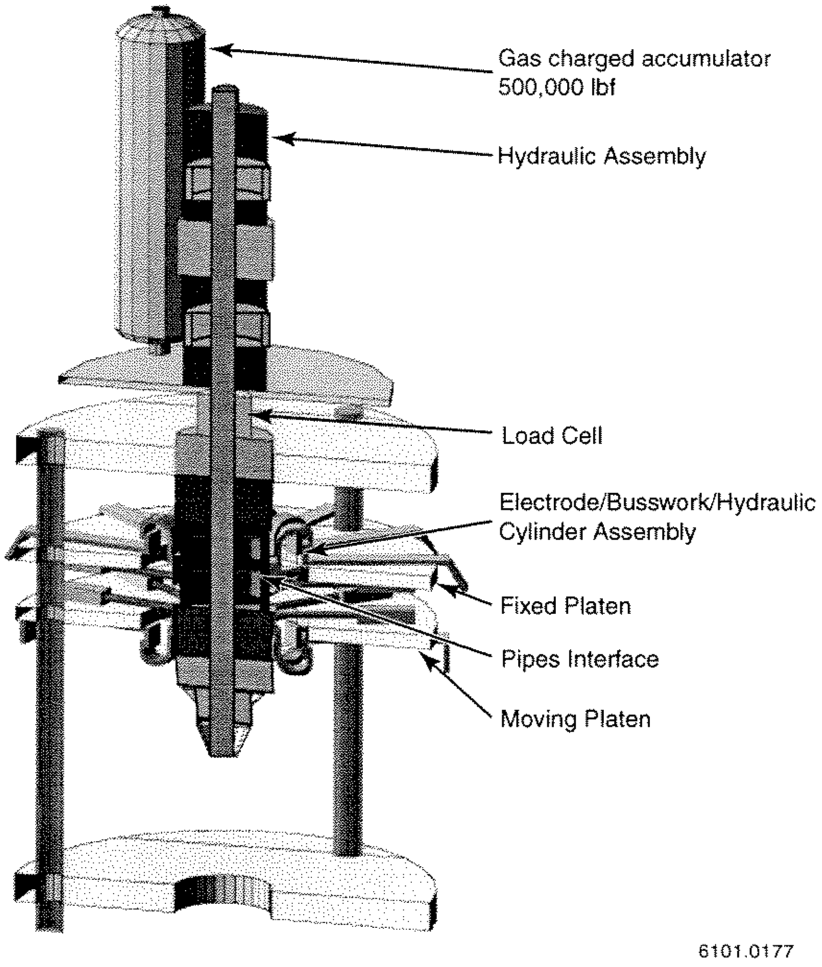
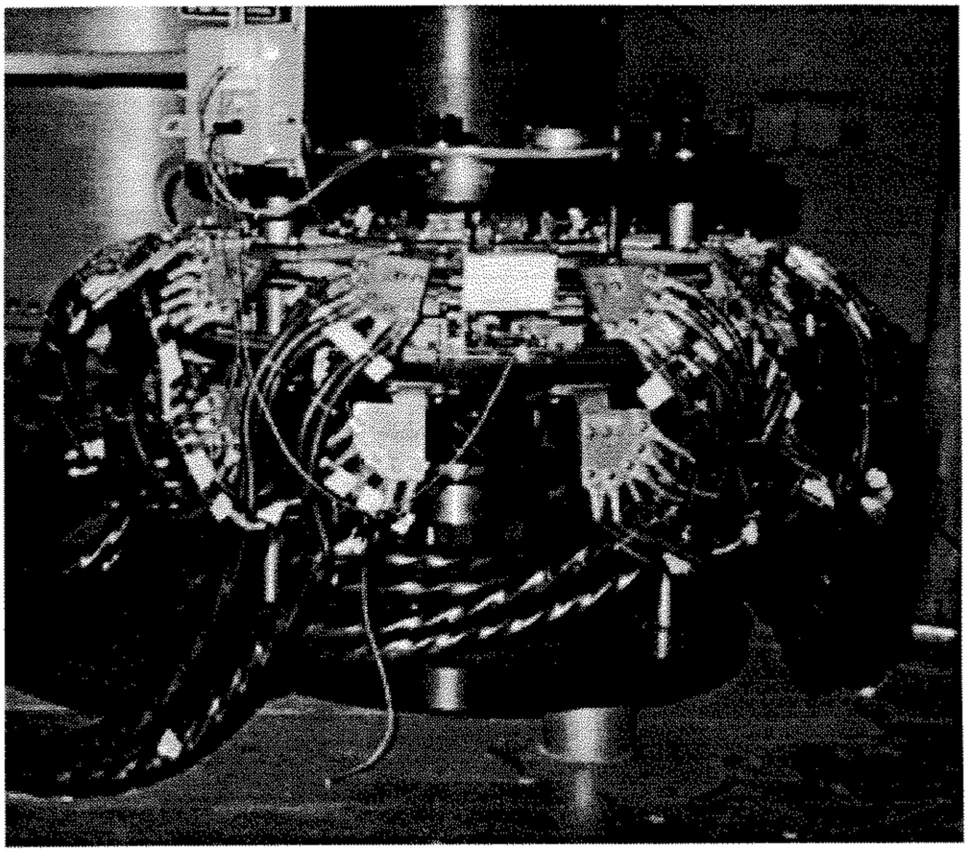


Figure 4. Schematic of 12 in. welding machine without cables



S6101.0241.1

Figure 5. Photograph of the "upset module" of the 12-inch welding machine with hexapolar cables attached

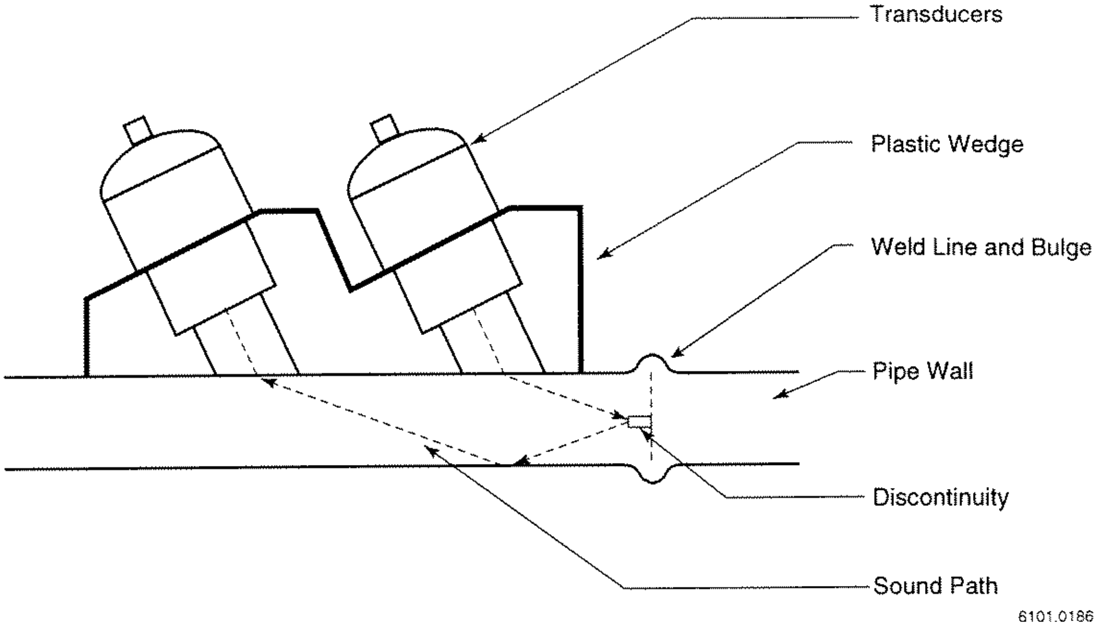


Figure 6. Schematic of tandem probe showing ray diagram for weld inspection

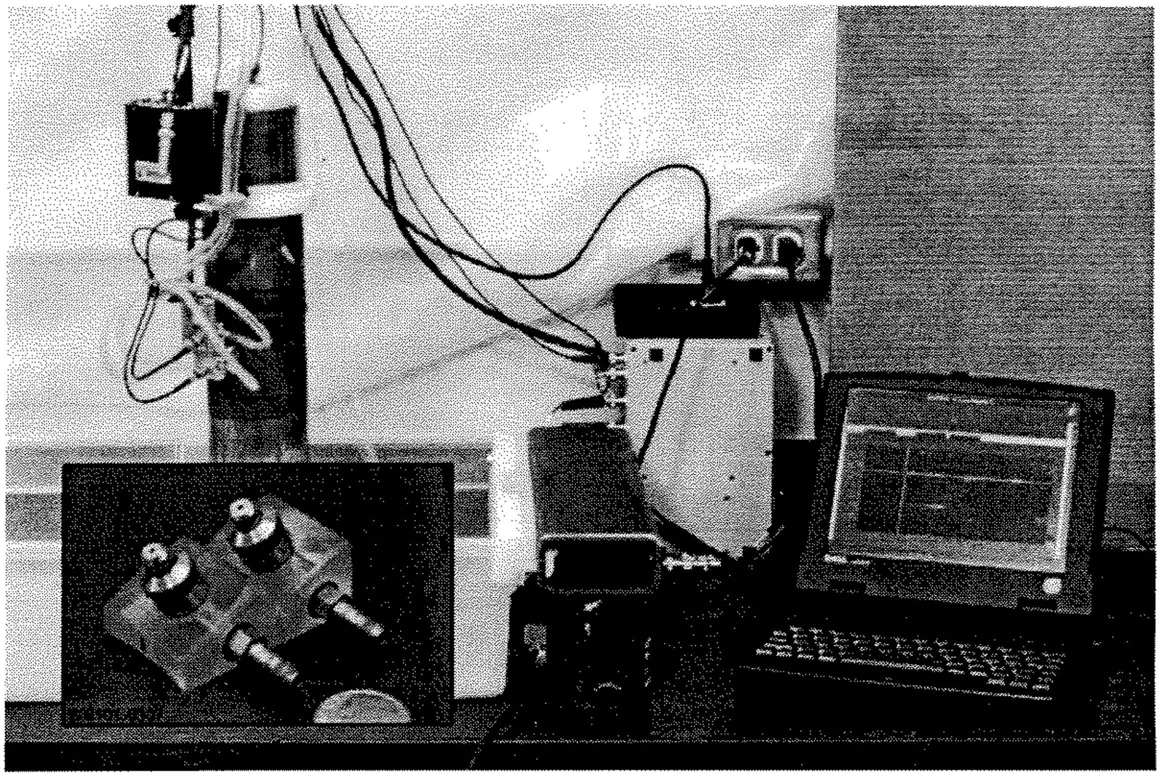


Figure 7. Photograph of the mechanized ultrasonic test apparatus showing the manual scanner attached to a pipe assembly, pulser-receiver (white box) and laptop computer. Laptop computer contains 40 MHz A-D converter "PC card" and software for ultrasonic test data acquisition and display. Inset shows tandem probe used to inspect weld plane in homopolar welds.

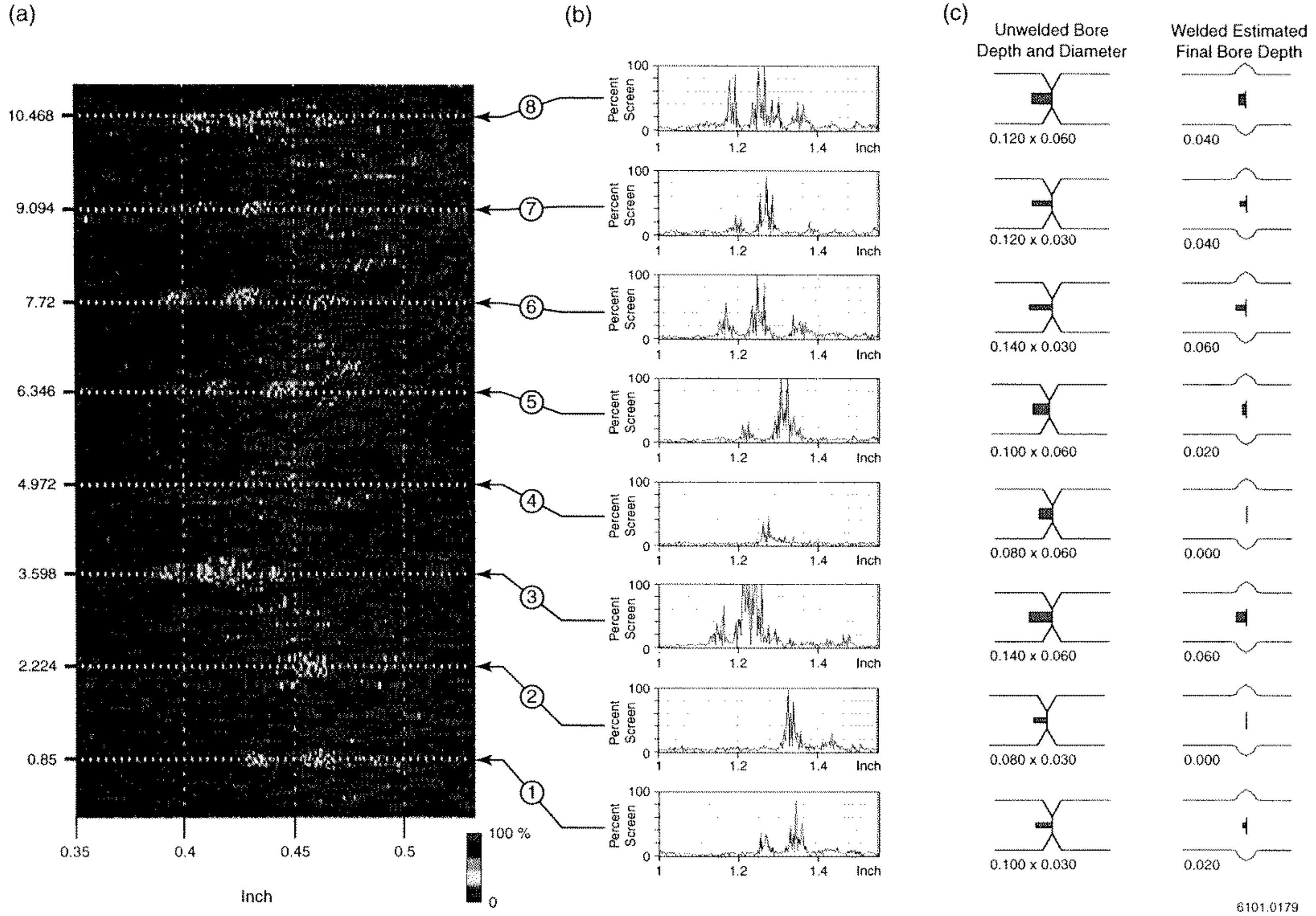


Figure 8. Ultrasonic test results of single circumferential scan of weld B19.1 with sketches of flat-bottomed holes before and after the weld. a) Stacked A-scan display showing indications at 8 locations from a single circumferential sweep (vertical axis). b) Single A-scans at each site. Horizontal axis is axial distance; vertical axis is amplitude of rectified wave. c) Schematic of weld interface geometry before and after weld showing diameter and depth of each flat bottomed hole. Estimated final depth is based on actual forging length.

APPENDIX A

PUBLICATIONS

Publications

Deepwater Pipeline Technology Conference, New Orleans, March 9-11, 1998.

Hudson, R.S, R.W. Carnes, Jr, and S.P. Nichols, "Homopolar Welding for J-Lay Pipeline Constructions."

Offshore Pipeline Technology Conference, Oslo, Norway, Feb. '98.

Carnes, R.W., Jr, R.S. Hudson, and S.P.Nichols., " Advances in Homopolar Welding of API Linepipe for Deepwater Applications."

Joining and Welding Conference, London, Oct. '97.

Carnes, R.W., Jr, R.S. Hudson, and S.P.Nichols., " Advances in Homopolar Welding of API Linepipe for Deepwater Applications."

Society of Petroleum Engineers Conference paper, San Antonio, Tx., Oct. '97.

Hudson, R.S.,et. al., " Advances in Homopolar Welding of API Linepipe for Deepwater Applications"

American Society for Nondestructive Testing Conference, Pittsburgh, Pa., Oct. '97.

Hudson, R.S.., et. al., "Developing a Nondestructive Testing Program for Homopolar Welding"

American Welding Society Resistance Welding Conference, Chicago, IL., Oct. '97

Hudson, R.S., " Advances in Homopolar Welding of API Linepipe for Deepwater Applications"

American Welding Society Poster Session, Chicago, ILL, April 1996,

Hudson, R.S., "Homopolar Welding for J-Lay Applications: Recent Developments"

Energy Week Conference, Houston, TX, January 1996

Hudson, R.S., R.W. Carnes, Jr., and T.J. Moon, "Homopolar Pulse Welding for J-lay Applications: Recent Developments in Heat Control" and

Pappas, J. , et.al., "Homopolar Welding J-Lay Application Economics"

Society of Petroleum Engineers Conference Spring 1995

Haase, P.W., R.W. Carnes, and R.S. Hudson, "Homopolar Pulse Welding for Offshore Deep Water Pipelines," Proceedings 27th Annual OTC in Houston, Texas, May 1-4, 1995.

Dissertations and Thesis

PhD Dissertation at The University of Texas at Austin, 1993

Harville, M.W., "Homopolar pulsed weld characterization and real-time quality assurance."

PhD Dissertation at The University of Texas at Austin, 1993

Haase, P.W., "A study of the effect of homopolar pulse welding parameters on microstructure and mechanical properties of carbon steel HSLA linepipe."

Masters Thesis at The University of Texas at Austin, 1996

Hudson, R.S., "Study of effects of contact resistance on homopolar pulse welding of API 5L X60 linepipe for deep water applications."

Patents Submitted

Patent issued on "Determining, controlling electrical resistance"

Patent covers use of electrode gap to control post weld cooling rate.

Patent Pending on "Method and Apparatus for Joining Metals"

Patent covers use of step and bevel geometry and high constant load parameters as developed for homopolar welding

Patent submitted on "Method for Reducing Contact Resistance"

Patent covers use of a compliant insert for improving the electrode performance on rougher, more uneven surfaces.

APPENDIX B

ADVANCES IN HOMOPOLAR WELDING OF API 5L LINEPIPE FOR DEEPWATER APPLICATIONS

Π

SPE 38840

Advances in Homopolar Welding of API Linepipe for Deepwater Applications

R.S. Hudson, R.W. Carnes, Dr. Steven P. Nichols, The University of Texas at Austin, Center For Electromechanics

This paper was prepared for presentation at the 1997 SPE Annual Technical Conference and Exhibition held in San Antonio, Texas, 5–8 October 1997.

Abstract

The University of Texas at Austin Center for Electromechanics is conducting a research program, funded by six oil companies, two industrial contractors, and two government agencies, to study homopolar welding of line pipe for J-Lay applications. In 1995, the third year of the five year research program, the set of weld parameters, those input variables used to control weld performance and quality, was expanded to include joint geometry, with dramatic improvement in the mechanical properties of two HSLA nominal 3-inch line pipe materials, X60 and X65. These improvements increased the Charpy V-Notch impact toughness properties to near parent metal values, while maintaining acceptable strength. After demonstrating repeatable performance with the new parameters, new research focused on real world effects including tolerancing the parameters and evaluating the effect of poor fit up resulting from misalignment and rough and wavy interfaces. During the final year of the research program, the pipe welding program has scaled up to 12-inch nominal line pipe, a sevenfold increase in cross-sectional area. The paper will cover basics of homopolar welding, weld parameters and modifications, effects of these changes on real time process data, mechanical properties, weld upset profile, HPW metallurgy, and the studies of real world effects. Results from homopolar welding of 12-inch pipe will also be presented.

Introduction

Homopolar Welding (HPW) is a resistance forge welding process that uses the high amperage direct current discharge from a Homopolar Generator (HPG) to produce full circumferential pipe welds in under five seconds without using filler metal. HPW is being developed as a candidate single station, or "one shot", welding method for J-lay pipe laying. With the continued discovery of deep water oil fields, the J-Lay method was developed to overcome the problem of buckling, occurring when the pipe enters the water from conventional S-lay barges. J-lay requires single station welding process because the pipe is welded vertically then lowered directly into the water[1]. Besides enabling pipe laying in deep water fields, the reduced cycle time per weld should lower the cost[2,3].

