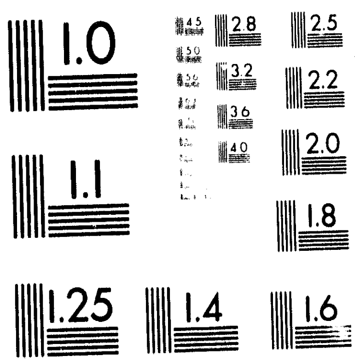
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TITLE: DIGITAL CONTROL AND DATA ACQUISITION FOR HIGH-VALUE GTA WELDING

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DIGITAL CONTROL AND DATA ACQUISITION FOR HIGH-VALUE GTA WELDING

T. G. George* and E. A. Franco-Ferreira**

ABSTRACT

Electric power for the Cassini space probe will be provided by radioisotope thermoelectric generators (RTGs) thermally driven by General-Purpose Heat Source (GPHS) modules. Each GPHS module contains four, 150-g, pellets of $^{238}PuO_2$, and each of the four pellets is encapsulated within a thin-wall iridium-alloy shell. GTA girth welding of these capsules is performed at Los Alamos National Laboratory (LANL) on an automated, digitally-controlled welding system. This paper discusses baseline design considerations for system automation and control, and strategies employed to maximize process yield, improve process consistency, and generate required quality assurance information.

Design of the automated girth welding system was driven by a number of factors which militated for precise parametric control and data acquisition. Foremost among these factors was the extraordinary value of the capsule components. In addition, DOE order 5700.6B, which took effect on 23 September 1986, required that all operations adhere to strict levels of process quality assurance.

A detailed technical specification for the GPHS welding system was developed on the basis of a joint LANL/Westinghouse Savannah River Company (WSRC) design effort. After a competitive bidding process, Jetline Engineering, Inc., of Irvine, California, was selected as the system manufacturer. During the period over which four identical welding systems were fabricated, very close liason was maintained between the LANL/WSRC technical representatives and the vendor. The level of rapport was outstanding, and the end result was the 1990 delivery of four systems that met or exceeded all specification requirements.

INTRODUCTION

On-board electric power for the spacecraft used in NASA's 1997 Cassini mission will be provided by three radioisotope thermoelectric generators (RTGs) thermally driven by General-Purpose Heat Source (GPHS) modules. Each GPHS module (Figure 1) contains four, 150-g, pellets of $^{238}PuO_2$, and each pellet is encapsulated within a shell of DOP-26 iridium alloy. The iridium-alloy shell is composed of two cups that are girth welded over the plutonia fuel pellet. The bottom cup incorporates a 0.13-mm thick weld shield (Figure 2), and is identified as the weld-shield cup. The upper cup (Figure 3), is identified as the vent cup, and contains a frit vent that allows the capsule to release helium generated by decay of the $^{238}PuO_2$. To permit decontamination of the welded capsule, the external opening of the frit vent is covered by a 0.13-mm thick cover of DOP-26 iridium foil; the vent is activated immediately before service by mechanical removal of this decontamination cover.

Fueled capsules for the NASA Galileo and ESA Ulysses space probes were girth welded at WSRC (formerly the Savannah River Plant) in the early 1980s using a computer-controlled gas-tungsten-arc (GTA) welding system which was designed and built in-house. However, in 1984,

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fueled clad production at WSRC was suspended. In 1987, in anticipation of resumed production to support the Cassini mission, WSRC conducted an in-depth assessment of the Galileo/Ulysses GPHS welding system. The results of this review indicated that:

- While the welding system had performed satisfactorily, the process yield would not be acceptable for subsequent heat source production, given expected changes in fuel cost and availability.
- The open-loop control scheme used by the welding system was inherently inaccurate.
- The computer used to control the welding operation was dated, and, in relation to newer machines was quite limited in terms of data acquisition and control capabilities.
- The lack of precision associated with the stepping motors used to operate the welding fixture was unacceptable.

As a result of this review, WSRC began work on a design concept for a new GTA welding system. During the 1987-1988 period, a preliminary design concept was developed, and experimental verification of some concept features was obtai: ~d.

