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REMOTE AUTOMATIC PLASMA ARC-CLOSURE WELDING OF A DRY-STORAGE CANISTER FOR SPENT NUCLEAR FUEL AND HIGH-LEVEL RADIOACTIVE WASTE*

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ABSTRACT

A carbon steel storage canister has been designed for the dry encapsulation of spent nuclear fuel assemblies or of "logs" of vitrified high level radioactive waste. The canister design is in conformance with the requirements of the ASME Code, Section III, Division 1 for a Class 3 vessel. The canisters will be loaded and sealed as part of a completely remote process sequence to be performed in the hot bay of an experimental encapsulation facility at the Nevada Test Site. The final closure to be made is a full penetration butt weld between the canister body, a 12.75-in O.D. x 0.25-in wall pipe, and a mating semiellipsoidal closure lid. Due to a combination of design, application and facility constraints, the closure weld must be made in the 2G position (canister vertical).

A process selection study and process verification testing program culminated in the selection of plasma arc welding, using the autogenous keyhole technique, as the welding process to be developed for making the final closure weld. Specifications were prepared for

*Work sponsored by the U.S. Department of Energy under the following contracts:

- Experimental Demonstration Package Program, Contract No. CPFF-854 (with Rockwell Hanford Operations, Division of Rockwell International).
- Commercial Waste and Spent Fuel Packaging Program, Contract No. DE-AC08-81NV10171.

a completely automatic, programmable plasma arc welding system including an automatic welding head custom designed to interface with the canister closure configuration. A system conforming to these specifications was then procured on a competitive basis; delivery to Westinghouse AESD/Pittsburgh was in April, 1980. A program of experimental welding was then initiated in which a number of welding procedure details were investigated and, more significantly, the capabilities and shortcomings of the welding system were assessed and appropriate improvements made and/or defined.

In October, 1980 the system was shipped to the encapsulation facility at the Nevada Test Site, operated for USDOE by Westinghouse AESD/Nevada. Here the final phases of equipment system modifications and welding procedure development were conducted. These efforts resulted in the definition of a completely automatic welding procedure for performing the subject closure weld with the loaded canister and welding head located remotely in the encapsulation hot bay. The weld is performed using the keyhole technique, and is autogenous except for a small filler metal addition made at the point of final keyhole closure to permit meeting the maximum allowable undercut limit imposed by the controlling specification.

The welding system is described, and the final welding procedure is described and discussed in detail. Several aspects and results of the procedure development activity, which are of both specific and general interest, are highlighted; these include:

- The critical welding torch features which must be exactly controlled to permit reproducible energy input to, and gas stream interaction with, the weld puddle.

- A comparison of results using automatic arc voltage control with those obtained using a mechanically fixed initial arc gap.

- The optimization of a keyhole initiation procedure.

- A comparison of results using an autogenous keyhole closure procedure with those obtained using a filler metal addition.

- The sensitivity of the welding process and procedure to variations in joint configuration and dimensions and to variations in base metal chemistry.

Finally, the advantages and disadvantages of the plasma arc process for this application are summarized from the current viewpoint, and the applicability of this process to other similar applications is briefly indicated.

INTRODUCTION

In support of the Nuclear Waste Terminal Storage Program a carbon steel dry storage canister, compatible with currently licensed truck-mounted shipping casks, was designed for the packaging of spent light water reactor fuel assemblies to be emplaced in various envisioned geologic repository experiments and demonstrations. A later expansion of scope resulted in the design of an alternate (but externally identical) version for packaging of "logs" of vitrified high level radioactive waste.

The selection of a joining process to be used for making the final hermetic structural closure of the canister was an important aspect of this design effort. Early in the program, a process selection study was performed[1] which resulted in the identification of three viable process candidates. These were plasma arc welding (PAW), using the autogenous keyhole technique; pulsed-current gas metal arc welding (GMAW); and pulsed-current gas tungsten arc welding (GTAW) with filler wire addition. A verification testing task was then undertaken in which the feasibility of each of these candidates was experimentally assessed and demonstrated. Finally, a trade study and evaluation was performed which resulted in the selection and recommendation of PAW as the preferred approach.

The implementation of this recommendation included the procurement of a PAW equipment system, a demonstration of the ability to perform a fully automatic closure weld using this system, the development of a detailed closure welding procedure, and the installation and qualification of the system and procedure in the field facility where remote encapsulation operations will be performed. The details of the implementation sequence constitute the balance of this paper.

CANISTER DESIGN DESCRIPTION

The carbon steel storage canister design configuration is shown in its two alternative versions in Fig. 1. Each canister (less contents) is an assembly of six components: body, lower end cap, support ring, closure lid, assembly (backing) ring and lifting pintle. The body is a section of ASTM A106 (or A53) Grade B pipe, nominally 12.75-in O.D. x 0.25-in wall x 160-in long. The lower end cap is fabricated from a standard 2:1 ellipsoidal end cap made from 0.38-in thick ASTM A516 (or A515) Grade 70 plate. The support ring is 0.5-in thick ASTM A36 plate. A canister body subassembly is made from these three parts by tack welding the support ring to a tapered seat machined inside the lower end cap, and then joining the lower end cap to the body with a full penetration structural weld.