Homopolar Offshore Pipeline Welding Research Program. A consortium of six oil companies (Amoco, BP, Exxon, Mobil, Shell, and Texaco) and a welding contractor (CRC-Evans) funded this joint industry program (JIP) at The University of Texas at Austin Center for Electromechanics, beginning in February 1993, to develop homopolar welding for J-Lay applications. Since that time, an additional equipment contractor (Parker Kinetic Design) and two federal agencies (the Office of Pipeline Safety of the DOT and the Mineral Management Services of the DOI) have joined the program. The major objectives of the research program have been achieved. They include:

- optimize weld parameters for homopolar welding 3-inch HSLA API 5L line pipe
- investigate a range of materials with varying strength, wall thickness, composition, heat treatment and manufacturing method
- produce 3-inch welds with acceptable mechanical properties
- improve the finished weld profile
- design and build a laboratory welding fixture for joining 12-inch Schedule 80 line pipe
- demonstrate homopolar weldability of 12-inch pipe
- transfer technology in preparation for commercialization of HPW
- develop an NDE program

One of the first requirements of the research program was developing an acceptance criteria for the welding program that was compatible with existing welding codes. John Hammond, with BP Exploration of London, developed this document, known as the "Hammond Criteria", which has served to guide the research through the development of a new welding process[4].

Recent Advances. During the second and third year of the program, the weld parameters, those inputs used to control the welding process and weld quality, were significantly expanded on 3-inch pipe welds as a new approach to welding, using HPGs, was investigated. The results were dramatic: besides producing higher, more uniform impact toughness in two high strength materials, process robustness increased substantially. During the fourth and current years, preparation and production of 12-inch pipe welds are underway.

Homopolar Welding

A homopolar welding system consists of a homopolar generator and a hydraulic welding fixture. The homopolar generator is an inertial energy storage device that provides the mega-ampere direct current electrical pulse to resistively heat the joint for welding. The hydraulic welding fixture delivers the current to the workpiece, provides the forging force to upset the heated interface material, and maintains alignment during upset.

Homopolar Generators. Homopolar generators are simple industrial machines that convert the stored rotational kinetic energy of its spinning rotor to direct current electric energy by electromagnetic induction. The low voltage, high current discharge, characteristic of these machines, makes them well suited for electrical resistive heating. A magnetic field imposed across the electrically conductive rotor produces a voltage and supplies a characteristic current pulse when connected to a discharge circuit. The principle of electromagnetic induction is demonstrated in the Faraday disc, or more fundamentally by moving a straight conductor though a magnetic field[5].

HPG Parameters. The parameters governing the HPG output current are the discharge speed and the field current magnitude. The discharge speed determines the magnitude of the stored inertial energy and the field current magnitude, which induces the magnetic field across the rotor, controls the shape of the current pulse. Higher field current settings shorten the pulse length and increase the magnitude of the peak discharge current[6].

The Hydraulic Welding Fixture. This fixture consists of a hydraulic press capable of delivering the forging load and the portion of the discharge circuit that delivers the current pulse to the workpiece. The copper electrodes deliver the current for welding through the outer pipe wall and are uniformly spaced around the circumference of the pipe and clamped to its outer surface. In the laboratory fixture, short pipe sections are joined with the upset load applied through the ends. The load is controlled via a servo valve and a control system.

Fixture Parameters. The fixture parameters used to control the homopolar welding cycle include four load related parameters and one electrode parameter. The load control system permits stepping an initial load to an upset load after a preset delay and holding the upset load for a duration. Traditionally, the initial load setting controls the degree of heating at and near the interface and the delay setting controls the extent of diffusion of interface heat to the adjacent material. The upset load and duration control the extent of joint forging. The last primary fixture parameter is the electrode gap, which refers to the axial distance between the weld interface and the leading edge of the electrode. The electrodes act as a heat sinks and affect post weld cooling rates.

HPW Welding Cycle. A typical HPW cycle begins by accelerating the HPG to a preset speed, then energizing the field coils to produce a uniform magnetic field across rotor. Lowering the brushes produces a potential across them. At the discharge speed set point, a switch is closed and the stored energy of the HPG rotor converts to a direct current pulse as electromagnetic torque rapidly stops the rotor. The current is directed through the discharge circuit containing the workpiece. Due to its substantially higher resistance, the interface and adjacent material rapidly heat and soften permitting forging to form the finished weld. Homopolar welds have a narrow heat affected zone (HAZ) due to the short thermal cycle with resistance heating concentrated at and near the interface. Figure 1 shows a schematic of the homopolar welding process.

Traditional Homopolar Welding Methods. Traditionally, or prior to the latter part of the second year of the JIP, welds were performed using pipes prepared with smooth, flat ends and light initial loads followed by increased upset loads. With this method intense heat was generated at the interface of the lightly loaded, flat-ended pipes by carefully controlled contact resistance heating, and relied on axial thermal diffusion to heat and soften adjacent material for forging. This method was extremely sensitive to the uniformity of the contact over the interface, and experienced melting or near melting temperatures at the interface surface.

Modified Homopolar Welding Methods. The modified welding method uses shaped pipe ends and constant, high interface pressures to control resistive heating as the current pulse discharges through the weld circuit. Increasing the initial load to the upset load value combined with the reduced contact area of the shaped end increases the interface pressure as much as eighteen fold and results in a sharp reduction of interface resistance[7,8]. Increased current flow from the reduced interface resistance supplies more Joule heating in the shaped ends, thereby offsetting the reduction in interface heating.

The shaped pipe end, a modified double bevel preparation, was prepared by machining the pipe wall from both inside diameter (ID) and outside diameter (OD) surfaces, resulting in a reduction in cross-sectional area near the interface. The reduced cross-section increased the local current density and Joule heating rates, allowing improved control of temporal and spatial temperature profiles, without relying on thermal diffusion to heat adjacent material.

Modified Weld Parameters. The modified welding method added end geometry parameters and reduced load parameters. The new set of weld parameters consists of generator discharge speed and field current, hydraulic fixture constant load and electrode gap, and end geometry parameters consisting of contact width, bevel angle, and shape factor.

Material D Typical Hardness and Strength. A hardness traverse for a typical material D weld is presented in fig. 8. All welds in material D have a similar hardness profile: HAZ softening 5 to 7 mm on either side of the weld line and hardening at the weld line. The degree of HAZ softening and weld line hardening is primarily controlled by the discharge speed and field current parameter selection. Tensile specimens fail in the base metal at parent metal values.

Material B- 3-inch X60 ERW. A limited number of welds have been performed in material B using the modified parameters due to limited availability of material B. Weld parameters selected for material B welds were repetitions of those used on good quality material D welds. In all such welds, the thermal and mechanical response was similar to those of D material welds, and the mechanical properties of the welds met the acceptance criteria with the exception of the tensile strength, as reported earlier.

Material B Metallurgy. The base metal is a controlled rolled low carbon, Niobium micro-alloyed material, having a very fine grain, and the weld line microstructure has a similar fine grained microstructure (fig. 9 and 10). Moving through the HAZ, the carbide colonies become more pronounced due to the light banding in the base metal.

Material B Typical Hardness and Strength A hardness traverse for a typical material B weld is presented in figure 11. Compared to material D, the HAZ has a similar width but with more softening in material B, and lacks any weld line hardening. Tensile test specimens consistently fail at the weld line at 85-90% of parent metal strengths and display ductile fracture surfaces. These results are consistent with the thermal cycles in controlled rolled materials, and PWHT of these welds was observed to further soften the HAZ[13].

Real World Condition Welds. Twenty-five additional material D welds were performed using the modified weld parameters to determine tolerances on joint geometry, interface alignment and surface conditions. These results are summarized in table 2. In the tolerancing series, the joint geometry between the pipe pair differed in contact width, shape factor, and radial prep centerline position. All welds in the tolerancing series had circumferentially uniform contact area and pressure.

In the misalignment series, pipes with standard end preparations were misaligned by displacing the pipe centerlines radially and by tilting one of the pipes. The expected response to radial misalignment is circumferentially non-uniform heating from the variation in contact width and contact pressure around the interface surface. For angular misalignment, the expected response is increased contact pressure at the initial contact point. As previously mentioned, increasing the local contact pressure reduces the contact resistance and allows more current flow along that path.

In the surface condition weld studies, the interface surfaces of typical joints were single point lathe turned to produce substantially coarser finishes, cut with a full width shearing cutter, or machined to produce a wavy surface. Coarsest surface finishes exceeded 17.8 μm rms (700 μin.), and the wavy surface had a total wave amplitude of 127 μm (0.005 in.).

On the last four real world welds, the joint machining was performed using a commercial pipe-facing machine leaving a coarse, wavy finish on the interface surfaces. Typically, the joints are lathe-turned producing a smooth (<1.62 μm [64 μin]), flat surface. These welds displayed typical thermal and mechanical response and had exceptional impact toughness.

Despite parameter selection designed to produce unacceptable welds, overall, these welds achieved circumferentially uniform heating, and displayed typical displacement response. The effect of these weld parameters generally lowered the impact toughness, but only two failed to achieve the minimum average impact toughness. Three additional welds had an individual value below the acceptance limit.

Discussion and Summary 3-inch welds. The new welding method had several distinct benefits besides improving the mechanical properties and weld profile. Using a constant load simplified the control requirements for the upset load. Using a shaped end reduced the energy requirement for welding, permitting 14% lower discharge speed settings. The high constant load combined with the shaped end limited the peak temperature by forging material as it softened to its forging stress. These combined parameters prevent overheating because the opportunity for overheating, melting and melt expulsion/arcing, occurs early in the thermal cycle when the current is rapidly rising to its peak value. By permitting an "on-demand" forging action, hot material is extruded as it heats, rather than continuing to heat. With this type of process, the load system must be able to respond sufficiently fast to maintain a gapless interface. The continuous deformation during upset resulted in dynamic recrystallization, refining the grain and promoting grain growth across the interface.

In the 3-inch homopolar welding program, four materials were successfully joined achieving full strength or near full strength joints. While all met hardness requirements, the limit on achieving acceptance for offshore pipelines remained acceptable impact toughness. The modified weld parameters achieved acceptable results in the two high strength materials, but not the lower strength materials. The weldability of materials B and D was attributed to their clean chemistry and possibly the use of calcium as a manganese cleaner. Extensive studies to determine bounds of the process revealed that for a given material, acceptable welds were achievable over a broad range of parameters, permitting optimization of a single parameter.

Conclusions of modified parameter 3-inch welds. The results of the 3-inch welding program permit these conclusions:

- Material chemistry strongly influences the homopolar weldability of a material.
- High strength materials are easily joined.
- Modified weld parameters produce acceptable finished profile .
- Modified parameters make HPW more robust and more tolerant to real world conditions.
- Careful selection for weld parameters assures good welds in weldable materials.

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On the last four real world welds, the joint machining was performed using a commercial pipe-facing machine leaving a coarse, wavy finish on the interface surfaces. Typically, the joints are lathe-turned producing a smooth (<1.62 μm [64 μin]), flat surface. These welds displayed typical thermal and mechanical response and had exceptional impact toughness.

Despite parameter selection designed to produce unacceptable welds, overall, these welds achieved circumferentially uniform heating, and displayed typical displacement response. The effect of these weld parameters generally lowered the impact toughness, but only two failed to achieve the minimum average impact toughness. Three additional welds had an individual value below the acceptance limit.

Discussion and Summary 3-inch welds. The new welding method had several distinct benefits besides improving the mechanical properties and weld profile. Using a constant load simplified the control requirements for the upset load. Using a shaped end reduced the energy requirement for welding, permitting 14% lower discharge speed settings. The high constant load combined with the shaped end limited the peak temperature by forging material as it softened to its forging stress. These combined parameters prevent overheating because the opportunity for overheating, melting and melt expulsion/arcing, occurs early in the thermal cycle when the current is rapidly rising to its peak value. By permitting an "on-demand" forging action, hot material is extruded as it heats, rather than continuing to heat. With this type of process, the load system must be able to respond sufficiently fast to maintain a gapless interface. The continuous deformation during upset resulted in dynamic recrystallization, refining the grain and promoting grain growth across the interface.

In the 3-inch homopolar welding program, four materials were successfully joined achieving full strength or near full strength joints. While all met hardness requirements, the limit on achieving acceptance for offshore pipelines remained acceptable impact toughness. The modified weld parameters achieved acceptable results in the two high strength materials, but not the lower strength materials. The weldability of materials B and D was attributed to their clean chemistry and possibly the use of calcium as a manganese cleaner. Extensive studies to determine bounds of the process revealed that for a given material, acceptable welds were achievable over a broad range of parameters, permitting optimization of a single parameter.

Conclusions of modified parameter 3-inch welds. The results of the 3-inch welding program permit these conclusions:

- Material chemistry strongly influences the homopolar weldability of a material.
- High strength materials are easily joined.
- Modified weld parameters produce acceptable finished profile .
- Modified parameters make HPW more robust and more tolerant to real world conditions.
- Careful selection for weld parameters assures good welds in weldable materials.

12-inch Homopolar Welding Program

Success in homopolar welding of 3-inch schedule 60 line pipe led the way in the design of a fixture for joining 12-inch schedule 80 line pipe. The modified weld parameters demonstrated the robustness and simplicity of the process, while reducing some of the fixture requirements. The next section reviews the critical issues associated with scaling the process to a larger pipe, a larger cross-section, and prototype issues for a commercial fixture.

Design Requirements for Scaling Up. Designing a fixture to join nominal 12-inch schedule 80 line pipe based on 3-inch schedule 60 line pipe weld parameters constituted a sevenfold increase in cross-sectional area. Historically, the homopolar welding thermo-mechanical cycle was assumed to be independent of cross-sectional area joined. The process was treated as an adiabatic process, since the thermal cycle was so fast, and the peak current was reached in less than 4% of the pulse length. To achieve comparable thermal and mechanical responses in the workpiece, the local heating rates and stress distribution were maintained, and the joint profile was scaled using the wall thickness as the characteristic dimension.

To meet the thermal requirements, local current densities were maintained since the square of current density determines electrical resistance heating rates. For a comparable response throughout the heating cycle, the current density, based on the pipe cross-section, as a function of time was reproduced. In short, the total current profiles should have the same shape, including time to peak current (100 ms) and the pulse length (2.5 s) and they should scale with the cross-sectional area.

To maintain the stress distribution, the upset load requirements should scale with pipe wall area. Further, during upset, when the workpiece deforms, the rate of deformation was to be maintained.

Some of the general requirements for successful homopolar pipe welding are mentioned here for completeness:

- circumferentially uniform current distribution
- minimal circuit losses
- maintain axial alignment during upset
- limit electrode leading edge peak current density.

Prototype 12-inch HPW Machine. The first prototype HPW machine for joining 12-inch line pipe was implemented as a laboratory fixture primarily to demonstrate the scalability of HPW. Of interest was whether the required current pulse could be introduced into a pipe and whether the pipe would heat and forge similar to the 3-inch welds. To address scalability and minimize costs, the design requirement of applying the upset force through the pipe wall was deferred to the next fixture proposed as a prototype field HPW system.

The new welding machine consisted of a two piece welding fixture and three 10 MJ HPGs. The hydraulic load module of the welding fixture provides an upset load of 1.91 MN (430,000 lb) and an accumulator passively maintains a relatively constant force to the workpiece during deformation. An internal 101.6 mm (4 in.) diameter tension rod transmits the force from a pair of hydraulic cylinders configured in parallel and applies the upset load to the ends the pair 152 mm (6 in.) long pipes.

The other component, an upset frame, contains the electrodes and busswork to transfer the current through the workpiece and maintain the axial alignment during upset. Twelve pairs of hydraulic cylinders extend and retract the electrodes and limit transverse motion of the workpiece. The three 10 MJ HPGs are connected in parallel and capable of storing 30 MJ of rotational kinetic energy for welding. The system is designed for a peak current of 1.5 MA.

The First 12-inch Welding Series. After commissioning this new system, the first weld series began with the objective of establishing a set of baseline weld parameters that would produce complete welds comparable to 3-inch welds. The material selected for this first series, designated with the prefix "N", was substantially identical to material D, as both were provided by the same supplier. This material has a wall thickness of 0.50 in. and wall area of 12,419 mm^2 (19.25 in^2). Material composition is listed in table 1.

As of this writing, four 12-inch welds have been completed, with the third and fourth welds having sufficient energy to join the full wall and produce a finished weld profile similar to 3-inch welds (fig. 12). The process parameters, total current, interface voltage and displacement (fig. 13), indicate the similarity of the process to the 3-inch. (Compare to fig. 2) The peak current (1.43 MA), time to peak (0.094 ms) and pulse length (3 s) are similar to the 3-inch, indicating that comparable energy was delivered to the workpiece. The displacement and interface voltage responses display the same response as for 3-inch welds, with the exception of the more rapid initial displacement rate. The average energy density between the interface voltage probes was also comparable to material D welds.

Mechanical Properties. The mechanical properties and metallurgy of the initial material N welds were similar to material D welds, with the exception of the impact toughness. The parent metal is fine-grained similar to that of material D (fig. 14). Weld metal is slightly coarser, but still fine grained and the HAZ metal is coarser still (figs. 15 and 16). The hardness traverse shows similar weld line hardening surrounded by a narrow zone of HAZ softening (fig. 17). In the tensile test, the specimens broke in the base metal at parent material properties. These welds had unacceptably low impact toughness, displaying only limited shear fracture.

Discussion of First 12-inch welds. The first 12-inch weld series successfully demonstrated the scalability of HPW to larger pipe sizes and comparability of the process parameters used to monitor the process. This effort was unique in several ways. It was the largest cross-sectional area joined using HPW. It was the largest scale to date. It demonstrated the modified weld parameters scaled with cross-section. It demonstrated acceptable design considerations were appropriate for scaling up.

The failure to achieve acceptable impact toughness by the fourth weld is not unexpected. In previous welding programs, it has typically taken dozens of welds to identify weld parameters capable of increasing impact toughness, often never achieving acceptable toughness. For the first few welds, possible causes of low toughness may be related to the faster displacement rate or the slower cooling rate, both characteristics of the new welding fixture. The features of the fixture producing these effects were not in the primary design considerations. Presently, modification to the weld parameters are under consideration to adapt them to the new fixture.

NDE Program for HPW

The nondestructive evaluation (NDE) effort for the homopolar welding program consisted of two key components: process monitoring and nondestructive testing of the welds. As an automatic welding process, monitoring specific weld parameters was proposed as a method to control weld quality[6,14]. This research, based on traditional HPW method, suggests that monitoring the weld displacement may be one the best measures of weld quality. This approach appears applicable to the modified HPW process.

The other key component in NDE of HPW is developing appropriate nondestructive tests for HPW. Based on its similarity to friction welding, where the faying surfaces are held under constant pressure during the heating phase of the process, HPW was assumed to be susceptible to planar, no volume flaws, oriented along the weld interface. Problematic flaws included the cold weld and the array of microinclusions. The cold weld, or kissing bond, occurs when the softened weld metal makes intimate contact at the interface without forming a metallurgical bond[15]. The array of microinclusions occurs when the interface contamination is not fully expelled from the joint. Laminations and manganese sulfide stringers may also occur in HPW.

Based on its ability to detect these planar reflectors, automatic ultrasonic inspection (AUT) was selected as the best method for inspecting HPW. Additional features of AUT include high rate of inspection, immediate display and analysis of test results, provides a permanent record of each test, and allows post-inspection review and analysis of the test data.

Presently, work is underway to characterize the possible flaws and identify optimum probe configurations. The tandem probe is being investigated as a single probe capable of providing a go-no-go test for the presence of a flaw. This probe is designed to detect planar reflectors oriented perpendicular to the inspection surface, and as such might detect an array of microinclusions located on the interface.

Future Work

Work for the remainder of the present JIP includes continuing welding both three and twelve inch pipe and characterizing HPW flaws. The emphasis of the 12-inch welding program will be identifying weld parameters that increase impact toughness properties. The 3-inch welding program will continue to investigate fundamental relationships between weld parameters as they affect the process parameters and mechanical properties.