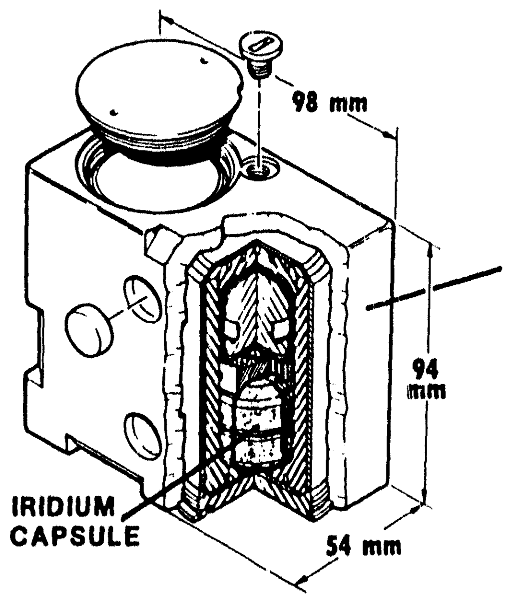

Figure 1. The GPHS Module.

In 1989, DOE transferred primary responsibility for the design and procurement of a new GPHS welding system from WSRC to Los Alamos National Laboratory (LANL), and directed that four identical welding systems, incorporating elements of the improved WSRC design concept, be procured. To support this procurement, WSRC and LANL jointly developed a detailed technical specification for the purchase of four, turn-key, welding systems.

DESIGN PROCESS

Design Considerations

The primary concern of the development team was the extreme value of each component of the

GPHS heat source that would be processed by the new welding system. Because of an ongoing restructuring of the DOE Weapons Complex, the costs associated with obtaining and processing the $^{238}PuO_2$ fuel, which historically had been available to heat source programs at no, or very low raw material cost, was expected to increase to levels in excess of $1750 per gram. In addition, because the responsibility for processing (and reprocessing) $^{238}PuO_2$ fuel had not been transferred from WSRC to LANL, and because thermal stresses associated with girth welding fracture the fuel pellet in a way that precludes its use in another capsule, each fuel pellet represented a unique asset (in the context of the Cassini program) that could only be replaced at the cost of significant schedule delays. Finally, the iridium cups welded over each fuel pellet had an approximate value of $30,000. Consequently, the cost of each GPHS heat source welded by the new system was expected to be approximately $300,000. Given that the process yield for girth welding during Galileo/Ulysses heat source production was approximately 73% (Ref. 1), it was apparent that the new welding system must deliver a significantly higher yield than its predecessor.

Another factor considered by the design team was how the new welding system could be configured to operate in a manner that would comply with applicable DOE orders and directives. Foremost among these was DOE order 5700.6B (Ref. 2), which took effect on 23 September 1986, and which required that all operations adhere to a much stricter level of process quality assurance than had previously been necessary. To comply with the relevant provisions of order

Figure 2. GPHS Weld-Shield Cup

Figure 3. GPHS Vent Cup

5700.6B, the new welding system would be required to operate in a manner that satisfied the following requirements:

- All process parameters must be closely controlled and verifiable.
- The welding system must be able to detect and correct unacceptable deviations in process parameters -- essentially a mandate for closed-loop computer control.
- The system must be configured to provide a verifiable record of performance.

In addition, the software used to operate the new system would be required to:

- Ensure that only authorized personnel, who have been appropriately trained and certified, may access and operate the system.
- Log or otherwise record the part number, date, and operator, for each girth weld performed.
- Log or otherwise record each program change, the change date, and the identity of the individual responsible for the change.

- Output or store performance records on a medium that can be maintained indefinitely, or, at a minimum, over the life of the program.

Development Of A Technical Specification

After considering the performance of both the Galileo/Ulysses GPHS welding system and changes in the operating environment of the heat source program, WSRC and LANL collaborated on the development of technical specifications for components of a new welding system. This specification was designed to correct the shortcomings of the previous welding system and to bring all aspects of the girth welding operation into compliance with DOE order 5700.6. Significant requirements of the specifications are discussed in the following sections.