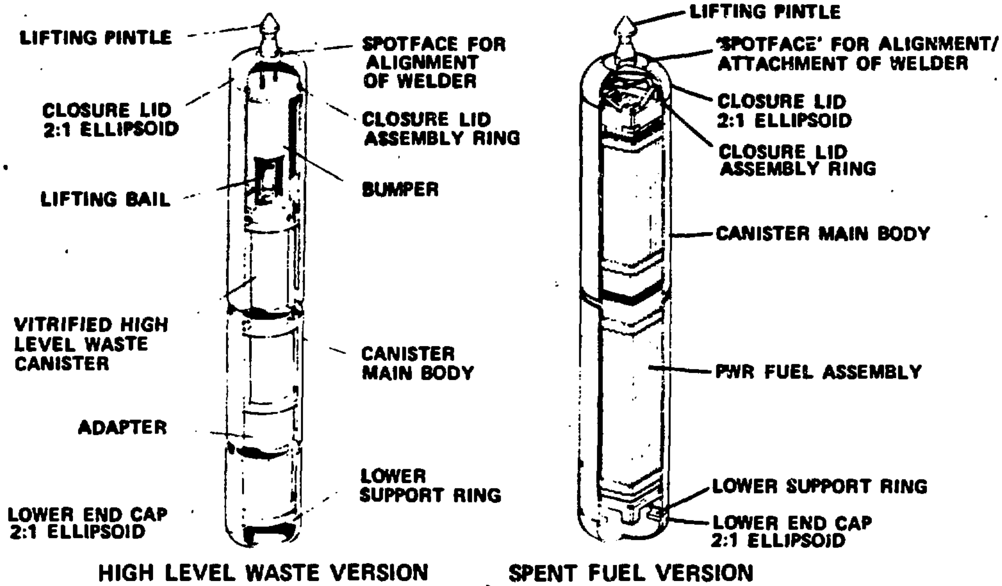

Fig. 1. Storage canister design configuration.

The closure lid is fabricated from an end cap identical to that used for the lower end cap. A hole bored in the center of the cap, and a surrounding flat machined surface, are used for aligning the ASTM A108 Grade 1018 lifting pintle which is then joined to the cap with a full penetration structural weld. The weld preparation on the bottom edge of the closure lid is machined parallel to the upper flat to permit use of the flat surface for mounting and aligning the automatic closure welding head. A closure lid subassembly is then completed by tack welding the assembly ring (made from any of a number of carbon steel grades) inside the lower edge of the lid.

Details of the closure lid/canister body weld joint configuration are shown in Fig. 2. Due to a combination of encapsulation facility constraints and concerns related to tilting and rotation of an unsealed canister containing a spent fuel assembly, the closure weld is made in the 2G position (canister vertical). The weld preparation is a 10-degree butt joint, angled upward from outside to inside through the canister wall. The close-fitting assembly ring spans the joint interface, and contains a deep circumferential groove located directly behind the interface. The ring serves three purposes: it facilitates assembly and alignment of the closure lid with the canister body, provides a shield to prevent weld splatter from impinging on the canister contents, and provides (via the groove) an escape plenum for the plasma gas column which penetrates the canister wall during welding. The plasma gas contained in the groove also provides an inert atmosphere purge which prevents burning of the weld root surface. This is somewhat superfluous in the current application, since the assembly will be backfilled with an

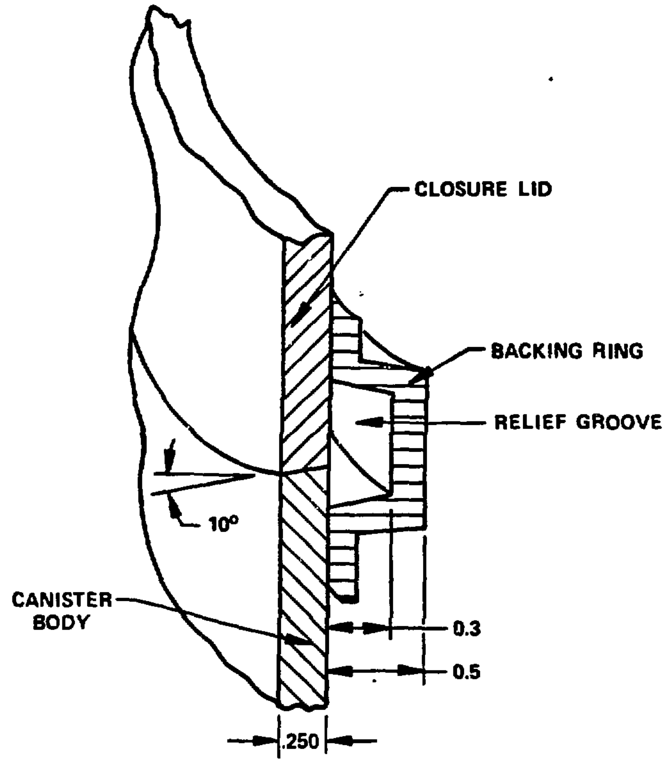

Fig. 2. Closure weld joint configuration.

inert gas mixture prior to welding, but could be very significant in other applications where the inert gas backfill would not be utilized.

CLOSURE WELD REQUIREMENTS

Two key factors influencing the selection of a canister closure welding process were the requirement for completely remote welding in the encapsulation facility hot bay, and the requirement that the canister design meet the intent of the ASME Boiler and Pressure Vessel Code, Section III, Division 1 for a Class 3 vessel. The first of these dictated that the process be highly reliable and amenable to fully automatic equipment system operation and welding process control.

Consideration of the second factor led to the stipulation that the design would exactly conform to Code requirements except in areas where those conflicted with the functional requirements placed on the canister for acceptable performance in its intended application. This affected the closure weld in the areas described below.

Weld Joint Design

The selected joint configuration is consistent with those allowed by Section III, Article ND 3352.

Weld Procedure Qualification

The final detailed welding procedure, with the equipment system installed in the remote encapsulation facility, will be qualified in accordance with the requirements of Section IX as specified in Section III, Article ND 4300.