After this JIP, a follow-on program is proposed to accomplish the following:

- Optimize weld parameters for large diameter pipe
- Complete HPW flaw characterization and develop prototype and commercial nondestructive test procedures
- Investigate homopolar weldability of other important material, like duplex, Cr-A, and titanium.

Commercialization Efforts

A joint effort by the industrial contractors of this JIP is placing a prototype HPW system in a land based operation as a low risk, first commercial operation. Parker Kinetic Designs has designed an industrial homopolar generator for joining 4, 6, and 8 in. diameter schedule 80 line pipe, with maximum pipe wall area of 8,387 mm^2 (13 $in.^2$). This machine produces 15 MJ at 3,440 rpm, uses rolling element bearings, requires an eight hour brush maintenance after 10,000 discharges, and is skid mountable. Its dimensions are 1.40 m (55 in.) long and 1.52 m (60 in.) diameter, and weigh 133 kN (30,000 lb).

Adapting the features of the laboratory fixture for field welding requires developing a method for gripping the pipe to apply the upset force. Field fixture design and testing is underway at CRC-Evans. Knowledge acquired from the 12-inch fixture at CEM will be incorporated in the design of the next HPW fixture.

Acknowledgments

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Table 1. Material Data

Weld Prefix Code	A	C	B	D	N
API 5l Grade	X52	X52	X60	X65	X65
Outside Diameter	3.5	3.5	3.5	3.5	12.75
Wall Thickness	0.438	0.438	0.300	0.315	0.50
Type	seamless	ERW	ERW	seamless	seamless
Heat Treatment (Not On Mill Test Report)	Hot rolled	normalized	controlled rolled	quenched and tempered	quenched and tempered
Ladle Chemistry					
C	0.23	0.11	0.13	0.08	0.08
Mn	1.04	1.13	0.65	1.29	1.29
P	0.010	0.014	0.005	0.011	0.011
S	0.009	0.005	0.004	0.002	0.0017
Si		0.28	0.22	0.19	0.19
Al		0.037	0.042		
Cr		0.073	0.03		
Mo		0.028	0.01	0.22	0.215
Ni		0.07	0.01		
Cu		0.13	0.02		
Cb		0.034	0.18	0.032	0.032
Ca			0.0048	0.0026	0.0026
Ti		0.008			
V	0.08	0.040			
B		0.0003			
Ti-Al				0.035	0.035
Iiw C_{eq}	0.42	0.34	0.23	0.34	0.34
Yield Strength (Ksi)	66.0	59.5	79.5	71.6	71.6
Tensile Strength (Ksi)	94.4	79.5	86.1	80.7	80.7
% Elong In 2"	30	37	22	26.6	26.6
Impact Toughness (J [ft-lbs])	85 (63) full size	214(158) full size	81(60) half size	168(124) half size	<358 full size
Vickers Hardness	193	171	182	185	219

Table 2. Summary of Mechanical Test Results for Material D Welds

	Units	Ideal Conditions	Real World Conditions
# Welds Performed		70	25
# Weld CVN Tests		63	21
CVN Ave.	J	109.1	101
CVN Ave. St.Dev	J	37.7	34.6
# Fail Ave. Criteria		5	2
Min CVN Ave.	J	85.6	75.9
CVN Min St.DEV	J	39.9	44.5
# Fail Min Criteria		4	3
# Weld Tensile Tests		29	
Yield Ave	MPa	500	
Yield St.Dev	MPa	9.5	
Tensile Ave	MPa	567	
Tensile St.Dev	MPa	9.5	
% EL Ave		26	
% EL St.Dev		1.85	

Table 3. Range of Weld Parameters for Ideal Condition Welds

	Unit	Minimum Value	Maximum Value	% Variation
Discharge Speed	rpm	2000	2200	10
Field Current	A	300	390	30
Load	kPa	200	267	25
Joint Angle	Deg	30	45	33
Contact Width	mm	1.905	3.81	50
Shape Factor		0	1	100

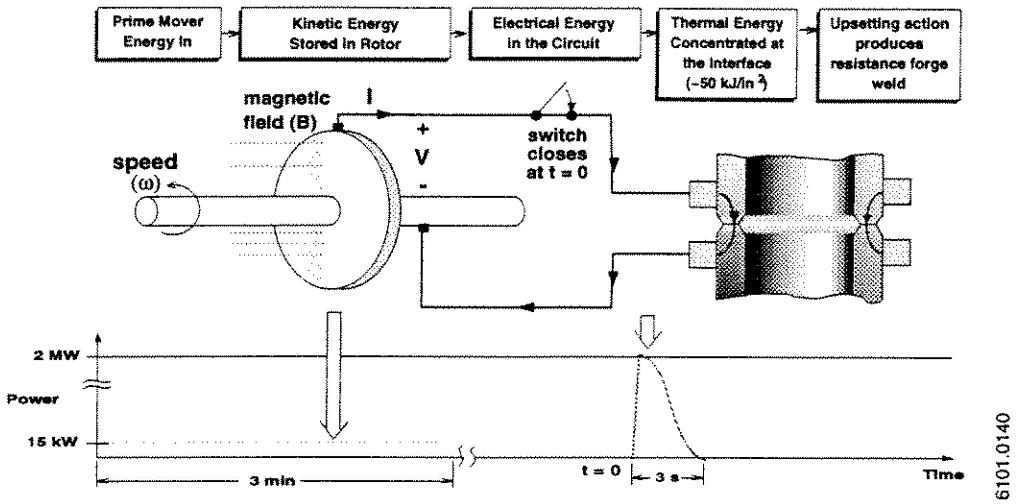

Fig. 1 - HPW process schematic.

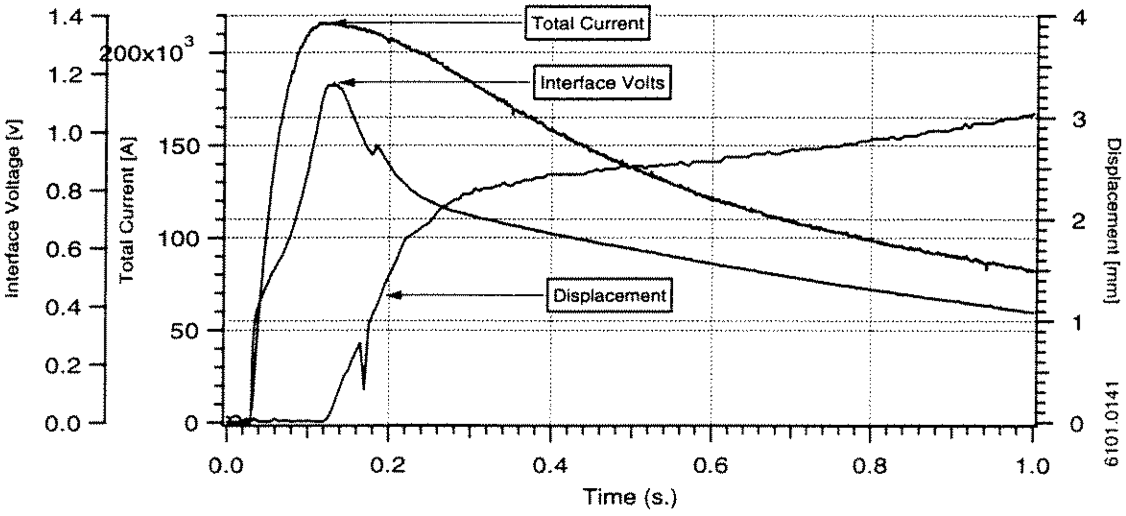

Fig. 2 - Typical Material D Process Data.

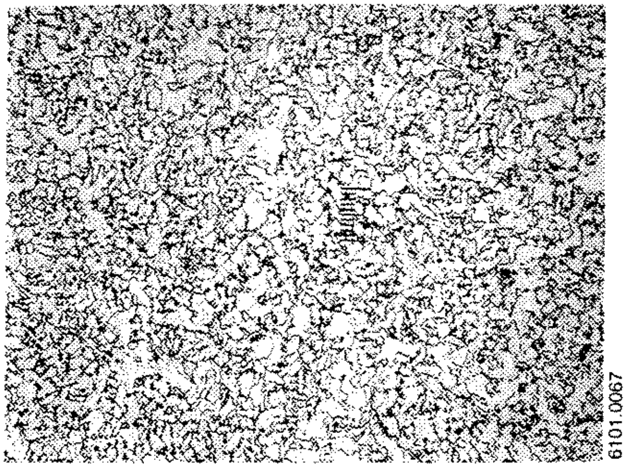

Fig. 3 - Material D parent metal microstructure.
(scale maker =20 μm)

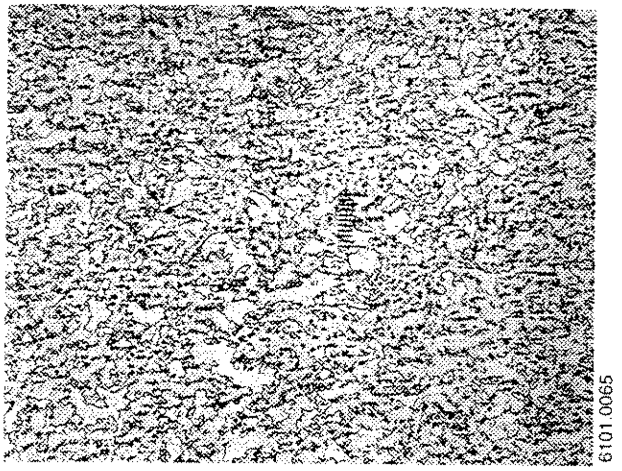

Fig. 4 - Material D weld line microstructure.
(scale maker =20 μm)

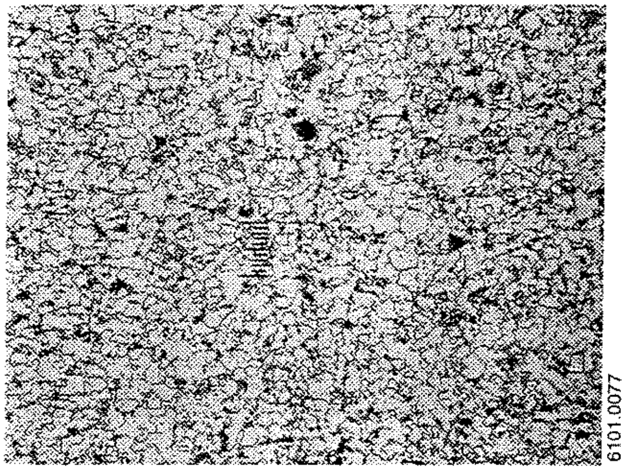

Fig. 5 - Material D HAZ microstructure.
(scale maker =20 μm)

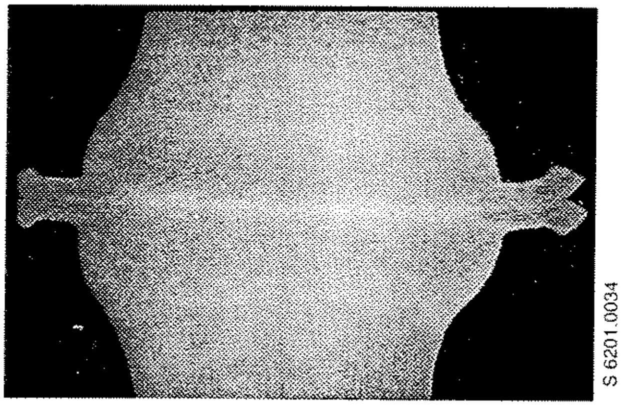

Fig. 6 - Material D weld macrostructure.
(magnafication 5×)

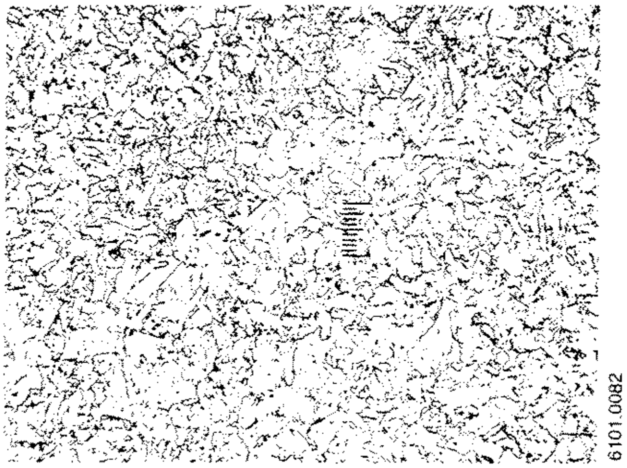

Fig. 7 - Material D fin microstructure.
(scale maker =20 μm)

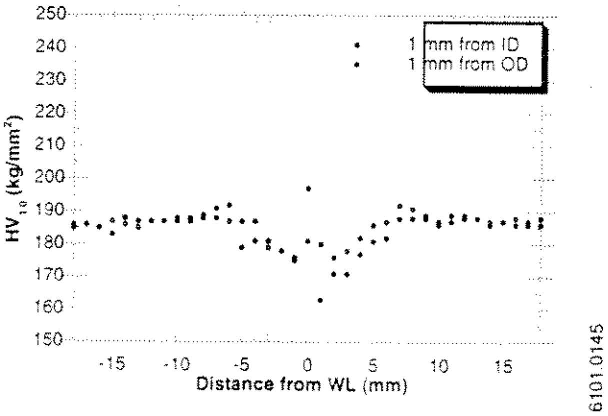

Fig. 8 - Typical material D macrohardness traverse.

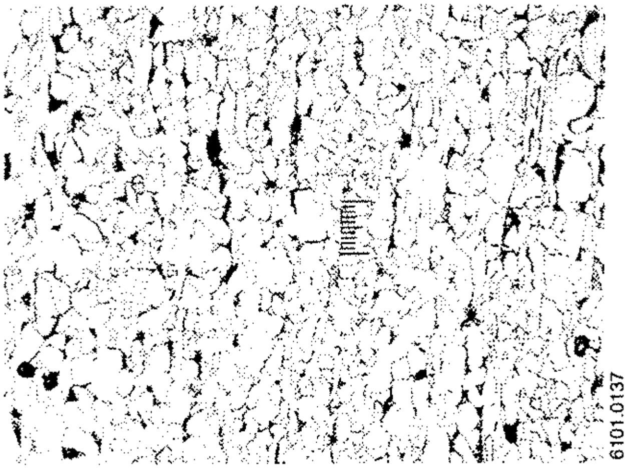

Fig. 9 - Material B parent metal microstructure. (scale maker =20 µm)

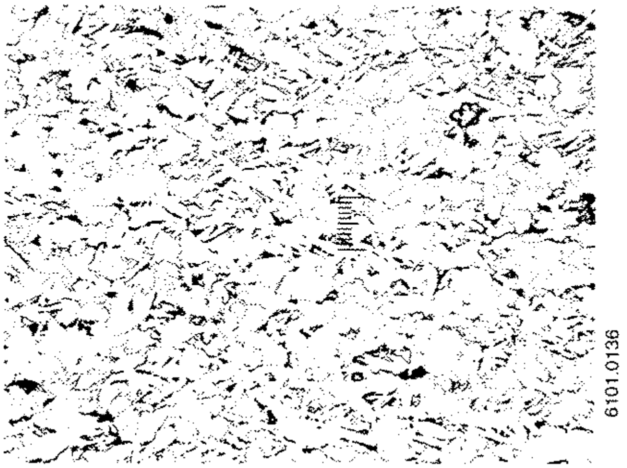

Fig. 10 - Material B weld line microstructure. (scale maker =20 µm)

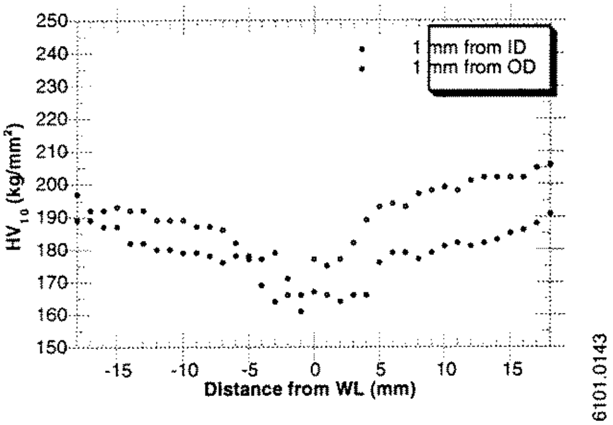

Fig. 11 - Typical material B macrohardness traverse.

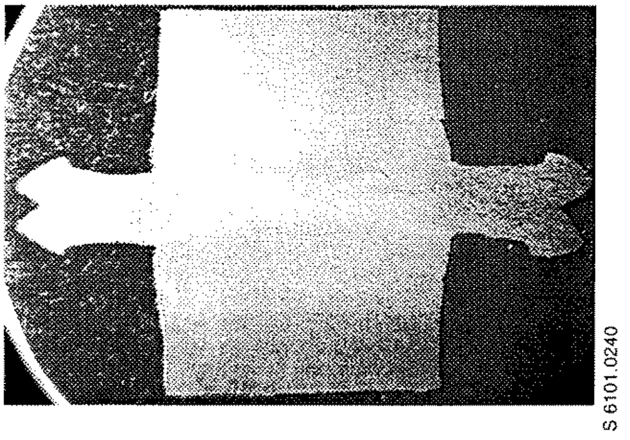

Fig. 12 - Material N weld macrostructure. (magnafication 3×)

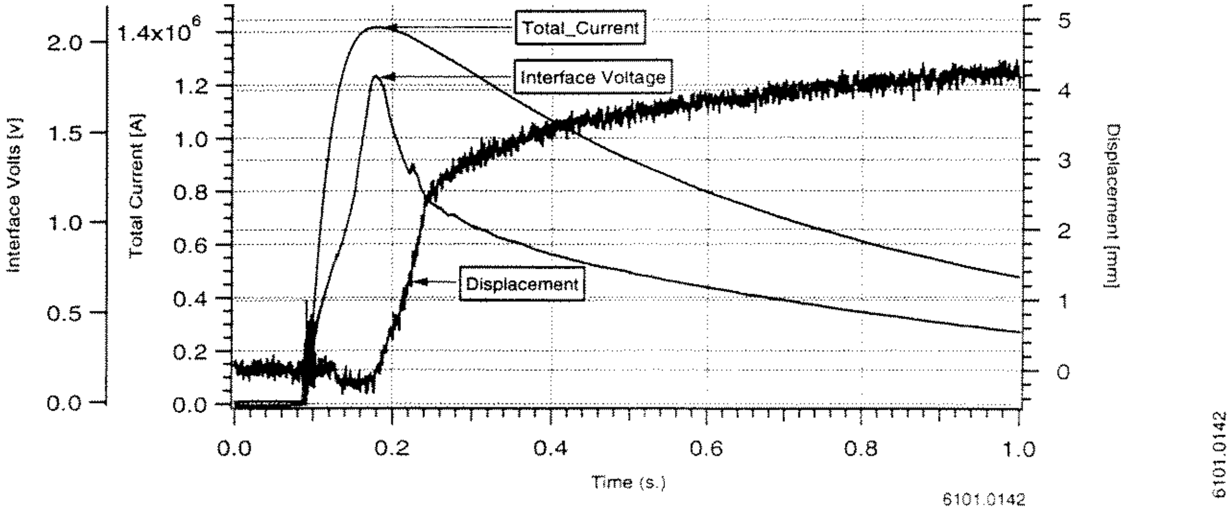

Fig. 13 -Typical 12-inch material process data.