The Welding Fixture

Because many of the welding problems experienced during Galileo/Ulysses heat source production could be traced to variability in the initial positioning of component parts and a lack of precise rotational control, the technical specification required that:

- The new fixture would provide a controlled load across the weld joint, by means of a gas cylinder, to keep the capsule closed during welding, and eliminate the need for tack welds.
- The upper and lower chucks would be synchronously driven to eliminate the possibility of relative slippage between the vent and weld-shield cups.
- The starting rotational position (absolute zero) of the upper and lower chucks would be established by means of a cam and a proximity sensor.
- The upper and lower chucks would be configured to accept a tooling ring into which each cup could be preloaded and precisely indexed.
- All functions performed by stepping motors in the Galileo/Ulysses welding fixture would be performed by more precise and accurate methods, such as a motor/encoder (for turntable rotation) and gas cylinders (for linear torch positioning and upper chuck closure).

Computer Controller

The specifications for the computer controller defined a unit that would correct the shortcomings of the previous system and that would be capable of using the precise position and rotational data provided by the new welding fixture.

To eliminate the inherent inaccuracies of the previous welding system, which utilized open-loop parametric controls, the technical specification required that the most important process parameters such as weld travel (or part rotation), current, and shielding-gas flow. Arc voltage, which was primarily a function of the preset arc gap, was to be monitored but not controlled. Because the welding operation was of such short duration (approximately 12.0 seconds), the control system was required to monitor, and if necessary correct, the values of significant weld parameters at least 10 times/second.

Another requirement was that the engine of the computer controller should be as generic as possible, preferably based on a 286 or 386 CPU. Similarly, the controller was required to utilize conventional disk formats for internal and removeable data storage.

Software

The specifications developed by the WSRC/LANL team required that the software used to operate the computer controller would be both menu driven and "user friendly." The software was also required to incorporate an access control scheme that would prevent operators from modifying the weld program, while at the same time allowing them to perform welds. For personnel with an appropriate access code the process of creating or modifying a welding program was to be as simple as possible, even for complex programs that included rapid parametric changes (upslopes/downslopes).

Data Acquisition

At a minimum, the new welding system was required to be capable of monitoring and recording the values of significant weld parameters 10 times/second. This compilation of parametric data, as well as time, date, and operator information, was required to be available for review by means of the computer monitor or a hard copy output. For archival purposes, the system would be configured to store the data file for each weld on a floppy disk.

DESCRIPTION OF THE NEW GPHS WELDING SYSTEM

By late 1989, a detailed technical specification for the new GPHS welding system was developed on the basis of the WSRC/LANL design effort. After a competitive bid process, Jetline Engineering Inc., of Irvine, California, was selected as the system manufacturer. Jetline's overall design approach was to use an appropriately modified standard computer control system in conjunction with a custom designed and built welding fixture. During the period over which four identical welding systems were built, very close liason was maintained between WSRC/LANL technical representatives and the vendor. The level of rapport was outstanding, and the end result was the 1990 delivery of four systems that met or exceeded all specification requirements. The major design features of these new welding systems are discussed in the following sections.

Welding Fixture Configuration

Like the original WSRC welding system, the new GPHS welding fixture (Figure 4) consists of a turntable with a horizontal plane of rotation, and a retractable top chuck. The welding torch is retractable, and slides in and out horizontally. All of the fixture components, with the exception of the torch, gas cylinders, and motor/encoder, were fabricated from 304 stainless steel. The unit has a weight of approximately 45 kg, and was designed to be separated into two modules (torch carriage/gas cylinder and turntable) that enable it to be passed through a glovebox airlock. More detailed descriptions of the individual fixture components are given below.

Rotational Drive

The original WSRC welding fixture utilized a stepping motor, and a timing belt with a 5:1 reduction, to rotate the turntable. The open-loop configuration of this drive system did not permit unambiguous angular positioning or accurate measurement of rotational speed. In contrast, the new unit's rotational drive consists of a precision DC motor geared to drive both the turntable and upper chuck by means of a 200:1 harmonic drive and 1:1 anti-backlash spur gears. A tachometer generator coupled to the shaft of the DC motor provides rotational speed information to the closed-loop computer control system. The angular position of the turntable is precisely determined in 0.0045-deg increments by means of an optical encoder coupled to the motor shaft.