Weld Inspection

Inspection is relevant both to qualification and to the acceptance of production welds. Techniques applicable to the completed weld joint fall into four categories, as summarized below:

Visual Examination - The requirements for a Class 3 vessel are stated in Section III, Articles ND 4424 and ND 4426.1. With reference to Fig. 3, these are basically as follows:

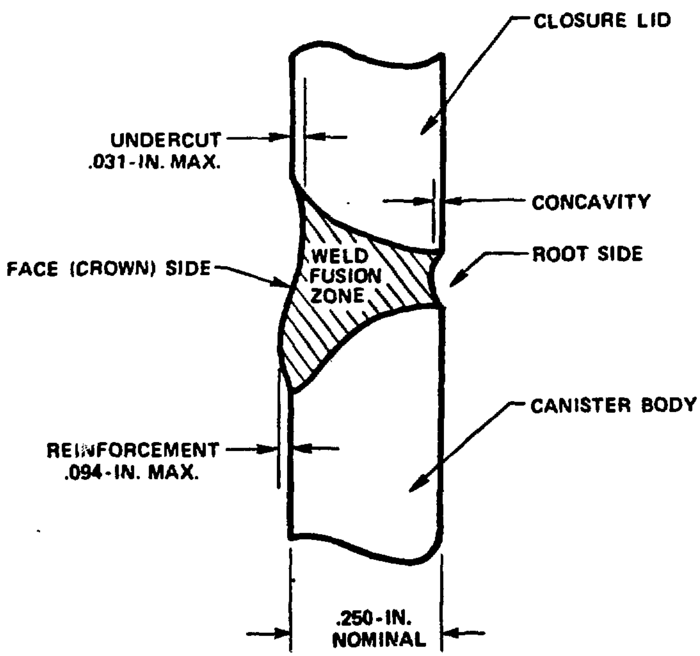

Fig. 3. Definition of closure weld features.

- Weld bead surfaces must be free from coarse ripples, grooves, overlaps, porosity and abrupt ridges or valleys.

- Undercut shall not exceed 1/32 in and shall not encroach on the required section thickness.

- Reinforcement shall not exceed 3/32 in.

- Concavity on the root side is permitted when the resulting thickness of the weld is at least equal to the thickness of the thinner member.

Nondestructive Surface Examination - The applicable techniques are liquid penetrant and magnetic particle testing. These "hands-on" procedures are not feasible for inspection of production welds, since the radiation levels preclude personnel access to the unshielded canister following closure welding. For procedure qualification, it was judged that neither technique would provide significant information beyond that obtained in the other examinations and tests to be utilized. Thus nondestructive surface examination was not performed on this program.

Nondestructive Volumetric Examination - The applicable techniques in this category are radiography and ultrasonic testing. Although not required for weld procedure qualification, welds were radiographed in accordance with Code procedures to provide additional verification of weld joint integrity. In production welding, radiography is not feasible due to the presence of a diffuse, high-intensity radiation source inside the canister. Elimination of radiographic inspection is acceptable provided that the weld procedure is qualified and that a reduced weld efficiency (45 percent in this case, per Section III, Article ND 3352.1(c)) is used in design calculations. Ultrasonic testing is conceptually feasible for volumetric examination, but is not a Code requirement. Since standard ultrasonic testing equipment is not available for the configuration and encapsulation conditions of this canister, ultrasonic examination was not included in the inspection requirements.

Destructive Examination and Testing - The applicable requirements, as stated in Section IX, Article QW451 consist of tensile tests, bend tests and certain documentation actions.

The tensile test specimen definition for pipe welds is provided in Section IX, Article QW452.1(b), together with the requirements placed on the tensile testing procedure. The acceptance criterion is that measured tensile strength of the welded specimen must be greater than the minimum allowable tensile strength of the weaker base metal (in this case, the canister body).

Section IX, Article QW466 provides the necessary bend test specimen definitions, a listing of which tests must be performed and the requirements for the bend testing procedure. The acceptance criteria for all bend tests is that all "open defects" must be less than 1/8-in deep after bending, except for cracks initiated at the edge of the specimen which did not initiate at slag inclusions or internal weld defects. (No limit is placed on the size of edge cracks which initiate in sound weld metal.)

No elongation measurements, hardness testing or metallographic examination is required by the Code for weld procedure qualification. However, these were performed on qualification weld specimens to develop a more complete characterization of the structure and properties of the canister closure weld.

PLASMA ARC WELDING SYSTEM

System Procurement

Following the preparation of an appropriate equipment specification[2], based on the canister design and on the physical and environmental constraints of the application and the encapsulation facility, a competitive procurement cycle was initiated. This culminated in the placement of an order with Hobart Brothers, Inc. of Troy, OH. The Hobart system included automatic welding heads designed and fabricated on a subcontract basis by The General Atomic Company of San Diego, CA. The system was delivered to Westinghouse AESD/Pittsburgh, PA in April, 1980, where acceptance testing was successfully performed to complete the procurement activity.

As-Delivered System Description

The principal components of the welding power supply/ control system are shown in Fig. 4. The features and functions of these components are briefly described as follows:

Hobart Cyber-Tig CT-300 DC Power Supply - Rated for 300 amps/20 volts at 100 percent duty cycle, with 80 volts maximum at open circuit. Dual welding current ranges (3-30 or 3-300 amps). Module also contains programmer and meters for welding current and power supply output voltage.

Hobart 800 Series Programmer - Provides basic capability for programmed automatic control of the closure weld cycle, including current upslope during weld initiation, current taper during main weld cycle, and current downslope during weld termination. Also controls prepurge and high-frequency arc starting. Provides appropriate interfaces for cycle features controlled by other system components.