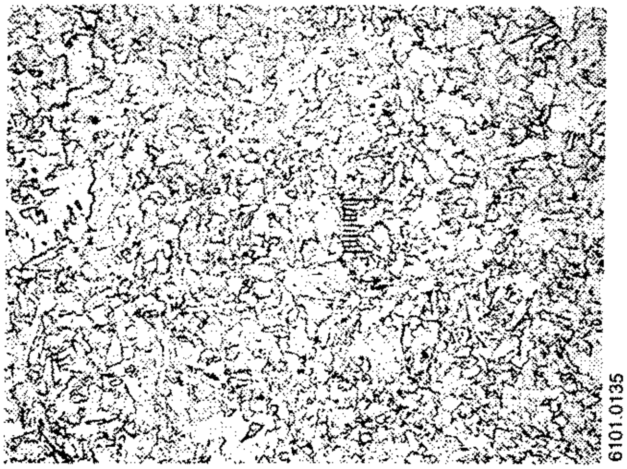

Fig. 14 - Material N parent metal microstructure. (scale marker =20 μm)

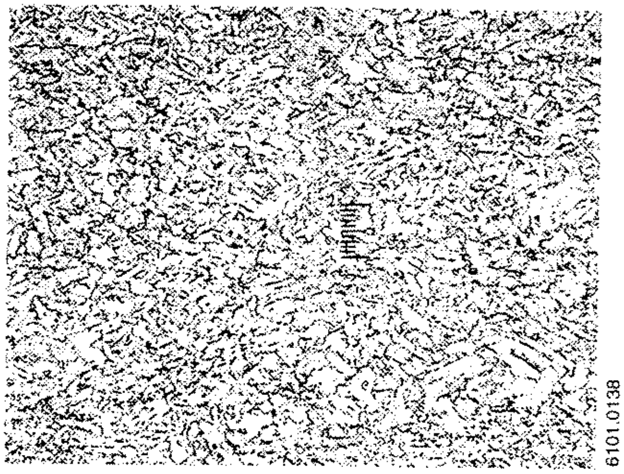

Fig. 15 - Material N weld line microstructure. (scale marker =20 μm)

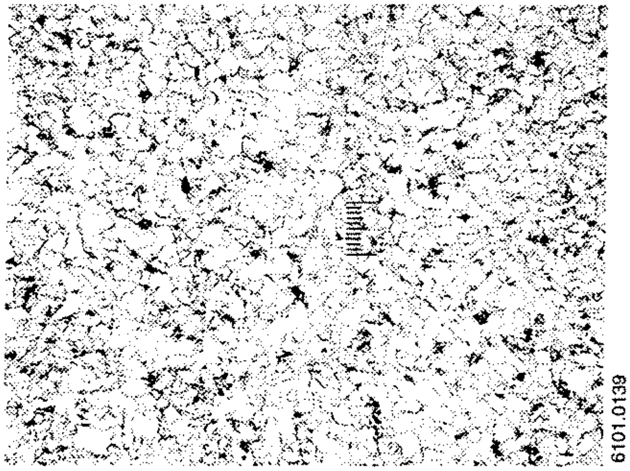

Fig. 16 - Material N HAZ microstructure. (scale marker =20 μm)

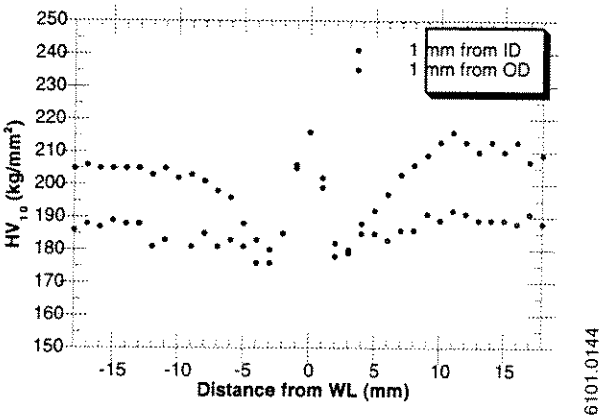

Fig. 17 - Typical material N macrohardness traverse.

APPENDIX C

DEVELOPING A NONDESTRUCTIVE TESTING PROGRAM FOR HOMOPOLAR WELDING OF API 5L LINE PIPE

Developing a Nondestructive Testing Program for Homopolar Welding of API 5L Line Pipe

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Homopolar Welding (HPW) is a high speed, electric resistance forge welding process being developed for offshore, deep water pipe laying using the J-Lay method. With this method, the welding operation must be accomplished at a single station, since the pipe is welded vertically then lowered directly into the water. The HPW research program, in its fifth and final year at the University of Texas at Austin Center for Electromechanics, is funded by six oil companies (Amoco, BP, Exxon, Mobil, Shell, and Texaco), two independent contractors (CRC-Evans and Parker Kinetic Design), and two government agencies (The Office of Pipeline Safety of the DOT and the Mineral Management Services of the DOI). The objectives of the program included optimizing weld parameters to produce strong, tough welds in nominal 3 inch pipe, then building a welding fixture for larger diameter pipe. Successfully joining larger diameter pipe would demonstrate the scalability of the HPW and be the first step in developing a commercial production fixture for J-Lay. In addition to developing the welding process, a final objective of the program was developing a nondestructive evaluation (NDE) program for qualifying the new welding process and for use on the J-Lay pipe laying operation.

The main steps in developing a NDE program consisted of characterizing possible HPW flaws, identifying the best suited NDT method, developing appropriate tests and calibration standards, applying the method, and correlating the results with weld and real time process parameters, destructive testing results, and microstructural features. A literature search was conducted on similar solid state and electrical resistance welding processes to determine the typical flaws and what process characteristics caused their formation. By comparing HPW to other solid welding processes, flaws more likely to occur in HPW could be determined.

Compared to other solid state welding processes, HPW is fast, with the weld completed within five seconds after discharge. A singular feature of homopolar welding is the power source, a homopolar generator (HPG), which converts the stored rotational kinetic energy of the rotor to a direct current mega-ampere electrical pulse. The pulse reaches a peak current density for low carbon steels of 70 kA/in^2 in 100 ms, with a total duration under three seconds. Like other electrical resistance welding processes, the current pulse is conducted to the workpiece mounted in an upset fixture. The interface and adjacent material heats resistively in response to the current and an upset load forges the joint.

Recent changes to the HPW method resulted in a weld line microstructure similar to parent metal with no evidence of the original interface. Flow of interface and adjacent material as it upsets reorients the axial banded microstructure to varying degrees, producing visible flow lines in the material adjacent to the original interface. Earlier in the program, the original interface was often marked by a fine inclusion line with a notch or fine crack extending from outside or inside weld bulges to the pipe midwall. Cross-sectional areas joined in the current program range from 3.0 in^2 the three inch pipe to 19.25 in^2 in twelve inch pipe.

The literature search focused on solid state welding processes including flash butt welding (FBW), high frequency electric resistance welding (HFERW), friction welding, (FW) and diffusion bonding (DB). The findings from this study identified two distinct solid state welding process types and their associated flaws as determined by the presence or absence of an interface gap at welding. Open gap methods include FBW and HFERW and have molten metal present at the interface during the welding cycle. Closed gap methods have no molten metal present as high interface pressures maintain a gapless interface during joining. The specific flaws associated with the open gap welding process included penetrators, flat spots, and microinclusions and were attributed to poor process control. In contrast, closed gap processes do not heat the interface material to melting temperatures. The specific flaws associated with closed gap methods include "kissing bonds" or cold welds and arrays of microinclusions and appear to have resulted from poor process control. Table 1 presents a summary of literature search results.

Table 1 :Summary of Possible Defects in Solid State Welds

Method / Defect	Electric Resistance Weld	Flash Butt Weld	Friction Weld	Diffusion Weld	Homopolar Weld
Hook Cracks					
Penetrators - Flat Spots	+	+			
Decarburization	+	+	+		
Cold Welds			+	+	+
Partial Bonding	+	+	+	+	+
Weld Area Crack	+	+	+	+	+
Inclusions	+	+	+	+	+
Porosity	+	+	+	+	+
Hydrogen Entrapment	+	+	+	+	+

+: indicates possible occurrence

Homopolar welding is most like closed gap welding methods. For closed gap processes, cold welds result when the softened interface material makes intimate contact without forming a metallurgical bond. Arrays of microinclusions result when interface contaminants are disrupted but not fully expelled from the interface, leaving partially unbonded regions. These solid state welding flaws are characterized by having area but no thickness, oriented parallel to the weld interface, and located anywhere on the plane of the original interface. One of the difficulties in detecting such flaws in HPW is the narrowness of the weld region with its rapidly changing grain size and orientation and mechanical properties.

The NDT method selected for HPW must be able to detect HPW flaws, have fast inspection and analysis time, and provide a permanent record. The NDT methods considered include radiography, ultrasonics testing, eddy current testing, and mag particle and other surface inspection techniques. The NDT method chosen for inspecting solid state welds with the microinclusions and cold welds was automatic ultrasonic testing (AUT). Ultrasonic testing was selected based on its ability to detect planar oriented reflectors located through the wall thickness over radiography and eddy current testing. AUT provided repeatable testing results, improved resolution of small reflectors, a permanent record of the test results, and short inspection and analysis times.

In the early stages of the program, homopolar welds in three inch pipe were sent to independent NDT companies for ultrasonic testing. Welds were scanned manually and automatically, using pulse echo, through transmission dual probes, and tandem dual probes, at 5, 7.5 and 10 MHz. Scan angles were typically around 70°. Welds with indications were destructively tested by removing metallurgical specimens from sectors with and without indications for comparison. One set of welds was destructively tested using a more laborious technique. From three welds, five to six specimens were cut from each, then successively ground, polished, etched, and examined for microstructural features associated with the indications. This process was repeated six to eight times grinding through four thousands inch (0.004") at each stage to observe any changes in microstructure associated with the indication.

Overall, early ultrasonic testing of the three inch pipe was unsuccessful for a number of reasons, primarily due to the lack of a calibration specimen representative of the typical flaws. To correct this deficiency, a set of welds was produced containing intentionally placed flaws typical of closed gap welding processes. 50 μ thick tungsten foil and 12 μ diameter tungsten powder were placed at discrete sites on the interface prior to welding to simulate a kissing bond and an array of microinclusions, respectively. One additional weld was made with eight flat bottomed holes bored into one of the pipe ends at four different depths and two different diameters to provide a small reflector at or near the weld line. After welding, the upset consumed part of each hole, and in two cases, the entire hole.

The set of welds with intentionally placed flaws was sent out for EMAT and radiography. EMAT tests of this series found all indication using a 2 MHz transducer and a patented pitch and catch diffraction technique. Radiography detected only the larger flaws: some of the flat-bottomed holes and some of the tungsten foil flaws.

A single channel, laptop computer-based automatic ultrasonic test system was purchased to permit development of appropriate tests and calibration procedures for homopolar welds at the Center for Electromechanics. Probes used to interrogate the weld line include pulse-echo, TOFD, and tandem. Of these probes, the tandem was considered the best suited to detect any reflectors oriented along the weld plane (Figure 1). From the geometry of the weld, any reflectors located along the weld plane will return some energy to the receiver. Separation of the transducers controls the focal point of the probe. A proposed go-nogo test uses a modified tandem probe design with a single transmitter and multiple focused receivers, positioned and tilted to interrogate the entire wall. With a single sweep, the entire weld interface would be inspected. (Figure 2).

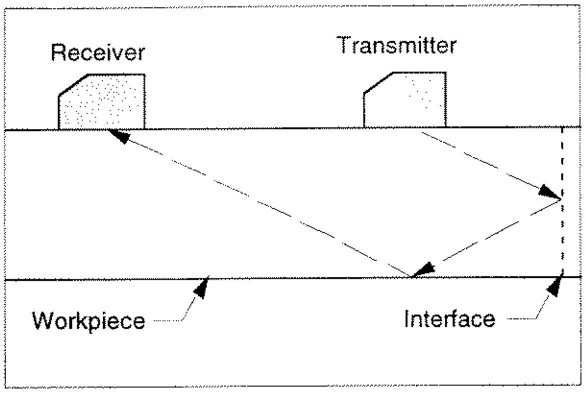

Figure 1. Schematic of tandem probe

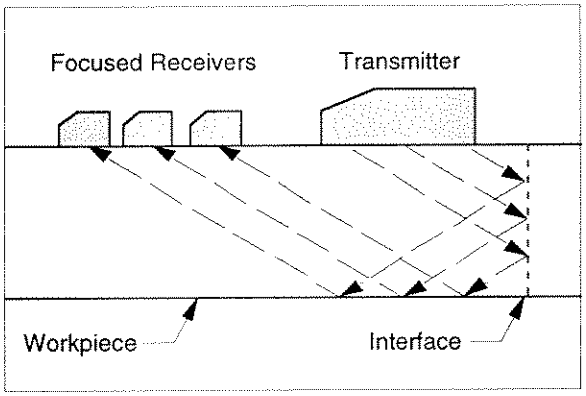

Figure 2. Schematic of go-nogo multiple receiver tandem probe

An array of microinclusions or a kissing bond, if present, would be located along the weld plane. While a single microinclusion would not scatter sufficient energy to be detected,. the combined scattered energy of an array should be detectable. The kissing bond has characteristically low reflectivity, but with the tandem probe geometry, all reflected energy is received. Strong single reflectors located along the weld plane would be easily detected. At the sensitivity needed to detect an array of microinclusions, their echo saturates the screen.

The short term objectives of the NDE work include:
1. Evaluation of three inch pipe welds with intentionally placed flaws.
2. Comparison of the echodynamics for welds performed with substantially different weld parameters that produced acceptable and unacceptable properties in the weld metal.
3. Development of tests for detection of base metal microstructural characteristics contributing to unexplained property changes around the circumference of the weld.

Successful test techniques will be applied to twelve inch pipe welds. A follow-on program to the present research program is proposed which will include a fracture mechanics study of homopolar welding and a nondestructive evaluation program. The goal of the NDE program will be a qualified NDT method for HPW. Microstructural characterization of HPW is also proposed.

As homopolar welding is commercialized, developing procedures for setting weld parameters for new materials and shapes may benefit from a nondestructive microstructural characterization technique. Correlation of NDT results with weld parameters, real time process parameters, and mechanical test results may decrease the number of tests required to achieve the desired properties and qualify the process at the same time. When HPW is a qualified welding process, it is expected that real time process monitoring will be the primary method for quality assurance similar to other automatic welding process.. Despite this, 100% inspection of deep water pipe line welds is expected, and an AUT system should meet the requirements. Besides assuring no unacceptable defects are present in the weld, the AUT system could be applied to monitor the circumferential uniformity of the process for statistical control purposes.

APPENDIX D

HOMOPOLAR WELDING COMMERCIALIZATION EFFORT PREPARED BY PARKER KINETIC DESIGNS, INC.

University of Texas Center for Electromechanics
Homopolar Offshore Pipeline Welding Research Program
Joint Industry Program

HOMOPOLAR WELDING COMMERCIALIZATION EFFORTS

by

Parker Kinetic Designs, Inc.

COMPANY BACKGROUND

Parker Kinetic Designs, Inc. (PKD) is a Texas corporation formed in 1984 to commercialize pulsed power technology developed at the Center for Electromechanics at the University of Texas at Austin (CEM-UT). The company has an exclusive world-wide license to the technology which has resulted in nearly three dozen equipment and process patents. The patents, owned by both UT and PKD, have resulted from several hundred man-years of development effort. The company is jointly owned by Dresser Engineers and Constructors, Inc. (90%), and the University of Texas System (10%).

Through the Patent and Technology License Agreement between PKD and the University of Texas, the company has access to past, present, and future technology and expertise at CEM-UT. The Center is recognized as the country's foremost research and development group in the area of advanced rotating machinery for pulsed power.

PKD has an experienced and effective management and multidisciplinary technical team in place which has a thorough understanding of the technology, and is pursuing commercialization of its industrial applications. The principal focus of PKD's effort is to expand, refine, and identify additional applications for two unique electric generators, the homopolar generator and the compulsator. The goal of the company is to become the supplier of pulsed power generators directly to end users or to systems integrators that possess unique knowledge in targeted market areas such as welding, heating, brazing, and other metals treating and fabricating processes.

Although the company has been in operation for more than twelve years, only in the last two years has the commercialization of the technology been the primary focus of PKD. Since its inception, PKD has covered a significant portion of its operational costs through U. S. Government contracts supporting pulsed power research. Substantial and valuable experience has been gained in the design, construction, and implementation of pulsed power equipment for the Department of Defense.

The company has a limited but excellent track record of delivering high-quality, dependable pulsed power systems. PKD has designed, manufactured, and installed two complete pulsed power systems, including auxiliaries and controls. The first system is a portable skid-mounted unit with a single homopolar generator and is currently in use in the Netherlands for electromagnetic launch research (EML). The second system is a permanent installation currently in use at CEM-UT and consists of six homopolar generators, auxiliaries, and controls. The system also is used for EML research as well as other research purposes. Both systems have exceptional records of dependability.

Marketing efforts of the company are expected to be achieved through affiliation with "strategic" partners in selected areas. Several potential partners have been identified and joint efforts are underway to develop applications and customers for the technology.

COMMERCIAL APPLICATIONS FOR PULSED POWER

Historical Applications

In the continuous duty mode, the homopolar generator has been used to provide DC power in the place of unavailable or expensive alternating current. Westinghouse Electric developed a continuous duty homopolar generator in 1934 to seam-weld tubing. This tube manufacturing facility operated successfully into the 1950's until the plant shut down. Other applications include the U.S. Navy's continuing interest in homopolar motor-generators for quiet electric drives in submarines.

The pulsed duty mode of the homopolar generator is typically used when rapid energy deposition is desired, such as with welding. In 1959, General Electric produced a homopolar generator that successfully produced electrical arcs in a wind tunnel research program.

CEM-UT has been developing various pulsed duty applications for the homopolar generator since 1972. Early interest in the homopolar generator came from the nuclear industry for use of the pulsed power output to produce the large magnetic fields that could contain fusion experiments. Using the six-generator power supply at CEM-UT, a world record magnetic field measured at 20 Tesla was produced in a single-turn toroidal coil. In 1980, the U.S. Army took significant interest in homopolar generators as a pulsed power supply for driving electric guns. These electric guns (referred to as *electromagnetic launchers*, or *railguns*) were developed for mounting on tanks and electrically shooting a projectile at more than twice the velocity achievable by conventional gas guns.

Modern Commercial Applications

More significant for industrial use, several research programs have developed the use of the homopolar generator's pulsed power for welding and heating of metals. Beginning in 1977, both the U.S. government and commercial agencies began funding research into the use of pulsed-duty homopolar generators to rapidly heat metals for welding and forming.

Homopolar Welding

Homopolar welding is a solid-state process (i.e. no melting of weld metal) that resistively heats the bulk metal around the interface between two workpieces and then forges the workpieces together. The entire heat and forge weld process requires only three seconds from initiation of the current pulse and produces a high quality, highly repeatable joint with no cast structure or inclusions. The primary advantage of homopolar welding is the ability to turn a process that is highly dependent upon the art and skill of the operator (such as arc welding) into a highly controllable, automated, true <u>manufacturing</u> process. In addition, because of the short duration of the current pulse and the minimal time required to ready the generator for the next cycle a single homopolar generator machine operator can produce the same amount of work that would typically require several welders.

Applications that have been investigated include: butt-welding of tubular goods for pipeline and piping systems, butt-welding and large area spot welding of structural shapes for high-rise building construction, large area spot welding for cladding, closure welds for containment vessels, full section butt-welding for aluminum smelter anode repair, and butt-welding of railroad rails for railway construction.

Homopolar Pulsed Heating

Heating for forging or annealing with the current pulse from a homopolar generator allows the entire workpiece to be brought to temperature more rapidly than otherwise possible. The primary advantage of homopolar pulsed heating for forming is the ability to very precisely control a rapid thermal cycle and metallurgy. In addition, the energy from the homopolar generator is stored and then delivered on an as-needed basis, unlike a conventional furnace that requires continuous temperature maintenance even when there are no workpieces. Applications that have been investigated include: hot rolling of aircraft turbine blades, in-die forging for near-net-shape forming, and pulsed annealing for precise metallurgical control.

Homopolar Pulsed Compaction

Another application that is a combination of welding and heating is homopolar pulsed compaction of metal particles for specialty metal production. For most specialty metals, very precise mixtures of metal particles are cold compacted into a low density, fragile mass and then vacuum melted to form a predetermined alloy. Homopolar generators can provide an electrical pulse to heat and join these particles into a high density mass with more repeatable chemical mixture. This would reduce the rework required to obtain the desired chemistry and potentially have significant effects on the cost of some specialty metals.

The same pulsed compaction process used to bond large metal particles for specialty metal production can be applied to powder metals to compete directly with powdered metal sintering. Homopolar pulsed compaction of powdered metals results in a compaction density and chemical mixtures not achievable by conventional sintering processes.