An optical proximity sensor, in conjunction with a cam mounted to the jackshaft between the upper and lower spur gears, precisely defines a zero point.

Welding Torch

Previously, the welding torch was mounted on a horizontal slide driven in and out by a stepping motor. The welding torch was a commercially-available air-cooled unit, and was mounted in the center of a four-pole magnetic-arc-oscillator coil. The arc-oscillator was used to refine the weld microstructure, and thereby moderate the hot-cracking tendency of DOP-26 iridium (Ref. 3). Electrode changes were difficult and time consuming because the pole-pieces of the oscillator coil were in proximity to the gas-cup assembly on the front of the torch.

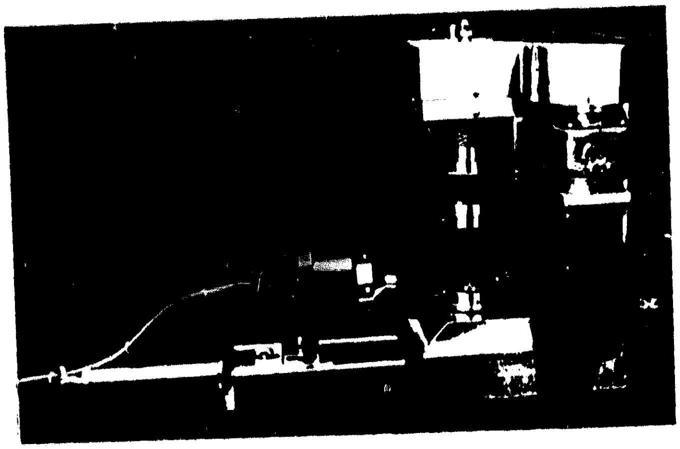

Figure 4. The New GPHS Welding Fixture.

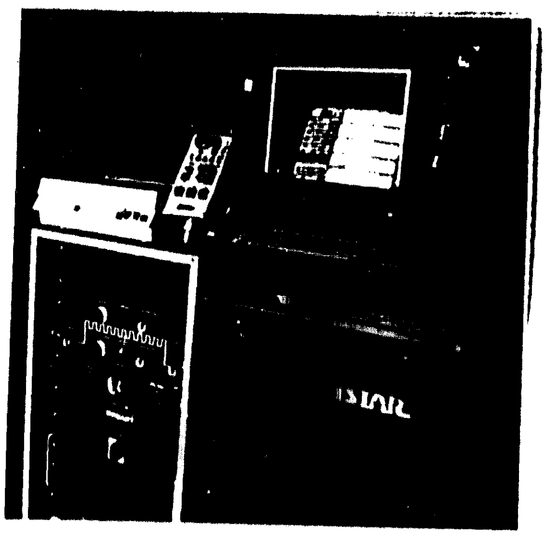

Figure 5. The New GPHS Welding System Uses a Hobart 150-amp power supply (left) and a JETSTAR computer controller (right).

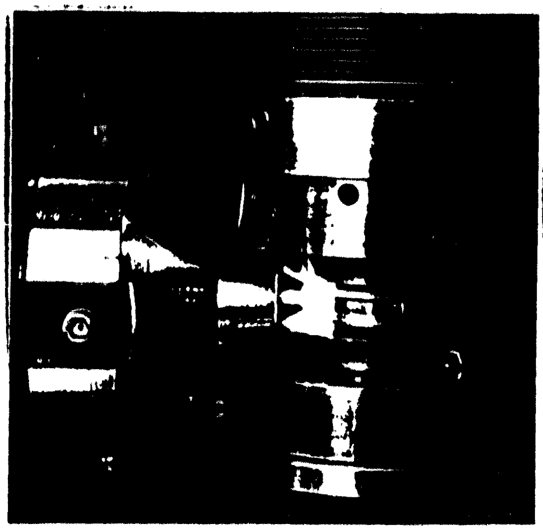

Figure 6. Girth Welding a GPHS capsule.

The welding torch on the new fixture was redesigned so that a separate gas-cup was not required; the torch body was made an integral part of the four-pole oscillator coil. The torch/coil assembly is attached to a carriage that is driven in and out between fixed stops by a single-acting, spring-return, He-powered pneumatic cylinder. Fine cross-seam and arc-gap adjustments of the electrode are made possible by manual cross-slides between the torch and carriage.