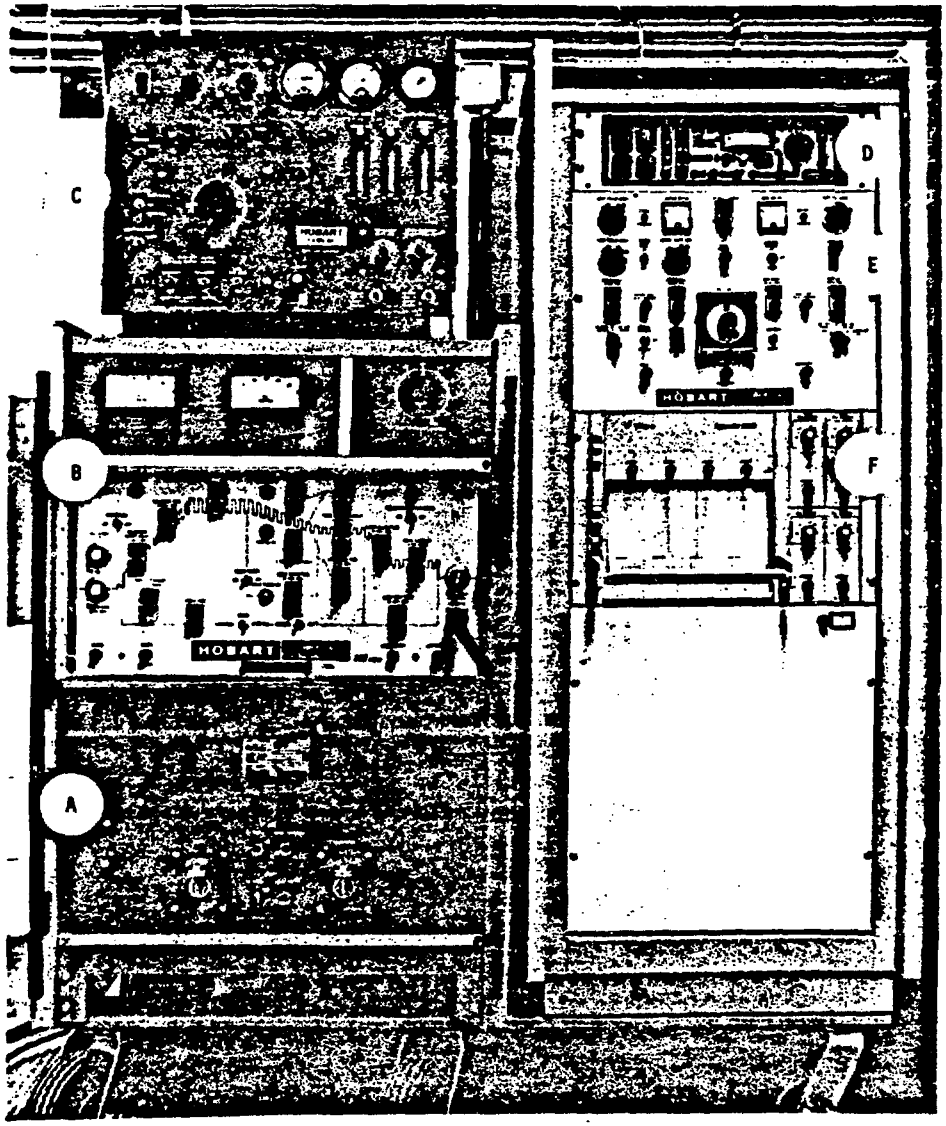

Fig. 4. Welding power supply/control system. (A) Power supply, (B) Programmer/meter panel, (C) Plasma control unit, (D) Arc voltage control unit, (E) Motor speed controller, (F) Four-channel recorder.

Hobart HPW-400 Plasma Control Unit - Regulates and meters the plasma and shielding gas flows to the welding torch; controls and displays pilot arc current and voltage; and controls the downslope of plasma gas flow rate during weld termination.

Cyclomatic Model 266 Arc Voltage Control (AVC) Unit - For PAW closure welding, this unit establishes and maintains the arc voltage in the transferred arc welding mode by continuously adjusting, through a feedback control system, the electrode-to-work separation necessary to maintain the arc voltage at the preset value. Two control ranges, 5-30 and 5-50 volts, are provided. A voltmeter continuously displays the average arc voltage as measured at the sensing leads on the welding head. A manual in/out torch-positioning setup control is also provided.

Hobart Cyber-Tig Motor Speed Controller - Controls the drive motors mounted on the automatic welding head which provide head rotation, filler wire feed and vertical torch travel. Contains set point potentiometers for the drive motors, master weld cycle timer for programming the duration of the complete weld cycle, programming controls for initiation and termination of filler wire feed, and override switches to permit manual operation of all three motors.

Gould 2400 Series Four-Channel Strip Chart Recorder - Records weld head rotation drive motor voltage, weld current, arc voltage and filler wire feed drive motor voltage.

Two additional system components are shown in Fig. 5. These are:

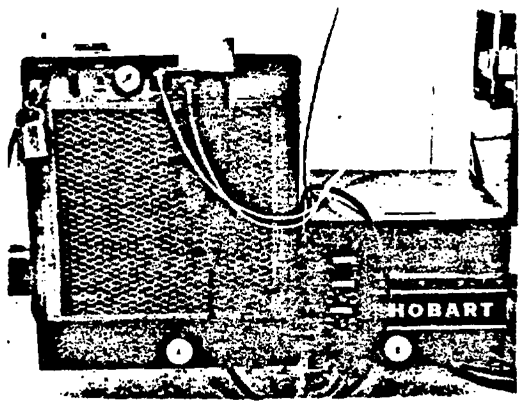

Fig. 5. Welding system components requiring location in hot bay. (A) Recirculating torch coolant system, (B) High-frequency arc start booster.

Thermal Dynamics Model HP 100 Water Circulator - Provides the necessary cooling water to the PAW torch. A recirculating system, installed in the hot bay near the welding station, is required due to restrictions (arising from nuclear criticality concerns) on flows of water through the hot bay shielding boundaries.

Hobart Model 1611 Remote Arc Starter - This booster unit for the high-frequency pilot arc ignition process, interposed between the power supply/control system and the PAW torch, is needed because of the long (~ 65 ft) electrical cables required for remote hot bay installation of the automatic welding head.