Plasma Spraying for Coating

Industrial applications for the compulsator typically rely on the higher voltage output and the continuous string of large current pulses it can provide. One industrial application that is currently being investigated is to use a combination of the railgun and the compulsator to electromagnetically "spray" a high integrity coating onto a base surface. This "spraying" action actually imbeds the sprayed material onto the surface of the base metal, forming a metallurgical bond as opposed to painting the surface. As an example, the pulsed spraying could be used to coat a ship's hull with a corrosion resistant material that would have a significant impact on the life and maintenance of the hull.

High Energy Rate Forging

This particular forging process uses a closed die and the stored energy of high-pressure gas to accelerate a forging ram to very high velocities. Using the compulsator and electromagnetic launch techniques, high-energy-rate forging can be accomplished at previously unobtainable forging velocities. This will produce near-net shape forging in materials and geometry's that previously could not be taken to near-net shape.

Electromagnetic Forming

Electromagnetic forming is a standard industry assembly technique that utilizes pulsed magnetic fields. The high current pulses of the compulsator makes it an ideal power supply for forming applications that cannot be performed by standard power supplies due to energy or current limitations.

Rapid Drying With Flash Lamps

The compulsator was originally invented for driving flashlamps which provide optical energy to laser beams for controlled thermonuclear fusion research. The compulsator can also be used to drive flashlamps for rapid heating of surfaces, such as paint on autos or appliances. Another application that requires rapid drying of a surface is production of newspapers and magazines, where the speed of printing is often limited by the drying time of the ink.

MARKET CONSIDERATIONS FOR NEAR-TERM APPLICATIONS

Presently, PKD is focusing on welding of tubular goods as the near-term market. The business strategy is to develop a strategic alliance with representatives in specific markets that will package and deliver a complete welding system utilizing the homopolar generator as the pulsed power supply. This strategy allows PKD to focus on its core talents of manufacturing homopolar generators while supporting the development of existing and new applications markets with strategic partners. It is anticipated that PKD will develop strategic alliances in the very near future in three tubular goods markets: offshore pipeline construction, oil and gas coiled tubing, and petrochemical piping fabrication.

Tubular Welding

The tubular welding market appears to be the most attractive for near-term applications of homopolar generators for several reasons. Welding of pipe and tubes is the most developed application from a technical standpoint. The first industrial application research program at CEM-UT was to investigate pipe welding (1977) and since then, several small programs have investigated the welding of various pipe sizes and materials. Although most of the programs were small and scattered, considerable progress has been made in developing the equipment and process parameters. Another reason that makes tubular welding appear to be the most likely near-term application is that progress in developing the process parameters has made it relatively simple to apply the technology to a number of different tubular welding markets. This means that the development work to address a new market can build directly upon the work already performed. The other reason that makes tubular welding an attractive early market is that homopolar welding directly addresses one of the key weaknesses in the existing marketplace: welders. In almost every tubular welding application, the availability of top-quality welders is a hindrance to the business operations. When the same size pipe welds must be made in a repetitive manner, homopolar welding can greatly outperform manual stick welders in quantity, quality, and cost.

Offshore Pipeline Construction

The application of homopolar welding for offshore pipeline construction has been under development for several years. For various reasons, pipelines in deep water are typically constructed by welding one joint at a time at a single welding station. This is in contrast to the construction method used in shallow water that takes advantage of several welding stations. Since all welding must occur at a single station in deep water applications, the speed of the welding process becomes critical in these very expensive construction projects. Homopolar welding offers a faster, higher quality welding process with reduced requirements for labor. These factors result in homopolar welding being capable of almost 2.5 times the number of welds per day. This results in a significantly reduced labor cost per weld and lower equipment rental costs (e.g. lay barge rental) for offshore pipelines. Deep water pipeline construction is a growth market. Evaluations are in progress that would estimate the potential market size for homopolar welding.

Other technologies have been competing for the deep water, single station pipe welding business for several years. Most notable of these is the multi-million dollar investment that one domestic pipeline contractor made in buying the rights to use a foreign flash-butt welding process. This technology was deemed unsuccessful when repeatable, acceptable welds could not be made and new equipment had to be built for each pipe size. Presently, there are five processes in competition for the deep water pipeline construction business in addition to homopolar welding: traditional manual stick welding, automatic (orbital) welding, radial friction welding, SAG forge welding, and threaded mechanical connectors. For the near-term, automatic welding will be the process of choice but competition will continue because the other processes offer a significant cost reduction potential. Analysis of these competing technologies indicates that homopolar welding offers a significant time, cost, and technical benefit over other technologies.

Other potential applications for homopolar welding in the pipeline industry include: on-shore fabrication of pipe strings for offshore spooling, overland pipeline construction, and coiled tubing repair for oil and gas well servicing. All three of these applications are natural outgrowths of the previous pipe welding development and in some cases involve the same customers, contractors, or strategic partners.

In-Shop Piping Fabrication

Fabrication of pipe strings for offshore spooling of pipeline would involve using the homopolar welding process to weld together 40 ft. joints of small diameter pipe (2" to 12" diameter) in an assembly (or *firing*) line. Overland pipeline construction is an outgrowth of the homopolar welding offshore pipeline construction process, with the additional requirements that the equipment be minimized and even more field portable, and the system be capable of welding larger diameter pipe (18" to 30" diameter). In both of these applications, the economic benefit of homopolar welding is primarily reducing the cost of the pipeline by speeding up the welding process and reducing the labor requirements. In addition, these applications can be turned into controllable manufacturing processes which further reduces costs by improving weld quality and repeatability, and therefore minimizing repairs.

The use of homopolar welding to assemble pre-fabricated piping spools for later installation in petrochemical and power plants has not had much technical development to-date but appears promising. The application builds directly on the development already performed, with the additional requirement that pipe shapes other than straight joints be welded. Significant development must still be performed to determine if pipe tees and elbows can be welded with homopolar welding, but the potential economic benefit of fast, high quality, repeatable welds indicates that the development is worth the investment.

Initial economic studies indicate that the cost of the homopolar welds in the piping spool fabrication application are significantly less than the per-weld cost of manual welds. In addition, a single-operator homopolar welding system can produce over ten times the number of welds per day as a single-welder, manual welding crew. With the piping spool fabrication market estimated at $300 million in Louisiana alone, this represents a significant potential market for homopolar welding.

Coiled Tubing Repair

Repair of coiled tubing is a unique application in that it does not require speed as much as the high quality obtainable by homopolar welding. Although full testing is yet to be performed, it is believed that a homopolar welded joint has a higher fatigue strength than the manual or orbital welds currently used. This increased fatigue strength would increase the usable cycles on a reel of coiled tubing.

Market Penetration

The primary disadvantage that homopolar welding has is the cost of the equipment, which is being addressed in two ways. An ongoing product development effort is focusing on decreasing the cost of the generators significantly. This will make the initial capital investment much more attractive and easier to justify. In addition, PKD is considering the strategy of leasing the equipment rather than selling. Although this forces the initial capital equipment cost on PKD rather than the customer, it also allows amortization of the welding equipment over several projects and maybe over several different applications. Therefore, no single customer in any single application need justify the high cost of equipment.

The difficulty with homopolar welding penetrating the market for pipeline spooling, overland pipeline, or coiled tubing repair is that the competition is well-entrenched. Manual welding is used extensively and orbital welding has an approximate 30 year history of development. It is believed that the homopolar welding process brings significant economic benefit, but suffers from being new to the market and simultaneously requiring significant initial capital investment.

As with the other tubular welding applications, the primary competition will come from the well-established manual welding process. However, it is expected that once homopolar welding breaks into just one tubular market, barriers in other markets will be reduced.

Aerospace Welding Applications

Another near-term commercial application area for homopolar pulsed welding of aerospace components for military and commercial airplanes and missiles. Specific applications include the HPW of various pressure vessels, cryostats, and large cross section components such as landing gear struts. Recent development work by PKD and UT-CEM has shown that full strength and parent metal toughness welds can be produced with the HPW process in such high strength materials as Ti-6Al-4V in an ambient welding condition with no protective inert gas shielding. Currently work is ongoing to verify the fatigue properties of these welds. Conversations with metallurgical and welding experts in this field have indicated a significant potential advantage for homopolar pulsed welding in this application area.

HOMOPOLAR PULSED WELDING EQUIPMENT DESCRIPTION

The Homopolar Pulsed Welding equipment description presented below describes a small 15 Megajoule system which could be used to weld up to approximately 15 square inches of high strength API linepipe. The system as described is configured for a horizontal application such as a land based spooling yard or S-lay barge application. Vertical application systems such as would be required in a J-lay operation or in a drilling application can be accomplished by removing the external welding fixture from the weld area once the homopolar weld is complete, and then accomplishing the external upset removal, inspection, and coating as necessary. Larger power supply systems capable of welding larger cross sections of material can be accomplished through use of multiple 15 Megajoule homopolar generators operated in parallel, through the use of larger 30 Megajoule or 50 Megajoule homopolar generators, or through a combination of both approaches. This paralleling ability of the homopolar generator produces the capability to accomplish large section welds of many tens to many hundreds of square inches in a few seconds with cycle times, including system motoring, of a few minutes.

Homopolar Pulsed Power Supply Description

The Homopolar Pulsed Power Supply will be a single skid mounted package including one electrically self-motored 15 Megajoule homopolar generator (HPG), field coil/armature configuration switch, and discharge initiation switch to control the pulsed output current of the HPG. The skid mounted package will weigh approximately 60,000 lbs., and have dimensions of approximately 10 ft. wide by 13 ft. long by 8 ft. high. The conceptual arrangement of the Homopolar Pulsed Power Supply skid is shown in the attached drawing (figure D1).

The homopolar generator is a 15 Megajoule machine with an open circuit output voltage of 80.5 VDC, and a rated maximum pulsed discharge current of 1,500,000 amperes. The equivalent circuit capacitance of the HPG is 4627 Farads. The HPG is shown in the attached drawings (figures D2-4). As can be seen from the cross section view of the machine, this HPG is a self motoring truncated drum style generator. The rotor of this machine is a solid chrome-molybdenum steel forging 31.00 inches in diameter by 30.67 inches long with a full speed rating of 3444 rpm. The overall dimensions of this machine are approximately 62.00 inches in diameter by 65.00 inches long, with an estimated weight of 30,000 lbs. The HPG is designed to allow easy replacement of the motoring and discharge brushes which have a rated design life of

10,000 full energy discharges between replacement. At full speed the machine is designed to have a brush slip speed of 142 meters per second. At a field excitation of 700 amperes, the air gap magnetic flux density in the HPG is approximately 1.50 Tesla. The HPG uses rolling element bearings for rotor support, and water cooled field coils. The rated full energy discharge cycle time for this machine is three minutes or twenty discharges per hour. The calculated motoring time for this machine at a motoring current of 2800 amperes is 2.5 minutes. In the industrial HPG, motoring brushes remain in constant contact with the rotor surface while discharge brushes only contact the moving rotor during the 3 second discharge. During discharge of the homopolar generator the machine is disconnected from the power grid other that the power required to provide field excitation. Field coil excitation power required from the DC SCR power supply during homopolar discharge is approximately 20 kW.

The second major component on the homopolar pulsed power supply skid is the field coil/ armature configuration switch (figure D5). This switch converts the HPG in effect to a series wound DC motor during motoring of the machines rotor by placing the four paralleled dual layer field coils (two per machine end) in series with the rotor. When the machine is ready to be discharged this switch reconfigures the system to the more classic pulsed homopolar generator circuit. The discharge initiation switch is designed to accomplish this reconfiguration under a no load (no amperage) condition with a design life of 10,000 cycles between contact maintenance.

The third major component on the homopolar pulsed power supply skid is the discharge initiation switch (figure D5). This unit is a 1,500.000 ampere air actuated, hydraulically locked galvanic contact switch similar in design to the discharge initiation switches that have been in use at CEM-UT on their industrial research HPG for over twenty years. The switch has a design impedance of less than 2 microhms, and a calculated operation time of approximately 10 milliseconds. As the rotor of the HPG slows down from discharge brush friction after a weld cycle has been started, operation of this switch is used to initiate the discharge of the homopolar (start the flow of homopolar discharge current to the workpieces) at the precise speed corresponding to the requirements of the particular weld to be made. The HPG is connected to the discharge initiation switch and then to the homopolar weld fixture using multiple six conductor, 800 mcm water cooled copper hexapolar cables.

The homopolar pulsed power supply components will be mounted on a rigid steel skid frame suitable for oil field or industrial duty. This skid can be quickly disconnected from the homopolar welding fixture and from the auxiliary support system skid if it becomes necessary or desirable to relocate the homopolar pulsed power supply. The skid will be equipped with standard oil field type skid lifting points to facilitate handling.

Auxiliary Support System Description

The homopolar welding system auxiliary support unit, as shown in the attached drawing (figure D1), will consist of a single rigid steel skid containing the field coil/motoring 300 kW DC SCR power supply; a 20 ton closed loop chilled water system; homopolar bearing oil supply and scavenge system; air compressor for discharge brush actuation, discharge initiation switch actuation, and internal alignment/ internal upset removal fixture actuation; closed loop hydraulic power supply for HPW external fixture actuation; and a motor control center to start/stop the various auxiliary support components. The estimated maximum electrical power consumption of the system is approximately 450 kW during the last portion of the motoring period as the HPG rotor nears its maximum speed. The auxiliary support system skid will be a rigid oil field/ industrial rated skid with lift points for easily handling. The estimated auxiliary support skid size is approximately 8 ft. wide by 15 ft. long by 8 ft. high. Estimated auxiliary skid weight is 20,000 lbs.

The 300 kW DC SCR power supply used for field coil excitation and HPG motoring will be a standard industrial air cooled, 480 VAC / 60 Hz / 3 Phase power input, 3000 ADC / 100 VDC output unit. This unit will easily supply the necessary motoring and field excitation power necessary for the HPG to reach its maximum rated speed and energy in less than two and one half minutes.

The closed loop chilled water system will be a standard air cooled, 20 ton (240,000 BTU/hr), 480 VAC / 60 Hz / 3 Phase power input unit capable of supplying approximately 50 GPM of chilled water at 55 ^{O} F when the ambient temperature is 95 ^{O} F. This cooler will be capable of maintaining three minute full energy discharge operation of the welding system at an acceptable operating temperature during the worst anticipated summer conditions. This system will supply chilled water to the HPG field coils, the HPG motoring Brushes, the HPG-to-switch and switch-to-fixture hexapolar discharge cables, and to water-to-oil heat exchangers on the HPG bearing lubrication and fixture hydraulic power supplies.

Pipe Preparation Equipment Description

The special reduced section end preparation necessary for Homopolar Pulsed Welding of pipe will be accomplished using standard commercially available pipe facing machines modified to produce the required profile. These machines are available from several sources, and can be supplied in either an air, electric, or hydraulic powered version. The modification necessary to produce the HPW weld preparation consists of rearrangement of the multiple ceramic or carbide machine tool inserts normally used to produce the more conventional pipe weld preparation into the proper position to produce the required homopolar preparation. In the recently completed Joint Industry Program conducted at CEM-UT, a commercially available pipe facing machine was used to prepare the pipe ends then produce welds in 3 inch schedule 80 pipe with completely successful results. Preparation of the larger pipes anticipated under this project (4 - 10 inch) will not present a problem using this technique. Additionally, during this procedure the outside diameters of the pipe near the ends where the welding electrodes will be attached will be brushed clean to insure proper electrical contact.

Internal Pipe Alignment and Internal Upset Removal Equipment

The homopolar system Internal Alignment and Upset Removal fixture will be an air actuated unit which provides both internal alignment of the two straight pipe sections to be welded as well as removal of the small internal upset generated on the inside pipe wall during the homopolar welding process. The internal upset will be removed immediately after the homopolar weld is completed. The external portion of the pipe upset generated during homopolar welding will be removed using a fixture described later.

The current plan is to provide a pair of internal alignment and upset removal fixtures to cover the anticipated pipe sizes (4" t0 10" OD). One unit would provide alignment and upset removal for the various schedules (wall thicknesses) of 4 and 6 inch pipe while the second unit would cover 8 and 10 inch pipe. Each unit will be equipped with two pairs of independently actuated grips which can be expanded on command to grip and align each pipe section to be welded. The two grips in a pair which position one of the pipe sections to be welded will be separated axially by a sufficient distance to insure accurate pipe angular alignment as well as radial internal alignment of the pipe inside diameters of the two sections to be welded. The internal alignment gripping pairs will be electrically isolated from one another to prevent current conduction through the internal fixture during the homopolar pulsed welding process. The internal fixture will be placed in the proper position inside the pipe by a solid reach rod which will be extended and retracted by an external drive system. For applications where a reach rod is impractical, a cable retrieved internal alignment fixture could be used. The reach rod, or retrieval cable, will also provide all required actuation air and electronic control signal communication as required.

The internal fixture will remove the internal upset of the welded pipe using an expandable shear blade which will be positioned against the inside diameter of the downstream pipe, and then moved axially a short distance to remove the small upset while it is still warm. The upset will be removed using a progressive spiral shearing motion to reduce the required upset removal force, and to provide a sheared linear remnant of the removed upset which can be easily removed from the retracted internal fixture prior to the next welding cycle.

External Homopolar Pulsed Welding Fixture

The external homopolar welding fixture will perform several functions. First, it will provide a soft, low pressure mechanical grip around the circumference of the coated pipe over an axial length of approximately 10 ft. on each of the pipe sections to be welded. This gripping action will occur on top of the external pipe coating, but be light enough to firmly grip the pipe without damaging the coating. The purpose of mechanically gripping the pipe over the relatively long length is to provide enough gripping surface area to frictionally apply the necessary homopolar welding upset force without damaging the pipes protective coating. This approach is similar to one presently used to mechanically assemble coated linepipe into a press fit connecting collar in other oilfield applications. The mechanical soft grip jaws will be replaceable to allow for maintenance, and to allow different thickness jaw inserts to be used for the different outside pipe diameters. Each of the mechanical grips will be segmented so the grips can adapt to small variations in pipe contour and still provide adequate gripping strength without coating damage. The mechanical grips will be either air or low pressure hydraulically actuated in an independent manner so that each grip can be actuated at the proper time in the welding sequence. As with the internal alignment grips, the external mechanical grips will be electrically isolated from one another to prevent current conduction during welding.

The second function of the external homopolar welding fixture will be to apply the electrical contacts or electrodes to the outside diameter of the pipe sections. These electrodes are applied near the ends of the pipe to be welded in the area of the pipe which comes from the supplier without external protective coating. The electrodes will be similar to the ones currently used on the CEM-UT Joint Industry Program 12 inch welding fixture. The electrodes will engage the aligned pipe, establish the proper contact pressure, and then lock in place to prevent pipe radial motion during the homopolar welding process. This approach has proven very successful in the CEM-UT fixture. The electrodes will be segmented into multiple contacts to allow adaptation to small variations in pipe external size and profile. Separate sets of electrodes will be provided for each pipe size specified in the system performance specifications. As used in the 12-inch CEM-UT fixture, replaceable thin flat copper braided cable material similar to battery cable will be placed between the solid electrode contacts and the outside surface of the pipe to compensate for mismatch between the two surfaces. Typical pulsed welding currents used in the homopolar pulsed welding process are approximately 70,000 amperes per square inch of pipe cross section for HSLA steels. Both sets of electrodes will be electrically isolated from the body of the external welding fixture to safeguard against conduction of the pulsed discharge current through some path other than the weld interface.

The third function of the external homopolar welding fixture is to provide the required forging force necessary to produce the finished homopolar pulsed weld. This force will be generated hydraulically using multiple cylinders attached between the two mechanical grip sections of the fixture. Typical homopolar weld forging pressures are approximately 20,000 pounds per square inch of pipe cross section. A second approach that will be investigated is the use of a single annular cylinder surrounding the pipe to produce the required forging force. Both approaches have been used with success in the past by CEM-UT during the conduction of various welding development programs.

External Weld Upset Removal Equipment

The external upset removal fixture will be a simple machining fixture which conducts a rotating cutter around the outer circumference of the pipe to remove the external upset created by the homopolar pipe welding process. The cutter radial position will be determined by the outer diameter of the as welded pipes to prevent the occurrence of an undercut. This procedure will provide a smooth burr free external pipe surface at the weld which will be well suited to the mechanized automatic ultrasonic inspection process which is to occur at production station 3 and the application of a protective coating over the weld area at station 4.