Welding Power Supply

The welding power supply selected for the new GPHS welding system was a 150 amp, commercially-available inverter unit (Figure 5). The power supply was designed to be computer operated in a closed-loop system, and has an output that can be controlled to within ±0.1 amp. The power supply was also configured with a high-voltage impulse-type arc starter.

Computer Controller

An integrated, PC-based (386) computer control system is used in conjunction with the welding fixture and power supply. The computer system, designated as a JETSTAR (Figure 5) by the vendor, continuously monitors and controls welding current, rotational speed, torch gas flow, and magnetic-arc-oscillator operation, and was designed to resist electrical interference caused by the arc starter and other external sources. The closed-loop control system allows the computer to monitor and correct each welding parameter 20 to 40 times/second. Although the computer also monitors arc voltage, the system was not configured to control this parameter.

Measurement and Control of Welding Parameters

The JETSTAR controller utilizes the Hall Effect to monitor the amount of current delivered to the arc by means of a teroid coil positioned around the return lead. The power supplied to each of the magnetic arc oscillator coils, for cross- and in-seam oscillation, is monitored in a similar manner. However, because the arc oscillator is not configured for closed-loop control, the JETSTAR only turns the oscillator on or off, and then determines if power is in fact delivered to the oscillator coils. Arc voltage is measured directly across the output terminals of the power supply.

Part rotation and position information are provided to the JETSTAR by means of the optical encoder and tachometer generator built into the welding fixture. The flow of shield gas to the welding torch is monitored and controlled by means of a mass-flow-controller calibrated to reflect the shield gas composition (75% He/25% Ar).

During the execution of a welding program, and depending on the number of tasks the computer is required to perform, the condition of each of the five welding parameters is monitored between 20 and 40 times each second. Each time that the computer determines a given parametric value it compares this quantity to the parametric value prescribed by the weld program. If the detected parametric value does not exactly match the prescribed value, the computer communicates with the appropriate external device (power supply, weld fixture drive, etc.) and attempts to increase or decrease its output. However, during each monitoring/control cycle, the computer is programmed to correct only a preset (by the system operator) percentage of the parametric deviation. Because numerous monitoring/control cycles occur each second, this scheme enables the system to essentially eliminate significant parametric deviations while at the same time avoiding the gross overcorrections sometimes observed with systems that employ deadband/response control.

System Software

The software is designed to control all functions relating to part set-up, welding, and inspection, and interacts with the operator in a "user friendly" manner. The software makes it impossible for the operator to progress in the prescribed operational sequence until all of the prior steps have been completed. In addition, the software is configured to provide 9 levels of access control, by means of a user-selected password and assigned access levels. This feature prevents unauthorized personnel from performing critical operations such as modifying a welding program or performing a weld, but also preserves access for personnel who may be required to perform oversight activities such as reviewing acquired data, verifying parametric settings, etcetera.

Another significant feature of the system software is that when a welding program is created, the time, date, and program author are recorded. Similarly, whenever an existing welding program is modified the time, date, and modification author are logged into the program file. All program creation and modification information is displayed whenever the data acquired during a girth weld is viewed (Appendix A).

To avoid issues of software configuration control, the source code for welding operations was not provided with the operating software. Although portions of the operating software are written in BASIC, C, and CLIPPER, it is impossible for the customer to make any changes in the way in which the system operates. This arrangement permits the software package to be qualified for use without the need for regular reevaluations. It should be noted, however, that current interpretations of DOE order 5700.6 require the user to have access to the software source code. This requirement was fulfilled by placing a copy of the system source code in escrow; the escrow agreement allows access to the source code in the event that the manufacturer should go out of business.