The General Atomic automatic welding head, mounted on a canister closure mockup assembly, is shown in Fig. 6. The functional components of this head are described as follows:

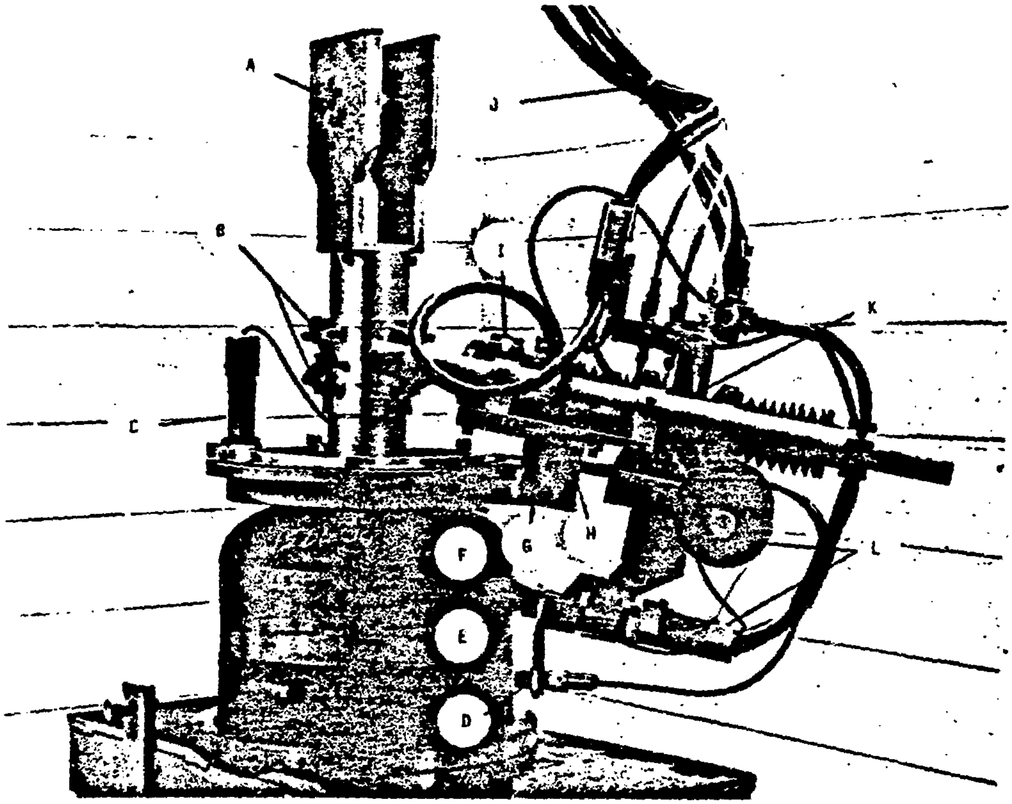

Fig. 6. Automatic welding head. (A) Lifting bail, (B) Attachment hardware, (C) Rotation drive motor, (D) Eddy current proximity sensor, (E) PAW torch, (F) Trailer shield, (G) Torch tilt angle adjustment, (H) Torch lead/lag angle adjustment, (I) Manual torch in/out controls, (J) Cables and hoses supported by overhead boom, (K) AVC drive unit, (L) Filler wire feed system.

Hobart Model HPW-400 Plasma Arc Welding Torch - Performs the canister closure weld. Mounted on brackets which permit adjustment of torch vertical tilt and horizontal lead/lag angles.

Cyclomatic Model 266 Arc Voltage Control Drive Unit - Drives the plasma torch toward or away from the weld joint as required to maintain the arc voltage at the preset value, and provides controls to manually adjust the torch/workpiece gap during setup.

Head Rotation Drive Motor - Drives the torch carousel through interaction with a stationary ring gear, thus rotating the plasma torch along the weld joint interface.

Vertical Torch Travel Motor - Drives the torch in the vertical direction (for setup or emergency adjustments) through a rack-and-pinion arrangement.

Filler Wire Feed System - Delivers weld filler wire to the weld puddle when/if required.

Eddy Current Proximity Sensor - Provides capability for establishing torch/workpiece separation gap at the preset dimension prior to initiation of transferred arc welding mode.

Attachment Mechanism - Three-clamp system for attaching the welding head to the closure lid such that the orbit of torch rotation is concentric with the lifting pintle axis and the plane of the orbit is parallel to the plane of the edge of the closure weld preparation.

Lifting Bail - Provides a means for lifting the welding head for installation on and removal from the closure lid, either manually or using remote manipulator-actuated equipment.

System Modifications

During the course of welding system installation, checkout, calibration and procedure development activities, certain highly desirable or mandatory modifications were identified and implemented. While many of these were considered normal for the process of making a complex custom-designed system operational, a few were of fundamental significance in the context of achieving acceptable system functioning and performance for the intended application. These latter items are briefly described in the following paragraphs.

The as-delivered system contained a master weld cycle timer for programming the duration of the complete weld cycle. During the early procedure development experiments, it was determined that the accuracy and repeatability of this timer were unacceptable for providing the necessary control over the points at which various weld termination sequences could be initiated. Analysis and vendor discussions led to the conclusion that no substitute timer having adequate range could be identified to provide the necessary capability.

Accordingly, an alternate control scheme based on azimuthal position sensing was conceived and implemented. Through incorporation of a microswitch and tripping pin on (respectively) the rotating and fixed elements of the welding head, plus restricted-duration precision timers with appropriate control system interconnections, the following cycle control sequence was established:

- Establish an exact azimuthal starting point reference by initial tripping of the microswitch prior to weld initiation.
- Sense exactly 360 degrees of weld travel by again tripping the microswitch as head rotation proceeds during welding.
- Initiate and control the weld termination sequence using restricted-range precision timers actuated by a signal from the above event.

A second area in which significant modifications were required was the control of weld travel speed as determined by welding head rotation rate. Despite a number of attempts to improve the accuracy and repeatability of the as-delivered open-loop motor speed control subsystem, in-cycle speed variations of up to 8 percent from the mean, and cycle-to-cycle variations of similar magnitude at a fixed speed control setting, continued to be experienced. Variations of this magnitude, with their attendant effect on weld heat input and bead shape, were judged to be intolerable for this application. The situation was resolved by replacing the entire as-delivered subsystem with a closed-loop control system incorporating an integrated gearmotor/tachometer drive unit. The functioning of the closed-loop system has subsequently been found to be entirely satisfactory.