Control System Description-

Control of the HPW system, including the HPG, its auxiliaries, and the welding fixture will be achieved with a single GE Fanuc, Series 90 Programmable Logic Controller (PLC). This rugged, industrial controller will provide fully integrated automatic control of the HPW system including: a) automatic start/stop and sequence control of the weld fixture, the HPG, and all of their respective auxiliary systems; b) monitoring of critical system speeds, pressures and temperatures for safety shutdown control (with appropriate system and operator initiated hold points); c) precision, real-time, automatic control of the key system operating parameters critical to weld quality.

The control system will include an environmentally hardened electroluminicant (EL) touchscreen as the primary operator interface. This rugged Operator Interface Terminal (OIT) is a simple to use, yet sophisticated interface, which in conjunction with the automatic control features programmed into the PLC, provide safe, flexible, and efficient operation of the HPG welding system. The OIT can be used for initiating the automatic weld process, initiating auxiliary system start/stop sequences, changing the system's basic operating set-points, and monitoring auxiliary system parameters for maintenance and diagnostic purposes. The OIT workstation will be at the front of a free-standing control console which also houses the system controller (PLC) and the systems DC control power supplies. This workstation will be the main control panel for all routine production requirements, as well as system configuration and diagnostics.

This control panel & OIT will provide all necessary control functions for personnel involved in running the system on a daily basis. It will provide simple, safe operation for the welding system. The system operator will only need to cause the end-prepped pipe to be placed in the weld fixture, turn the system's key-locked on/off switch to the ON position and wait for a "READY TO MOTOR" indicating light. The control system will sequentially start the chilled water, bearing lubrication, bearing scavenge, brush actuation air, and rotor vacuum auxiliary systems in the appropriate order. When the operator is prompted by the system with a "READY TO MOTOR" light, he may then press the "MOTOR TO SPEED" button. The generator will then motor to slightly above the preset weld discharge rpm and hold at that speed with a "READY TO WELD" indicating light. When the "WELD FIXTURE READY" light responds indicating that the fixture is ready to receive the weld current, the operator may then press the "WELD INITIATE" button on the control panel to initiate the pipe welding sequence. From "MOTOR TO SPEED" , through discharge, to the "WELD COMPLETE" indicating light, the entire weld sequence can repeat every three minutes. The weld itself is over in less than 5 second.

HOMOPOLAR PULSED WELDING ADVANTAGES AND ECONOMICS

Homopolar Pulsed Welding Advantages Over Conventional Processes

Homopolar Pulsed Welding (HPW) is a resistance welding process that utilizes both heat and deformation to produce a solid-state weld (no melting at the joint). Also, this process will often be referred to as Upset Welding because of the slight upset caused by the deformation (forging) process. The HPW heat is produced by the resistance to the flow of the large electrical current produced by the homopolar generator at the shaped end and interface of the abutting surfaces of the workpieces to be joined. Once the interface and adjacent material have been softened by electrical resistance heating, the weld is formed by the high pressure which forges the workpieces together. The entire heat and forge process requires only seconds and produces a high quality, highly repeatable weld with no filler metal, cast structure, or inclusions.

A wide variety of materials, shapes and sizes can be successfully joined by using HPW in either a single-pulse or continuous mode. Conventional resistance upset welding is limited to joining a maximum joint area of approximately 0.75 square inches for carbon steel. By applying HPW, the joint area can be greatly increased (exceeding many 10's of square inches) and is determined by the workpiece material and cross-sectional design.

HPW is an environmentally friendly and operator safe welding process generating no hazardous gases or fumes. The U.S. Department of Labor, Occupational Safety and Health Administration (OSHA) Regulations 29 CFR 1910.1000, requires that welding operators and other persons in the area must be protected from over exposure to fumes (particulate matter suspended in air) and gases produced by conventional arc welding processes. Threshold Limit Values (TLV) are specified and enforced by OSHA. Protection from excess exposure is usually accomplished by a ventilation system which is expensive to purchase, costly to install, requires continuous inspection and routine maintenance. When exposure after ventilation exceeds TLV or where very toxic materials require a supplement to ventilation, personal respiratory protection devices must be used by all persons working within the exposed area.

HPW does not require a shielding gas and therefore does not require the use of potentially dangerous gas cylinders as does the majority of the arc welding processes. A shielding gas is commonly supplied in cylinders with very high internal pressures exceeding 4,000 psig and more. Gas cylinder storage and handling is regulated by several government agencies.

Since HPW does not require a shielding gas, it therefore does not require the apparatus for withdrawing gas from the cylinder or delivering it to the weld zone. This apparatus includes pressure regulators, flowmeters, hoses, connectors, valves, manifolds and piping systems. This apparatus is expensive to purchase, costly to install, requires continuous inspection and routine maintenance. Faulty apparatus and leaking systems represent a significant expense for most end users in wasted shielding gases. But most important, shielding gases are colorless, odorless and can displace the air (oxygen) needed to sustain life. For this reason, faulty gas control apparatus and leaking gas distribution systems represent a significant health hazard.

Advantages of HPW Versus Conventional Welding Processes

- **Increased Power**. The HPG is significantly more powerfully than traditional welding power supplies (up to 50 times), and not limited by either size, orientation, or shape of the workpieces to be joined as compared to other conventional welding processes.
- **Increased Speed**. HPW is extremely fast taking less than 3 seconds per weld. This speed is up to 200 times faster than those produced by conventional arc welding processes.
- **Ease Of Control**. HPW has only three process variables - current, force and time.
- **Fewer Defects**. Typical arc welding defects such as porosity, missed joints, incomplete fusion, spatter, and solidification cracking do not occur in HPW.
- **Increased Quality**. The metallurgical properties of the weld metal and heat-affected zone in HPW are those of hot-worked materials. In other words, the strength of the weld zone is not reduced to that of an annealed structure, as in conventional arc welding.
- **Weld Heat Treatment.** The current pulse can be shaped to control weld heating and cooling rates and to accomplish postweld heat treatment.
- **No Expensive Welding Consumables**. HPW is a solid-state welding process requiring no filler metal. HPW does not require additional shielding, backing or purging materials such as fluxes or gases. This represents a significant saving in consumable material, handling and storage cost as compared to most conventional arc welding processes.

- **Minimum Tools & Accessories.** Most of the expensive tools and accessories (i.e. grinders, torches, cables, protective clothing, safety equipment, and etc.) required in support of the conventional arc welding processes will be eliminated with HPW.
- **Easy & Inexpensive Operator Training**. Because of operational simplicity on-site training is easily accomplished and often results in the training of several backup operators. In comparison, arc welding requires in-depth training with critical applications (such as welding pipe) requiring extensive welder certification. Approved arc welder training courses and certification programs require several weeks of special off-site instruction with periodic recertification. The lack of skilled or certified arc welders often force employers to pay for expensive off-site training so as to maintain a competent and certified work force.
- **Full Automation**. HPW is an advanced process easily adapted to computer controlled and/or fully automated material handling systems. A very fast and cost effective production system can be designed around HPW. The HPW system is not complex to use, does not involve rotating the part, and requires minimum maintenance.
- **Clean & Safe Environment**. HPW is a solid-state welding process with no fumes, gases or toxic materials that can impact the environment or clean air standards.
- **Easily Joins Difficult-To-Weld Materials**. Many alloys considered unweldable can be joined by HPW. For example, a variety of stainless steels (including A-286), superalloys (including TD nickel), refractory metals (including tungsten), grade 2 titanium, and aluminum alloys (including 2024) have been successfully joined with HPW.

Homopolar Pulsed Welding Economic Advantages

Several studies have been conducted to determine the potential advantage of Homopolar Pulsed Welding process in various pipe welding applications. The results of one such study are included in the paper "Homopolar Welding Development and Economics" presented by Parker Kinetic Designs, Inc. and the University of Texas, Center for Electromechanics at the Energy Week 96 Conference in Houston, Texas. This paper outlines the basics of an economic comparison between homopolar welding and conventional manual welding for a small diameter J-lay application. A copy of this paper is included at the end of this section for reference.

Another economic study that was conducted compared homopolar pulsed welding to conventional manual welding and to a submerged arc or automatic gas tungsten arc welding process used in an advanced quad joining concept for a land based spooling facility. Although the specific details of this study are protected under a confidentiality agreement between PKD and a Gulf of Mexico marine contractor, the results of the study showed a significant economic advantage for homopolar pulsed welding in this application. This study showed that HPW as compared to a manual welding process that is currently used resulted in a 50% reduction in cost per weld with a HPW system production rate that is twice the capability of the present manual system. When compared to the advanced quad joining concept, HPW resulted in a 25% cost per weld reduction at a production rate increase of 67%.

Both of these economic studies clearly indicate the potential advantages of a homopolar pulsed welding system for welding of offshore pipe.

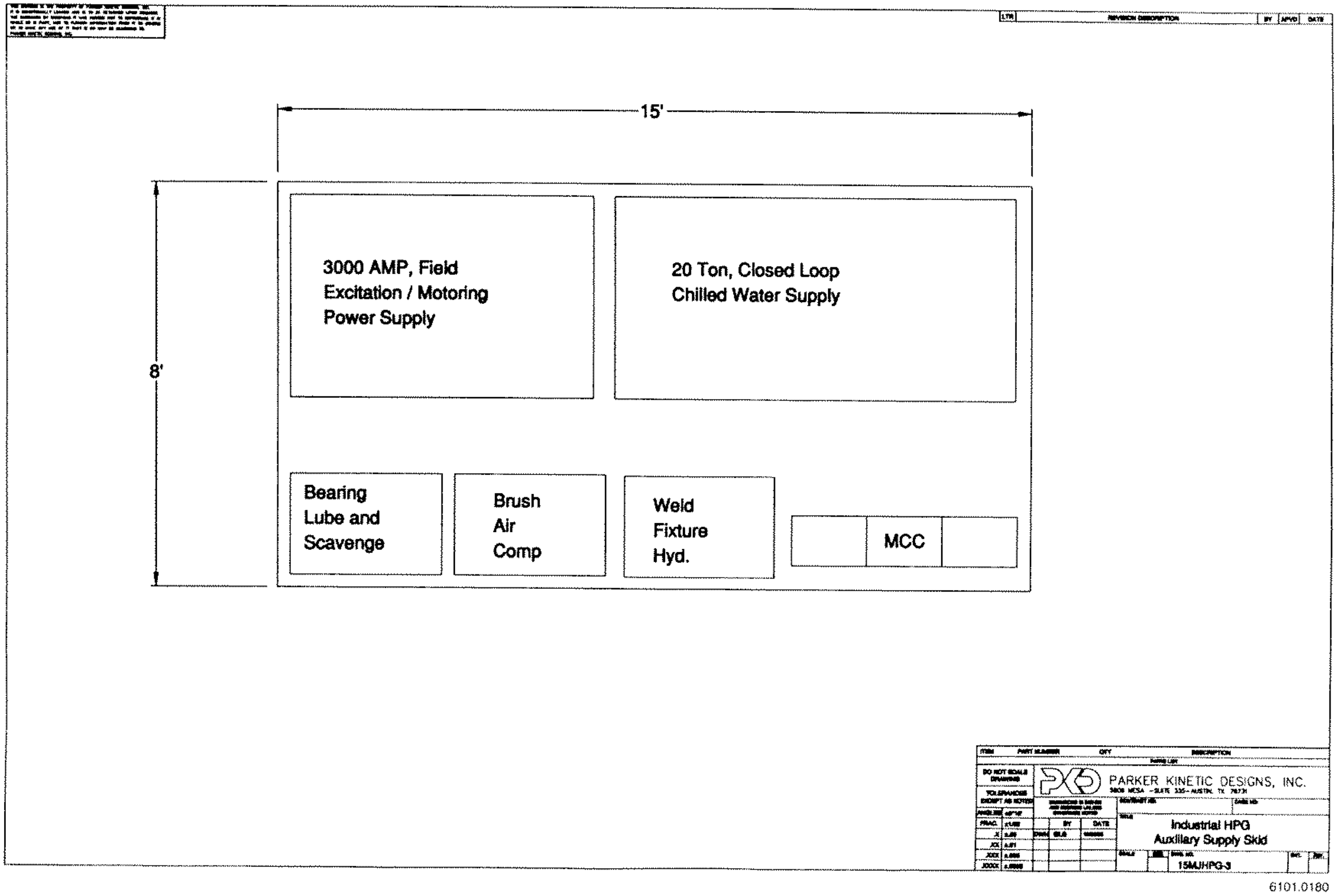

Figure D1. Conceptual arrangement of the homopolar pulsed power supply.

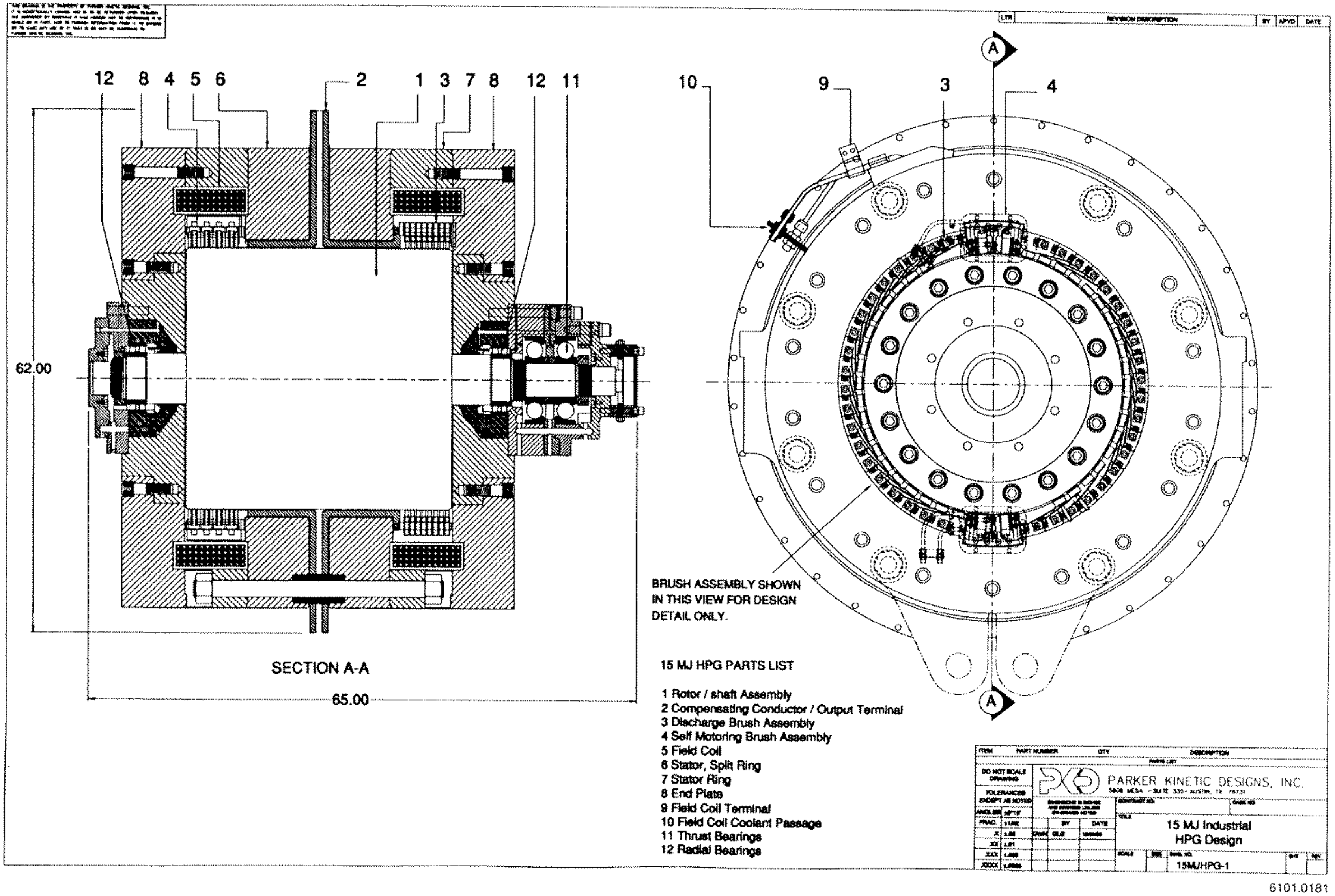

Figure D2. Drawing of 15 MJ homopolar generator

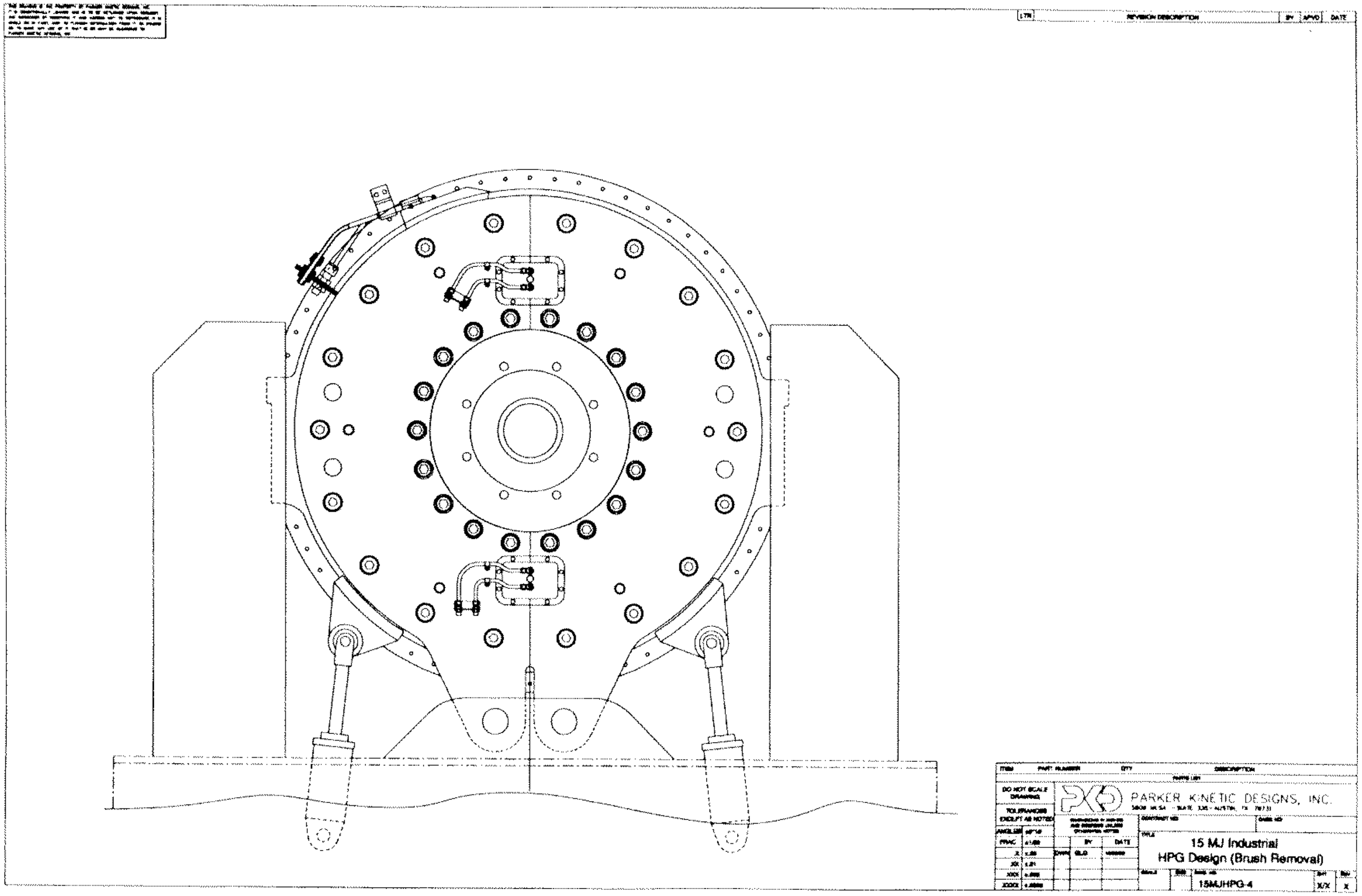

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Figure D3. End view drawing of housing (15 MJ homopolar generator) for brush removal