Data Acquisition

During girth welding, the JETSTAR controller records the instantaneous value of each welding parameter at the end of some predetermined (by the system operator) time interval. The minimum reporting interval permitted by the system is 0.1 s. After completing a weld, the computer uses the data acquired for each welding parameter, along with user-supplied information such as operator name, part number, date, and time, to produce a detailed report (Appendix A). The report is available as a hard-copy printout, or can be permanently stored on a standard floppy disc. Although the computer will overwrite report information stored in RAM each time that a weld is made, software provisions prevent all system operations until a report is successfully downloaded to a standard 1.44 MB floppy disk, in the form of two ASCII files. Approximately 2.2 KB of storage are required for the information from a single girth weld.

SYSTEM PERFORMANCE

One of the four new welding systems procured by LANL was set up in the Equipment Engineering Division at WSRC. Of the other three units, one was sent to to the Martin Marietta Energy Systems (MMES) Y-12 plant at Oak Ridge, Tennessee, and the remaining two were retained by LANL. The disposition of the four systems was based on the premise that WSRC would focus on adapting the original SRP welding process to the new equipment, and that subsequent weld development and production welding would be performed at LANL. The MMES unit was provided to permit rapid evaluation of the weldability of iridium cups fabricated at the Y-12 plant.

By 1 September 1993, the new welding systems had been used to perform a total of 52 welds over a variety of fuel simulants and 5 welds over plutonia fuel pellets. Although minor software modifications were necessary, the overall performance of these systems was outstanding, and exceeded expectations. No cracks or other anomalies were observed in any of the girth welds made using the new welding systems. A close-up view of a girth weld being made using one of the new systems is shown in Figure 6. The parameters developed for welding GPHS heat sources are listed in Table I.

Early in the weld development effort it became apparent that the welding system's maximum capacity for data acquisition, at intervals of 0.1 s, was excessive in terms of generating useful information. For acquisition intervals smaller than approximately 0.5 s, the difference between actual and target parametric values can appear to be significant (≈5%), particularly when the parameter in question is in the process of changing to a different target value (such as during an upslope, downslope, or rotation start). Of course, such relatively minor and short-lived parametric variations have a minimal effect on the resulting weld. Consequently, experience with the system and the GPHS welding program proved that a data acquisition rate of 1.0 s was sufficient to document the system performance without generating potentially misleading information.

Parameter	Setting/Value
Torque on Tooling-Ring Screw	15 inch-pounds
Capsule End-Load	30 pounds
Current	55.0 amp for 0.5 s; followed by 111.0 amp for 7.3 s; tapering to 22.0 amp over 3.0 s.
Voltage	arc-gap set at 0.035 in.
Part Rotation	stationary for 0.5 s; followed by 29.5 inch/min (8.0 rpm) for 10.3 s.

TABLE 1. Process Parameters for the New GPHS Weld System.

Another feature of the data acquisition that required minor modification was the format used to report acquired data. Because the standard JETSTAR report (Appendix A) contained a great deal of information that was extraneous in the context of GPHS heat source production, a LOTUS macro was written to tabulate the acquired data generated from each girth weld. The resulting report (Appendix B) presents the acquired data in a simplified format. Because the JETSTAR stores the data acquired from each weld in the form of two ASCII files, it was relatively easy to create a macro that would organize the data in a customized format.

SUMMARY

The new GPHS welding system incorporates a use-specific adaptation of a commercially available welding controller. It has been demonstrated that this welding system eliminates the problems encountered with a previous system by greatly increasing process control, while at the same time generating the QA and process documentation required by current DOE regulations.

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2. U.S. Department of Energy, 1986. Department of Energy Order 5700.6B. Washington, D.C.

3. Scarbrough, J.D. and Burgan, C.E. 1984. Reducing Hot-Short Cracking in Iridium GTA Welds Using Four-Pole Oscillation. Welding Journal 63 (6): 54-56.