Modifications were also required to the filler wire feed drive and control subsystem. The positioning mechanisms provided for the wire guide system were found to be inadequate for making the precise, repeatable guide settings necessary to feed wire into the keyhole closure region during weld termination. This was corrected by designing, fabricating and installing a replacement positioning system incorporating a dovetail slide and other precision adjustment capabilities. In addition, the wire feed control timer circuitry was reconfigured to permit the initiation of wire feed either before or after the initiation of final current downslope, in order to provide maximum flexibility in the development of a weld termination procedure incorporating filler wire addition.

Finally, it was necessary to modify the plasma torch orifice bodies in order to achieve predictable, repeatable energy input to the weld joint. This is discussed in detail in the section on procedure development.

WELDING PROCEDURE DEVELOPMENT

Materials

To provide specimens for procedure development and related investigations, mockups of the canister body and closure lid were designed as shown in Figs. 7 and 8. Body mockups were fabricated from seamless pipe, with both ASTM A106 Grade B (3 heats) and A53 Type S Grade B (1 heat) materials represented in the specimen population. Closure lid mockups were fabricated from end caps which were formed from plate; ASTM A515 Grade 65 (2 heats), A515 Grade 70 (3 heats) and A516 Grade 70 (4 heats) were included. End cap fabrication practices included cold forming with and without a subsequent stress relief heat treatment, and hot forming.

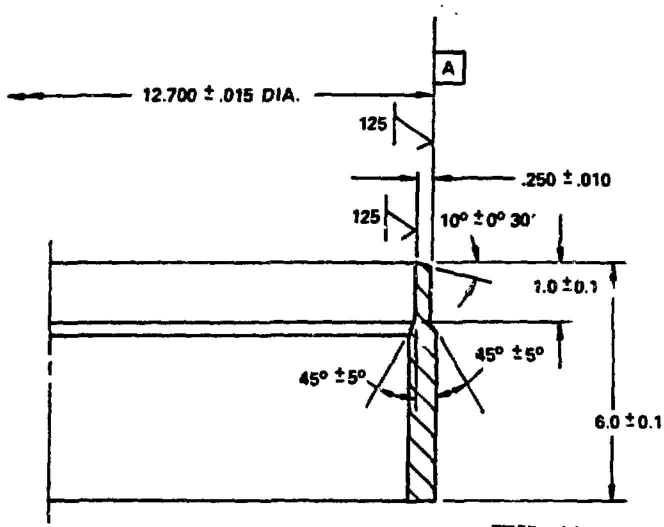

Fig. 7. Canister body mockup design.

The specification requirements for chemical composition, together with the heat analyses for all mockups used in the procedure development and qualification work, are given in Table 1. No basic weldability problems were experienced with any of these materials, although (as noted later) some significant grade-to-grade variations in weld bead shape were obtained with given welding parameters.

Filler wire, used in the keyhole closure region of a number of developmental welds and in the final procedure, was 0.035-in dia. AWS Type ER80S-D2. This was used for reasons of experimental convenience; any of a number of lower strength grades could have been satisfactorily substituted.

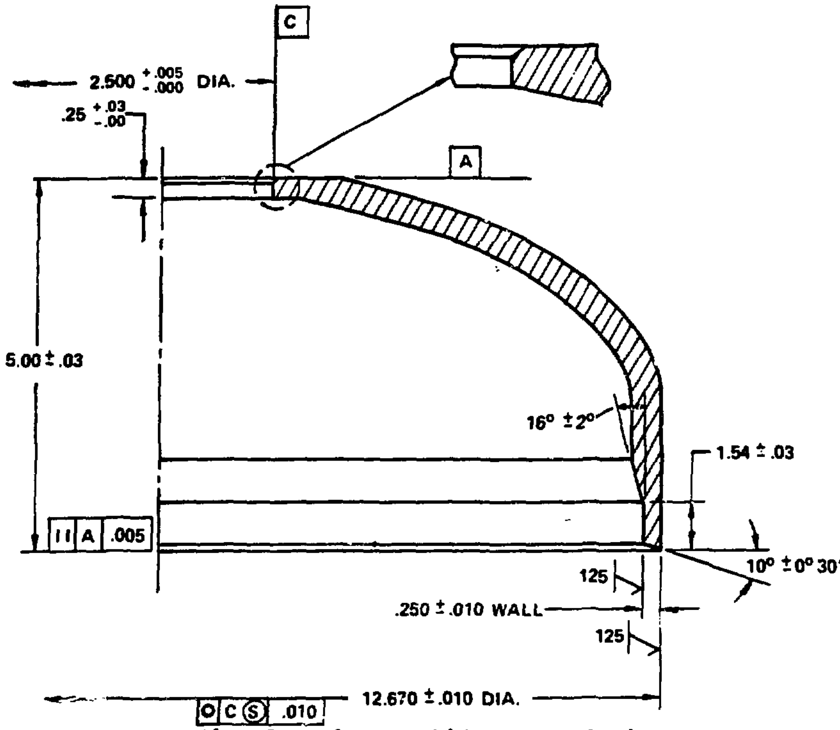

Fig. 8. Closure lid mockup design.

Procedure Description and Terminology

For convenience of discussion, the overall welding procedure will be divided into five separate parts, defined as follows:

Setup - Welding head is attached to the closure lid and adjusted; the head/lid assembly is then placed on the canister body. Final adjustments are made automatically. An inert atmosphere is established inside the canister assembly, and the system is ready for initiation of the welding procedure.

Tack Welding - Closure lid is tack welded to canister body.

Weld Initiation - Switch is made from pilot arc to transferred arc welding mode, keyhole is established and weld travel is initiated.

Main Weld - Autogenous butt weld is produced as the torch is rotated around the joint circumference.