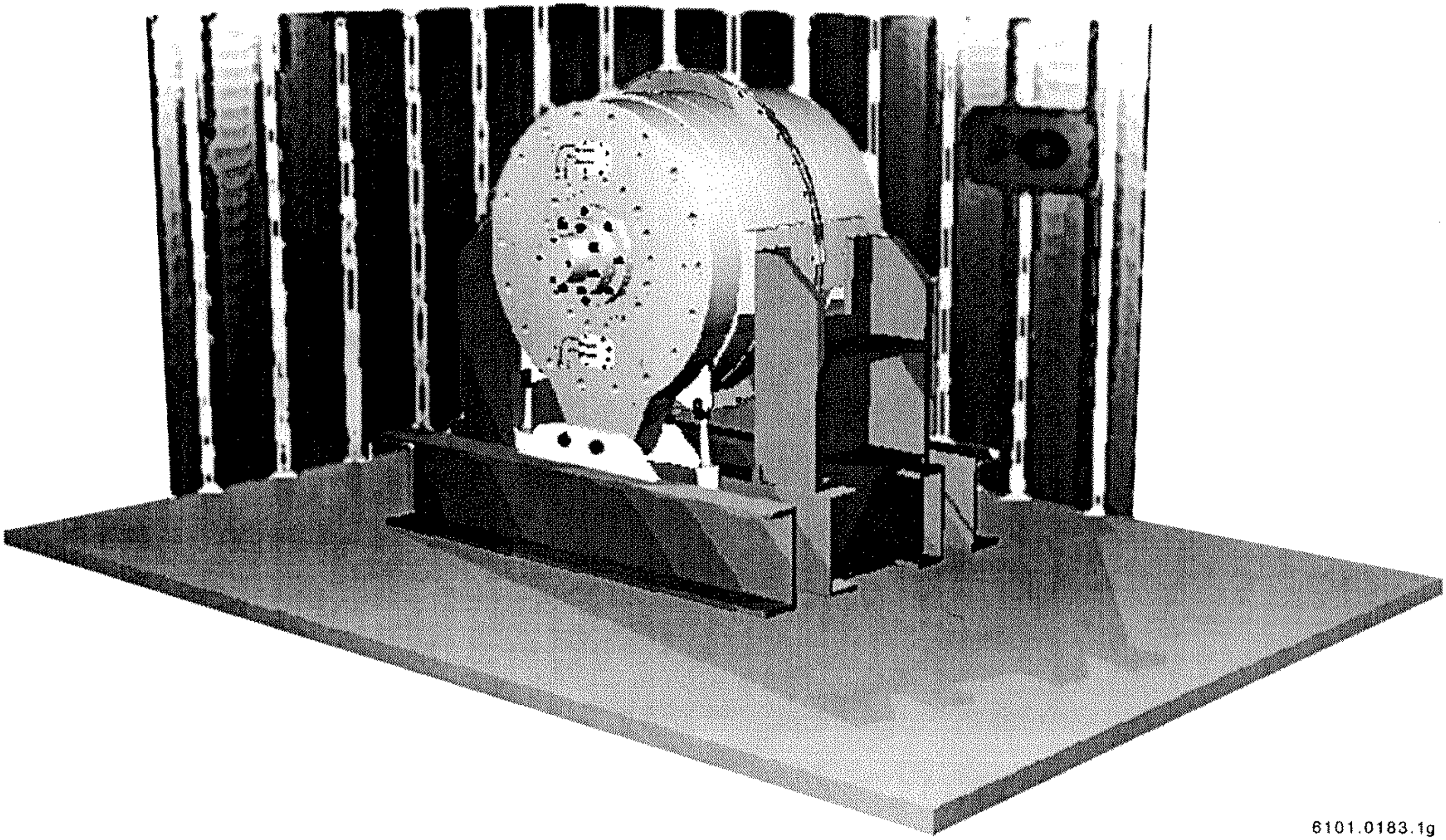

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Figure D4. 3-D rendering of 15 MJ homopolar generator

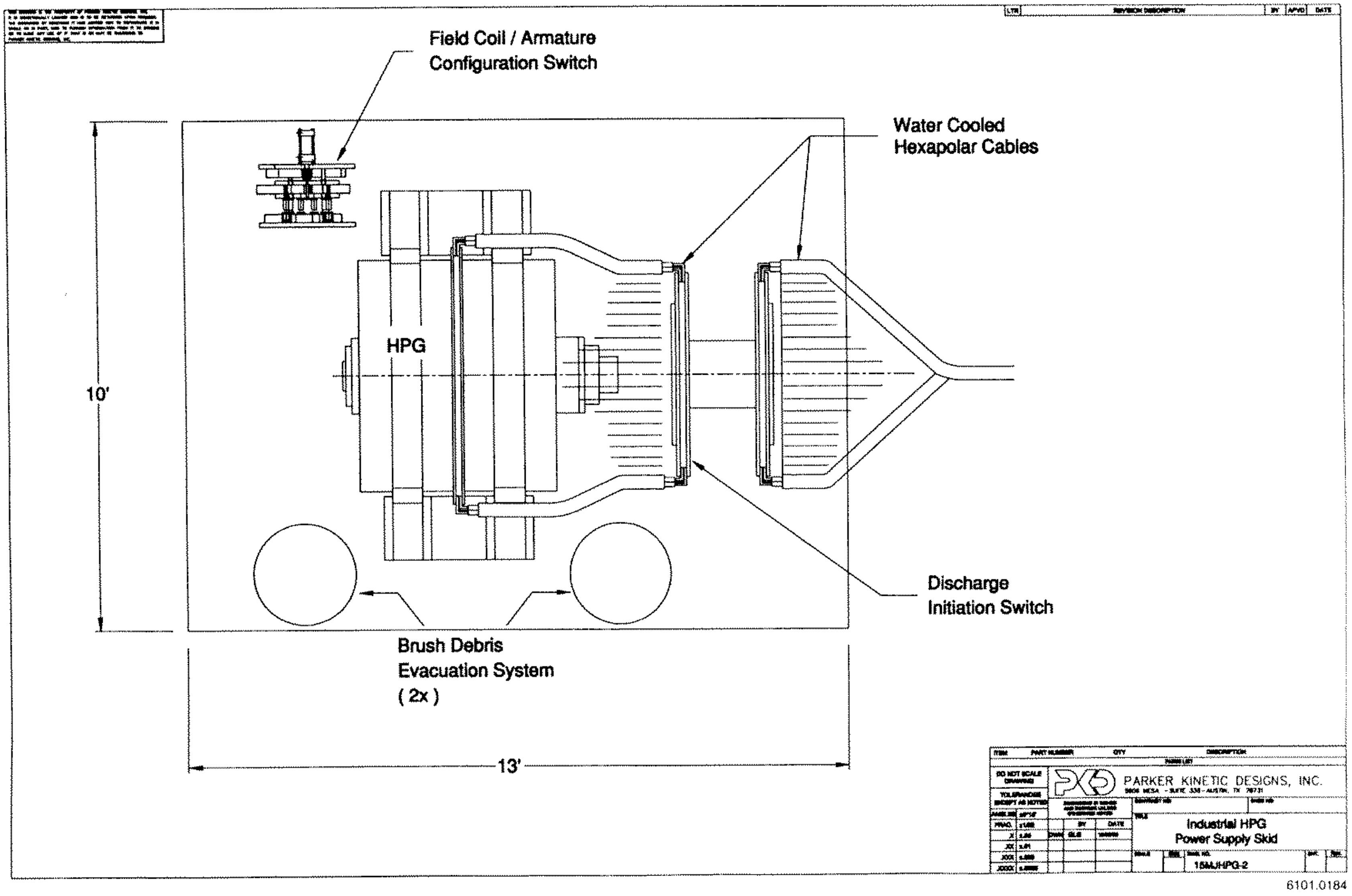

Figure D5. Drawing of coil/armature configuration switch and discharge initiation switch

Homopolar Welding Development and Economics

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Abstract

Homopolar welding (HPW) is a single–shot solid–state resistance forge welding process that is under development as a single–station pipe welding method. Weld quality issues have been addressed by a Joint Industry Program and the process economics favor commercial use. Fielding of a HPW system is dependent on process tooling design, the speed of the process, and the economics of the process. The HPW weld speed of three seconds makes weld advance times of 12 to 20 minutes possible and will result in a large reduction in overall pipeline construction costs. In addition, HPW is an inherently controllable process, so the weld power pulse will be tailorable to meet a variety of weld and material requirements

Homopolar welding process

Homopolar welding (HPW) is a single–shot solid–state resistance forge welding process that is under development as a single–station method to join API 5L carbon steel line pipe. A homopolar generator (HPG) is a high–current, low–impedance DC generator that was invented in the 1830's by Michael Faraday. The HPG's ability to generate million–ampere currents into near short–circuit loads makes it an attractive power source for resistance welding of large cross–sections.

HPW will bring several important advantages to pipeline construction. These advantages include a very short welding time, the ability to join difficult–to–weld materials, the ability to weld independent of pipe position, and the ability to exert in–process weld control. The increased welding speed will have a great impact on pipeline construction. The time required to make a homopolar weld is approximately three seconds and is independent of pipe size. As a result, the critical path in single–station construction will shift from welding to pipe handling. The solid–state nature of the HPW resistance forge process will allow solid–state welding to be applied to materials (such as corrosion resistant alloys, or high strength steels susceptible to overheating during welding) that are increasingly more difficult to weld with arc or fusion welding processes. Solid–state welding also means that the process will be independent of pipe position. In addition, the inherent controllability of an HPG will allow the conversion of highly variable processes, such as arc welding, into a highly controllable manufacturing processes. True process control is possible because both the HPG and the work piece performance are controllable, repeatable, and measurable.

Background of development

Michael Faraday invented the disk–type HPG in the 1830's when he proved the principle of electromagnetic induction (King, 1973). In 1934, Westinghouse Electric built an HPG to power a pipe seam welder at the Youngstown Sheet and Tube plant (Meyer, 1956). This welding line operated successfully until the Youngstown plant closed several decades later. Several other attempts were made to use HPGs as a continuous DC power supply for utility use, but the advent of inexpensive ac power from the utility grid slowed development for a time.

The University of Texas at Austin began developing HPGs in 1973 for pulsed duty in order to produce high magnetic fields. Several successful developments led to the construction of a 60 MJ, 9 MA HPG power supply at UT–Austin for use in electromagnetic launcher research. In addition, several programs began to investigate the use of pulsed–duty HPGs for the solid–state welding of various metals. As part of this development, in 1989 the National Science Foundation funded research into HPW as a single–station weld process for J–lay construction of deep water pipeline. This research evolved into a joint industry program sponsored by six oil and gas companies (Amoco, British Petroleum Exploration, Exxon Production Research, Mobil R&D, Shell Development, and Texaco) and two equipment manufacturers (CRC–Evans Automatic Welding Co. and Parker Kinetic Designs, Inc.). The JIP welding research is being conducted by the UT–Austin Center for Electromechanics.

State of development

The research has focused on demonstrating the quality of the homopolar welds in four pipeline materials and has been conducted using 3.5 in. pipe. Pipeline materials investigated for weldability with HPW include API 5L grades of (Haase, 1995):

Material A: X-52, seamless, hot rolled
Material B: X-60, ERW, controlled rolled
Material C: X-52, ERW, normalized
Material D: X-65, seamless, quenched and tempered

Numerous welds have been made in materials B & D and the technical requirements of the JIP have been met for these materials. Micrographs of welds made on materials B & D are shown in Figures 1 and 2, respectively. The micrographs were taken of the weld line at mid–wall and are 200x magnification. The welding investigations using materials A & C are not yet completed.

The JIP has built-in milestones with intermediate exit points if performance goals are not met. Weld criteria were set with input from all six sponsoring groups and were based on American and British standards. The JIP has met all of its goals so far and is proceeding on schedule.

The first goal to be achieved was to make welds with acceptable tensile strength. Once basic process parameters (current distribution, initial pressure, energy input, timing and upset distance) were optimized, making welds that exhibited acceptable tensile strength followed easily.

The second and more difficult problem was achieving acceptable Charpy V-notch toughness. Early welds showed circumferential impact toughness variations. A common result was several good Charpy readings along with one or more low readings. Eventually, researchers identified local brittle zones as the cause of the low toughness readings. Local brittle zone formation is a problem common to other resistance welding processes. However, the problem has been solved in higher-strength steel grades by tailoring the weld prep and the process parameters. Table 1 shows Charpy V-notch values from some of the most recent welds. However, another problem has been identified. Welds made in steels that get their strength from working during processing or from a forced thermal cycle, show a softened area about 5 mm on either side of the weld line. The current investigation will optimize the process to obtain acceptable toughness and hardness in these materials.

The third goal was to make a weld that had an acceptable as-welded finished profile. Welds whose original interface material is expelled past the exterior and interior surfaces exhibited the best toughness. As long as the amount of expelled material is minimized, then the amount of effort required to remove the expelled material will also be minimized. The weld profile shown in Figure 3 forms a slight bulge at the OD and at the ID. All of the undesirable material is in a fin which protrudes from the weld. This fin can be removed easily by a simple and fast process.

Several technical issues still remain before HPW is applied commercially. These issues include rapid non-destructive evaluation, robust fixturing, rapid alignment, upset removal or prevention, and scale-up to deep water pipeline sizes. Automatic ultrasonic testing will likely be used for rapid non-destructive evaluation of the homopolar welds in the field. However, since flaws are rarely seen in micrographs, only minimal work has been performed to characterize typical weld flaws. The next phase of the JIP will address flaw characterization and fast UT testing. Robust fixturing is important to HPW because accurate alignment of the pipe ends prior to welding is one of the most critical steps in the process. Performing this alignment quickly enough to meet the process time goal has not yet been demonstrated. Design of the process to remove upset material from the OD and the ID is underway. Upset removal is a standard process in the manufacture of seam-welded pipe. Scaling the welding process from 3.5 in. pipe to 12 in. pipe presents a new set of engineering issues. However, the JIP participants are well-experienced in the design of welding and offshore equipment. The engineering and design of the 12 in. fixture is already underway and the fixture test program will be designed to demonstrate all of the issues inherent to the performance of the scaled-up equipment.

Conceptual design of welding system

A HPW system will require a set of HPGs (enough to produce the required peak current plus a redundant generator), a welding fixture (to align the pipes, carry the current to the weld, and apply the forging force), tooling (to prepare the pipe faces for welding and to remove the material extruded during upset), and auxiliaries required to support the power supply and other welding equipment. A conceptual layout of how the equipment might be laid out on a ship is shown in Figure 4 with the HPW-related equipment and auxiliaries shown shaded. The welding fixture is shown oriented in the vertical direction for J-lay.

The preliminary design of the equipment is driven in a large part by the cycle time goals for HPW. The weld cycle time, shown in Figure 5, is based on an HPW weld time of three seconds. The UT scan time is based on a manufacturer's claim of one second per diameter-inch of pipe. Time for other tasks is based on the performance of the tooling and estimates for similar tasks in manual welding. The labor requirement to meet the cycle time is discussed in the next section.

Economic potential of HPW

The time required to complete a weld has a large effect on the pipeline lay rate. For a 12 3/4 pipeline welded manually, the welding time can represent up to 70% of the pipeline lay rate. Therefore, the speed that a weld can be accomplished will be one of the largest determinants of pipeline installation cost. Figure 6 shows the effect of weld cycle time on lay rate. The published lay rate for the Shell Auger J-lay and Enserch B388 S-lay deep water pipelines is shown for reference. McDermott constructed both pipelines. The Auger line was constructed using derrick barge DB50 and the Enserch line was constructed using derrick barge DB28 (LeBlanc, 1995). The calculation was made using the assumption that weld cycle time limits the lay rate without consideration for other limiting factors such as mooring advance rate. As cycle time decreases from 30 minutes to 20 minutes, the curve is nearly straight. As a result, the lay rate increases only marginally as cycle time decreases. Significant cost saving can be achieved when the pipeline lay rate is increased by a large factor. As weld cycle time decreases beyond 25 minutes per weld, the slope of the curve increases considerably. As a result, the goal for HPW was to be past this "knee" in the curve. When consideration is included for the time required for pipe positioning and alignment, ID and OD upset removal, welding time, automatic NDE, and coating, the minimum cycle time for HPW is 12 1/2 minutes.

Decreasing the weld cycle time from 30 minutes to 25 minutes represents an increase in lay rate of about 18% but saves only about 7% of the lay vessel cost. In contrast, decreasing the weld cycle time from 30 minutes to 12 1/2 minutes (a increase in lay rate of approximately 138%) represents a 30% potential savings of barge costs. If the vessel cost remains fixed, then the per-mile cost savings remains constant. The costs of a derrick barge and a drill ship were plotted against pipeline length for two different weld cycle times in Figure 7. The cost assumptions used for the derrick barge are that mobilization/demobilization costs $6,000,000. and rental costs $180,000. per day. The assumptions used in the drill ship calculation are a mobilization/demobilization cost of $1,500,000. and a rental cost of $120,000. The figure shows the total cost reduction increasing as pipeline length increases. However, the figure also shows that the large effect on cost savings for faster weld cycle times is strongly dependent on barge rental cost.

The continued development of HPW is dependent on its value to the market. The discussion above demonstrates the economic potential for HPW. However, the process can only be economic if the investment and operational costs of HPW can be shown to be competitive with conventional welding methods and other single station weld processes.

J–lay welding economic comparison

The J–lay welding economic comparison is based on deep water J–lay of 12.75 in. OD pipe laid from a derrick barge. The pipe joints were assumed to average 160 ft in length. The effective workday length used was two shifts of 11.5 hours each. Given the published J–lay vessel advance rate of 1.41 miles per day for Auger, the effective joint–to–joint cycle time was 29.7 minutes. The HPW joint–to–joint cycle goal of 12.5 minutes translates to a vessel advance rate of 3.35 miles per day. This advance rate is possible for a barge equipped with dynamic positioning systems.

The operational cost estimate of HPW was made based on its amortized equipment and financing costs, equipment maintenance costs, fuel cost to operate the machine, and the cost of the vessel charged to an operating company. HPW equipment and maintenance costs were amortized over 4,281 welds per year for five years. 4,281 welds of 160 ft. joints is equivalent to 130 miles of installed pipeline.

NDE costs were considered to be a wash for the comparison. Nearly all undersea pipelines are now subject to 100% inspection, and ultrasonic evaluation of welds is becoming more common. Therefore, for the purposes of the analysis, it was assumed that the NDE cost for both conventional welding and HPW would be similar. This assumption was used even though the equipment would be rented for a shorter period of time for HPW than for conventional welding.

The cost of consumable items was also ignored. HPW has no consumables because it is a solid–state welding process. Since conventional methods consume considerable material, this assumption will also tend to reduce the cost benefit of HPW slightly.

Labor costs were also treated as equal for the purposes of the comparison. HPW–specific tasks will require the employ of fewer personnel than manual welding and automatic welding. The labor comparison is shown in Table 2 (Davis, et al., 1995). While making the comparison this way will tend to inflate the cost of HPW somewhat, the daily labor cost for HPW, conventional welding, and automatic welding are negligible when compared to the daily cost of the lay vessel or the HPW equipment.

The maintenance cost estimate for HPW equipment is shown Table 3. Most of the maintenance is preventative. Costs and frequency are based on operating experience. However, that experience came in a laboratory and not from experience on a lay barge. In order to be conservative in the calculation of the maintenance cost, frequency and cost per occurrence were increased. The major maintenance item is replacement of the HPG brushes. The per–weld brush wear estimate is based on full–energy, full–current discharge of the HPG and complete replacement of the brushes after 90% wear. Using these conservative estimates, the shortest pipeline installed length between maintenance tasks is 150 miles. Preventative maintenance tasks and brush replacement will take approximately one week of generator down–time to complete.

Vessel costs were assumed to include contractor personnel to operate the barge, contract labor, barge operations, additional vessels (such as pipehaul vessels and diver support), and consumables. The vessel cost does not include the cost of NDE equipment.