APPENDIX A. STANDARD JETSTAR DATA REPORT

JETLINE ENGINEERING
JETSTAR GTAW
ACQUIRED DATA REPORT

SERIAL NUMBER: FC0004\JAQ
PRINT DATE: 3/22/93

MP PROGRAM NO.:	1	DATE RUN:	12/22/92
DATE CREATED:	10/11/91	RUN BY:	T. G. George
CREATED BY:	E. Franco Ferreira	DESCRIPTION:	GPHS Girth Weld
LAST MODIFIED:	11/25/92	MP PART NO.:	1
MODIFIED BY:	T. G. George	ORIGIN (Y):	6.0000
MTO SEQUENCE:	Y	RTH SEQUENCE:	Y

CURRENT PASS: 1

WP PROGRAM:	1	DESCRIPTION:	GPHS Girth Weld
DATE CREATED:	10/28/01	LAST MODIFIED:	12/11/91
CREATED BY:	R. Jones	MODIFIED BY:	T. G. George
BACK PREFLOW(s):	0.00	BACK POSTFLOW(s):	0.00
OTH. PREFLOW(s):	5.00	OTH. POSTFLOW(s):	10.00
PART DIAM.(RPM->IPM):	0.00 Inches	HIGH FREQ.:	0

AUTO SEQ.:	0	RETURN HOME:	1	AUTO SEQ.:	0
PULSE LOCK:	0	STATIC PULSE:	0	NL COMPENSATE:	5
MONITOR WELD:	0	ACQUIRE DATA:	1	PRIORITY:	3
1ST CHANNEL:	WELD CURRENT	2ND CHANNEL:	ARC VOLTAGE	3RD CHANNEL:	TORCH GAS
4TH CHANNEL:	MAG OSCILLATOR	5TH CHANNEL:	WELD TRAVEL	6TH CHANNEL:	DISABLED
PART NUMBER:	PICS	ARC TRANSFER:	N/A	FILLER MATL.:	N/A
BASE METAL:	DOP26 IRIDIUM	ELECTRODE:	THORIATED W	WELD PROCESS:	GTAW
WELD JOINT:	SQUARE BUTT	CURRENT:	DC	SHIELD GAS:	HELIUM

NOTES: N/A

JETLINE ENGINEERING
JETSTAR GTAW
ACQUIRED DATA REPORT
PASS:1 WP PROGRAM: 1

TIME	CHANNEL	PEAK SET	PEAK ACTUAL	BACKGROUND SET	BACKGROUND ACTUAL	ERROR (%)
1.0	1 WELD CURRENT	111.00	110.20	0.00	0.00	0.7
	2 ARC VOLTAGE	14.50	15.20	0.00	0.00	4.8
	3 TORCH GAS	40.00	39.71	0.00	0.00	0.7
	4 MAG OSCILLATOR	1.00	1.00	0.00	0.00	0.0
	5 WELD TRAVEL	8.00	7.89	0.00	0.00	1.4
2.0	1 WELD CURRENT	111.00	110.80	0.00	0.00	0.2
	2 ARC VOLTAGE	14.50	15.20	0.00	0.00	4.8
	3 TORCH GAS	40.00	40.81	0.00	0.00	2.0
	4 MAG OSCILLATOR	1.00	1.00	0.00	0.00	0.0
	5 WELD TRAVEL	8.00	7.93	0.00	0.00	0.8

APPENDIX B. GPHS WELD RECORD

GPHS WELD RECORD

DATE: 3/22/93

GPHS CAPSULE:	FC0004		
MP PROGRAM:	1	WP PROGRAM:	1
DATE CREATED:	10/11/91	DATE CREATED:	10/28/91
LAST MODIFIED:	11/25/92	LAST MODIFIED:	12/11/91
MODIFIED BY:	T. G. GEORGE	MODIFIED BY:	T. G. GEORGE
WELD DATE:	12/22/92	TIME:	10:19:37
OPERATOR:	T. G. GEORGE		

TIME	CHANNEL	PEAK SET	PEAK ACTUAL	ERROR (%)
1.0	1 WELD CURRENT	111.00	110.20	0.7
	2 ARC VOLTAGE	n/a	15.20	n/a
	3 TORCH GAS	40.00	39.71	0.7
	4 MAG OSCILLATOR	1.00	1.00	0.0
	5 WELD TRAVEL	8.00	7.89	1.4
2.0	1 WELD CURRENT	111.00	110.80	0.2
	2 ARC VOLTAGE	n/a	15.20	n/a
	3 TORCH GAS	40.00	40.81	2.0
	4 MAG OSCILLATOR	1.00	1.00	0.0
	5 WELD TRAVEL	8.00	7.93	0.8

DATE FILMED

1 / 21 / 94

END