TABLE 1 Chemical composition of canister mockup materials for weld procedure development and qualification

		Composition (weight percent)				
		C	Mn	P	S	Si
Canister Body ASTM A106 Grade B	Spec. Limits	0.30 max	0.29/1.06	0.048 max	0.058 max	0.10 min
	Heat Analyses	0.16	0.83	0.009	0.013	0.19
		0.17	0.82	0.008	0.012	0.19
		0.17	0.82	0.007	0.012	0.19
Canister Body ASTM A53 Type S Grade B	Spec. Limits	0.30 max	1.20 max	0.05 max	0.06 max	--
	Heat Analysis	0.24	1.00	0.010	0.015	--
Closure Lid ASTM A516 Grade 70	Spec. Limits	0.27 max	0.85/1.20	0.035 max	0.04 max	0.15/0.30
	Heat Analyses	0.23	1.09	0.005	0.011	0.27
		0.24	1.01	0.006	0.017	0.25
		0.25	1.10	0.010	0.016	0.23
		0.24	1.06	0.008	0.017	0.25
Closure Lid ASTM A515 Grade 65	Spec. Limits	0.28 max	0.90 max	0.035 max	0.04 max	0.15/0.30
	Heat Analyses	0.20	0.79	0.011	0.028	--
		0.19	1.13	0.005	0.023	0.27
Closure Lid ASTM A515 Grade 70	Spec. Limits	0.31 max	0.90 max	0.035 max	0.04 max	0.15/0.30
	Heat Analyses	0.22	0.47	0.007	0.022	--
		0.27	0.75	0.010	0.023	0.22
		0.27	0.77	0.008	0.021	0.22

Weld Termination - Weld travel is terminated; weld current and plasma gas flow are terminated; keyhole is closed; weld bead shape in keyhole closure region is adjusted through filler wire addition, if necessary, to meet application requirements.

Certain system or setup features and welding parameters were fixed prior to the initiation of experimental welding, and maintained constant throughout the program. These are listed below:

- Plasma gas composition: argon.
- Shielding gas composition: argon.
- Electrode: tungsten/2 percent ThO_2, 0.125-in dia., tip ground to a point, 60-degree included angle.
- Torch plasma orifice: 0.125-in dia.
- Torch tilt angle: 10° (up).
- Torch lead angle: 0° (perpendicular to surface).

Setup

To begin the process of making a developmental weld, the closure lid and canister body mockups are thoroughly cleaned to remove soil, waxes, oils and other contaminants, with a final joint surface cleaning using oxylene or methanol solvent being performed just prior to use. The automatic welding head is attached to the canister lid subassembly, and all necessary checks and torch positioning or other adjustments made. (In an actual encapsulation, this would be the final hands-on activity prior to evacuation of personnel from the hot bay and initiation of the remote encapsulation process sequence.) The head/lid assembly is then lifted and placed on the canister body mockup, which is positioned on a baseplate or on a "full volume" simulator to be described later. (The actual remote encapsulation process sequence will be described toward the end of the paper.)

An inert atmosphere is then established inside the mockup assembly, either by purging through penetrations in the baseplate or by evacuation and backfilling of the simulator. Helium was used for this purpose throughout the development program. (In an actual encapsulation, either helium or a mixture of helium and another inert gas such as krypton or neon will be used. The helium will provide a basis for helium leak testing the canister after closure welding. The other gas, when used, will provide a means for assessing continued canister integrity after shipment under conditions where the detection of helium has ambiguous implications.)

Finally, the torch is automatically driven in toward the workpiece until the desired torch/work separation distance (i.e., arc gap)* is established through a signal from the eddy current proximity sensor to the AVC drive control. Welding is then initiated as quickly as possible to minimize the opportunity for helium out-leakage from the assembly.

Tack Welding

A set of three tack welds was adopted to prevent the development of an axial gap at the joint interface in response to weld solidification shrinkage forces produced early in the closure welding cycle. (Gaps as large as 0.06-in were observed in mockups closure welded without prior tack welding.) The 1- to 2-in long tack welds are made in sequence at 90°, 270° and 180° from the point where closure welding would be initiated. A keyhole is not established during tack welding; instead, the lid and body are melted to a shallow depth and then solidify to join the two pieces. The tack is completely remelted during the closure weld cycle, so there is no effect on the integrity of the final weld.

Two tack welding procedures were investigated. The key parameters of the first of these are:

- Travel speed: 4 in/min.
- Plasma gas flow rate: 2-3 cfh
- Weld current: 100 amp
- Arc voltage: 28-30 volts
- Torch/work distance: 0.25 in
- AVC control: locked out

This procedure gave acceptable results for A516 Grade 70 closure lids, but cracking occurred in a few instances with A515 Grade 70 material. Accordingly, a second procedure was developed incorporating a filler addition to give a ~0.010-in reinforcement. This final procedure, performed with the AVC control locked out and using an initial torch/work distance of 0.25 in, is shown graphically in Fig. 9. This produced crack-free tack welds in all of the closure lids used in the balance of the program.

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* Throughout this program, torch/work separation distance is defined as the dimension EW shown in Fig. 12. The actual arc gap is the dimension FW shown in the same figure.