The estimated installation cost and days required to complete construction for pipelines from one to sixty miles in length is shown in Figure 8. The estimate includes all of the costs described above for HPW. The cost of the pipe is not included in either estimate. The conventional welding cost includes only the cost of the derrick barge rental. The vessel cost is included only for days when welding is being performed and partial welding days are not allowed in the calculation. The cost advantage of HPW is due mainly to its shorter cycle time and the effect that time has on the number of days required to complete an installation. Therefore, the cost advantage of HPW will be sensitive to the lay vessel cost.

S–lay welding economic comparison

S–lay construction costs were compared in a study by Davis, et al (1995). The comparison was based on construction of a 40 mi. pipeline in water depths ranging from 1,500 to 3,000 fsw. The nominal pipe diameter was 8 in. with a 0.375 in. wall. The study compared HPW to automatic and manual welding on a modified drill ship, a third generation lay barge, and a converted derrick barge. The authors found that the pipe advance time was 20 minutes for HPW, 28 minutes for automatic welding, and 35 minutes for manual welding. Cost savings of HPW over the other two methods were based on time, labor, materials, and equipment. The conclusion of the study was that HPW would save 6 to 12 per cent of pipeline construction costs over the other two methods, depending on the vessel used.

Figures

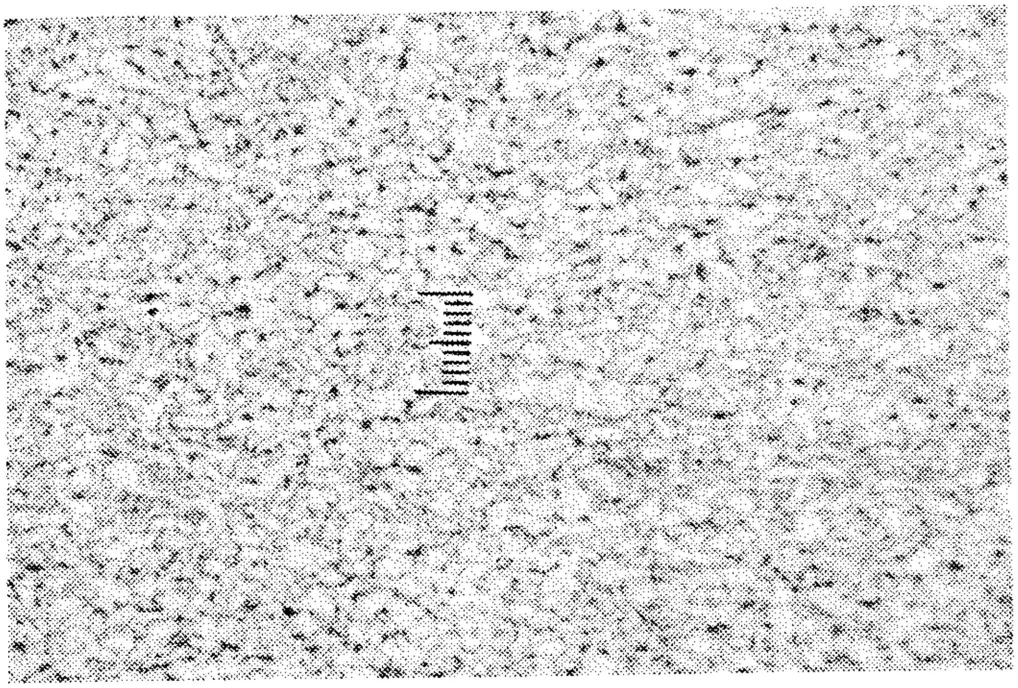

Figure 1. Micrograph of B18.2.

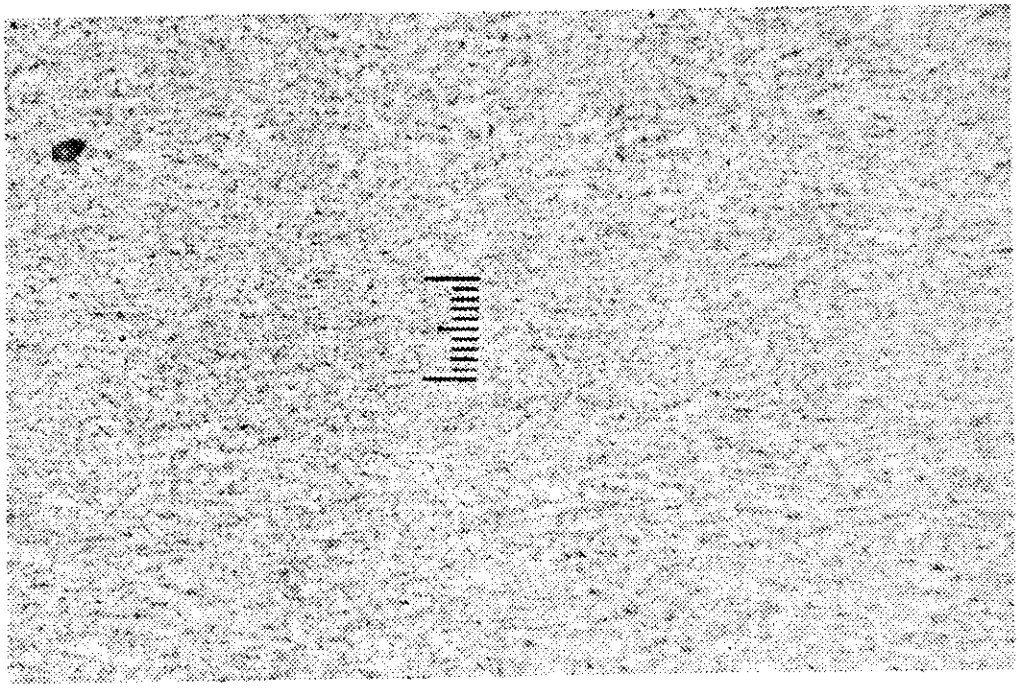

Figure 2. Micrograph of D3.2.

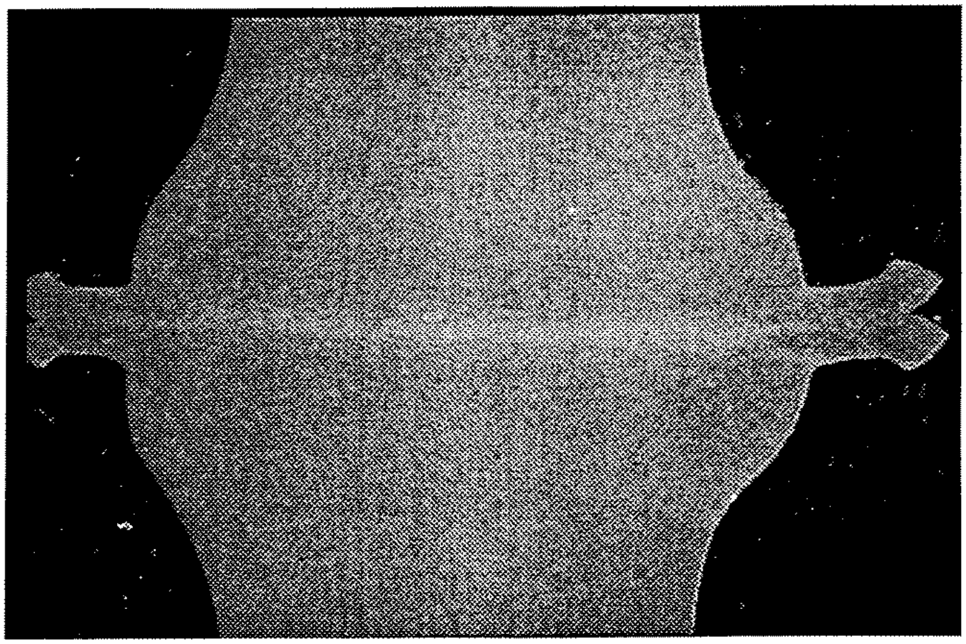

Figure 3. Macrograph of D7.2.

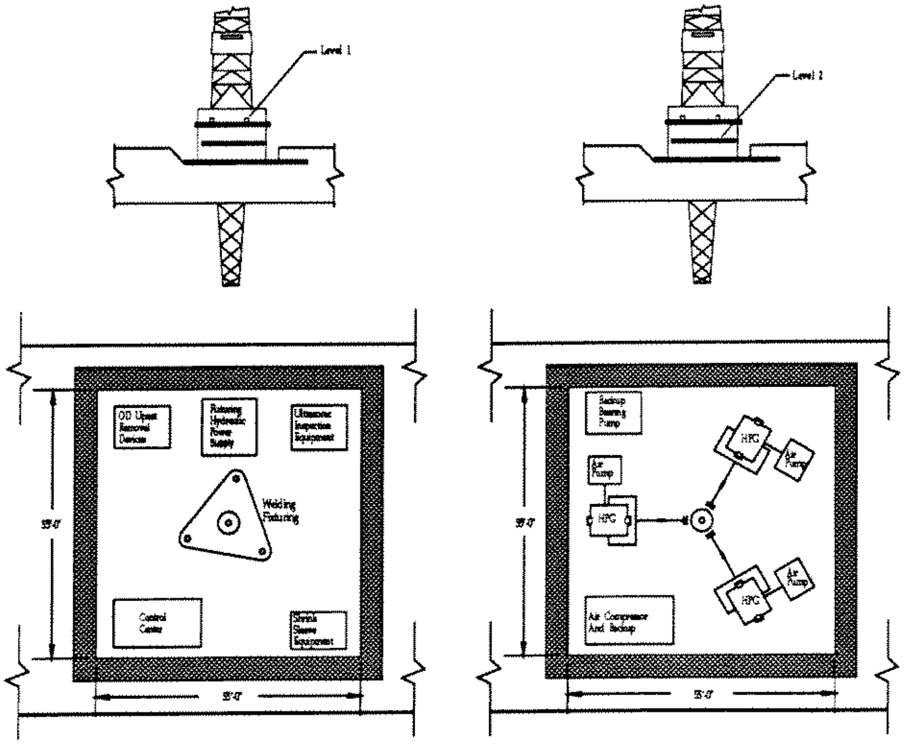

Figure 4. Welding system concept.

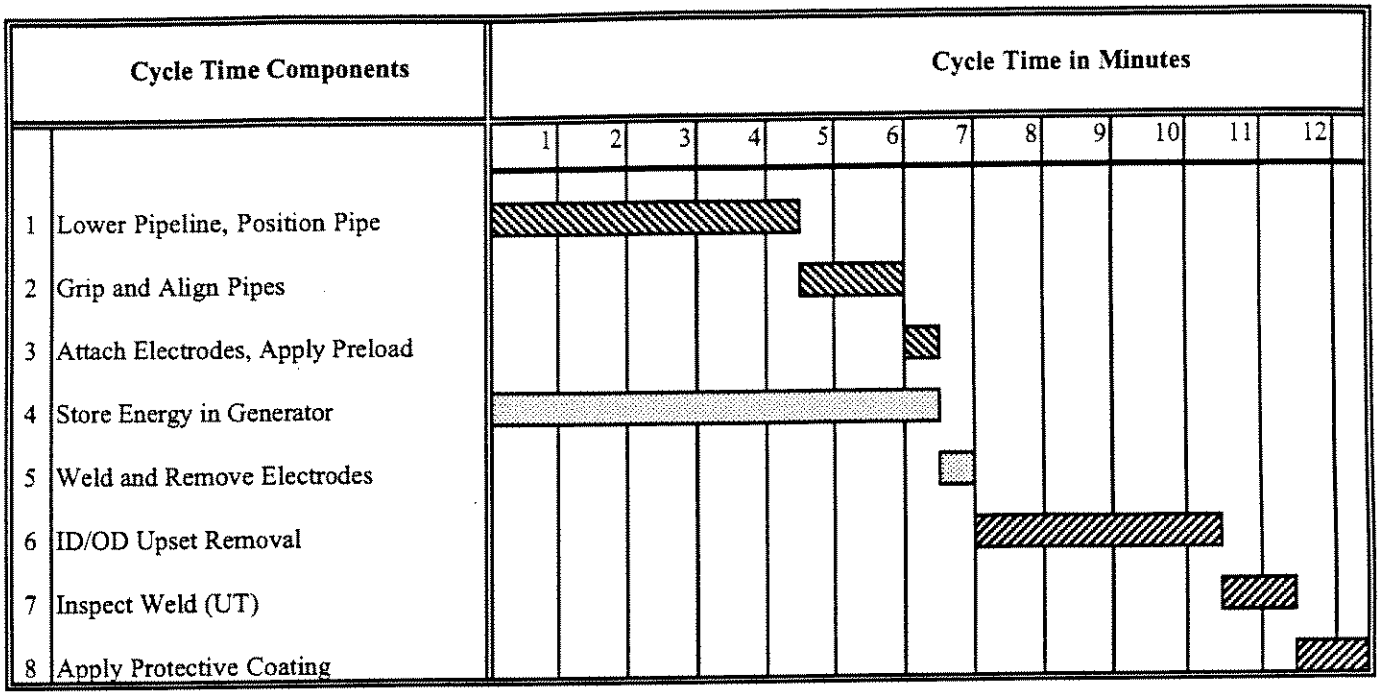

Figure 5. Process cycle time estimate.

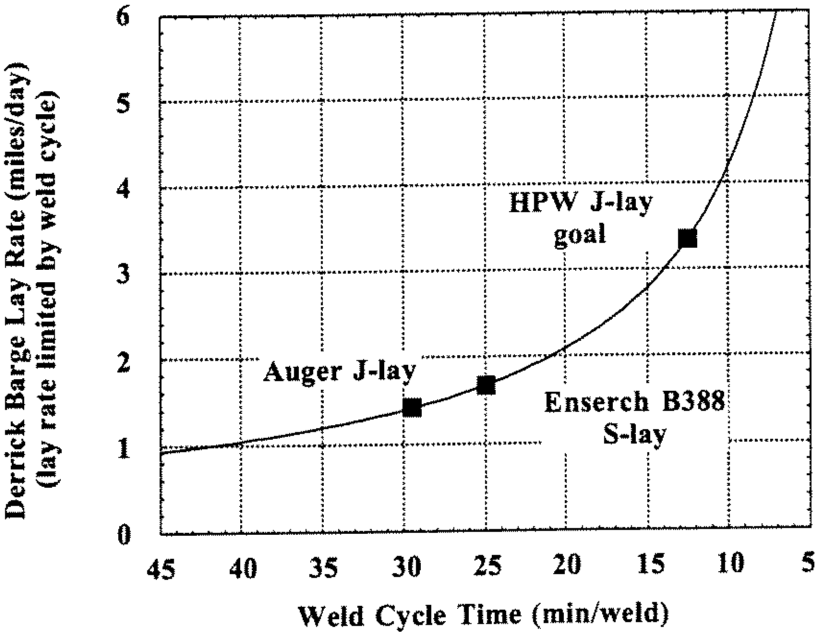

Figure 6. Lay rate is a function of cycle time.

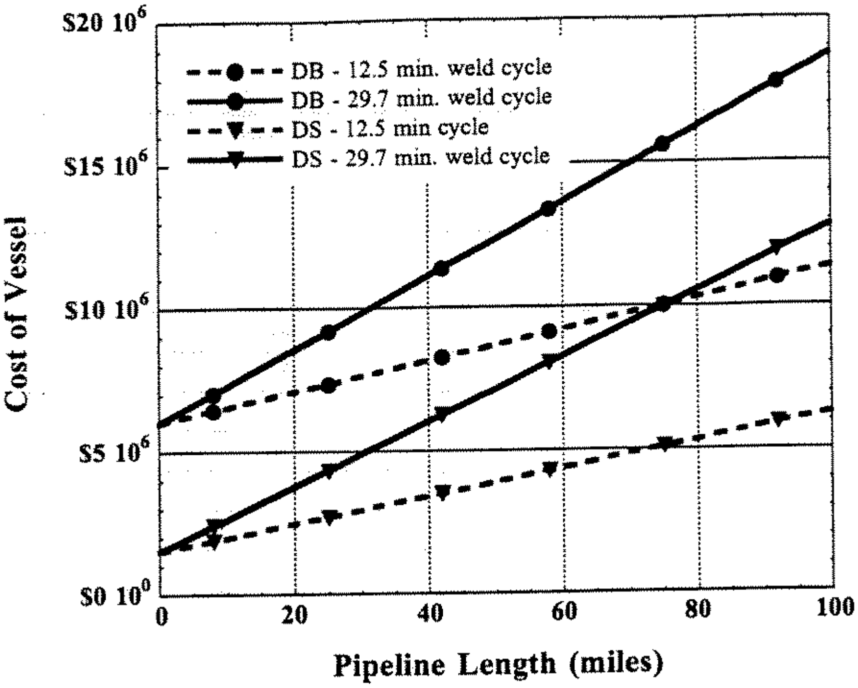

Figure 7. Vessel rental cost vs. cycle time.

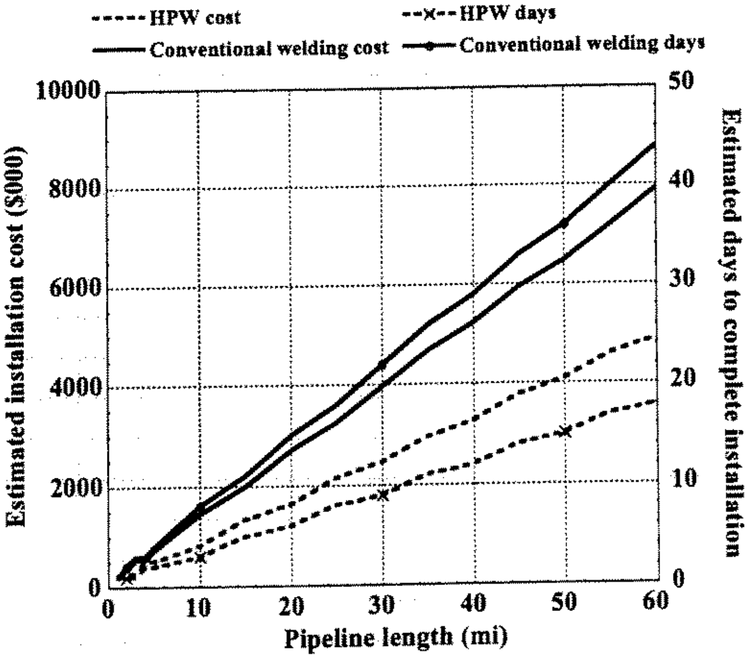

Figure 8. Comparison of installation costs.

Tables

Table 1. Impact toughness results confirmation series (half-size specimens).

Weld No	Mean CVN (ft-lbs)	Min. CVN (ft-lbs)	Max CVN (ft-lbs)
B18.1	75.4	68	86
B18.2	69.9	62	76
B18.3	66.0	53	78
B18.4	76.2	66	83
B18 Series	71.8	53	86
B Parent Metal	60.8		
D5.1	108.2	99	122
D5.2	106.2	70	124
D5.3	106.6	93	124
D5.4	85.9	72.5	102
D5.5	86.6	61	100
D5.6	103.6	94	116
D5 Series	99.5	61	124
D Parent Metal	123.6		

Test temperature 0°C, Mean value based on 5 specimens per weld.

Table 2. Labor requirements.

Labor Task	Number required per 23 hour workday		
	HPW	Manual	Automatic
Supervisor	1	0	1
Welding foreman	0	2	0
Welders	0	4	2
Technician	0	0	2
HPW operators	2	0	0
Welder's helpers	2	4	2
Facing machine operator	4	4	4
Rigging foreman	2	2	2
Riggers	4	4	4
Field joint hands	4	4	4
NDT services	2	2	2
Total	21	26	23

Table 3. HPW maintenance cost estimate

Maintenance Item	Occur. per year	Annual direct cost	Direct cost per weld
Replace HPG Brush sets	0.86	$26,334	$6.15
Calibration	1	1,710	0.40
Replace motor system oil & filters	1	1,560	0.36
Replace scavenge oil & filters	1	990	0.23
Flush cooling system	1	720	0.17
Replace HPG brush bladders	0.2	3,147	0.74
Replace fixture grips	1	2,190	0.51
Overhaul switch	1	7,880	1.84
Replace HPG bearings & seals	0.2	1,056	0.25
Replace aux. motors bearings	0.2	414	0.10
Replace aux. dynamic seals	0.2	414	0.10
Replace contacts on starters & contactors	0.2	714	0.17
Total maintenance		$47,129	$11.01

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