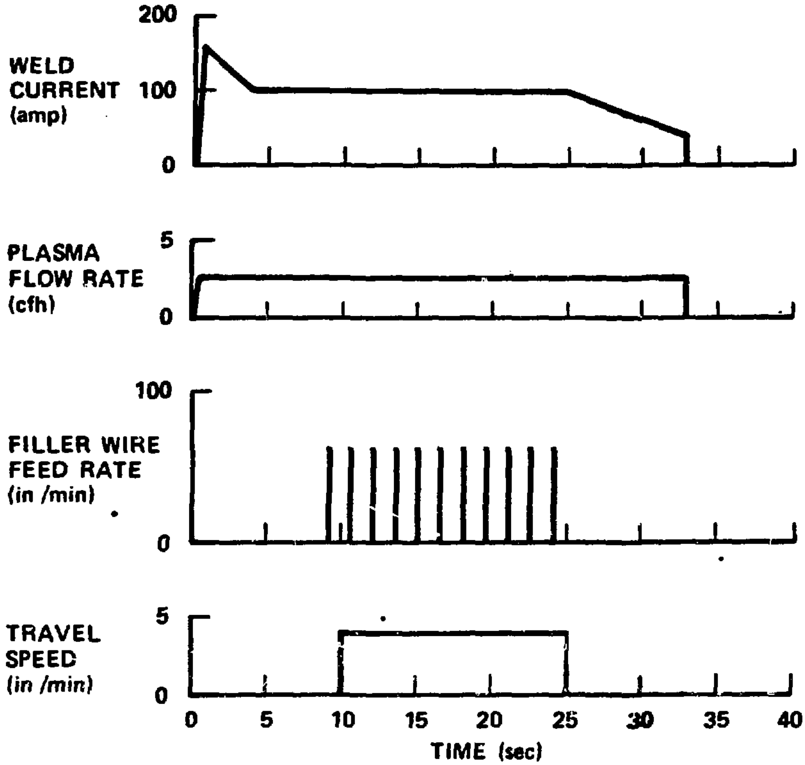

Fig. 9. Final tack welding procedure.

Weld Initiation

Three basic approaches to closure weld initiation were investigated, only one of which yielded entirely acceptable results. The first of these, shown graphically in Fig. 10(a), consisted of the following steps:

- With torch stationary, switch from pilot arc to transferred arc mode at a high weld current level, 190 amps, to establish a keyhole through the joint interface.
- With torch remaining stationary, after 7 second delay, increase plasma gas flow rate from pilot level of 2 cfh to main weld level of 7 cfh, and initiate weld current downslope.
- Downslope current in 8 seconds from 190 amps to main weld current level of (e.g.) 150 amps; initiate weld travel of (e.g.) 4 in/min at the end of this downslope.

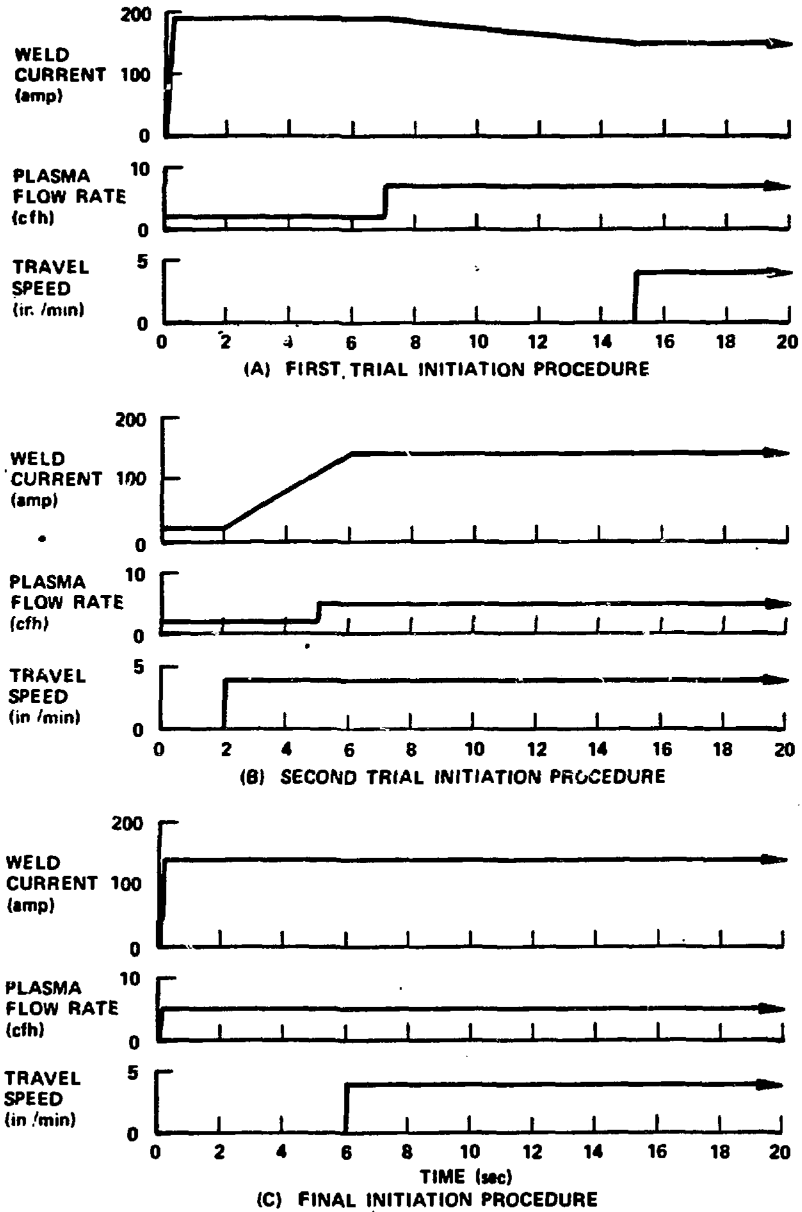

Fig. 10. Weld initiation procedures.

Two features of the resultant solidified weld start region were undesirable, and could not be satisfactorily improved with minor trial variations in initial current level and/or downslope time. First, a large residual through-hole was left at the start, which had to be assimilated into the weld puddle (in the overlap following the first 360 degrees of weld travel) before the weld termination procedure could begin; and second, substantial sagging of the starting puddle produced a "lump" of weld reinforcement at the lower edge of the weld bead face which violated the 3/32-in acceptance limit for reinforcement.

To improve the appearance of the weld start region and minimize the weld puddle perturbation during overlap, a second approach to weld initiation was developed. Shown graphically in Fig. 10(b), the final version of this approach consisted of the following steps:

- With torch stationary, switch to transferred arc mode at very low weld current level, sufficient to produce only shallow melting at the weld joint face.

- After 2 second delay, initiate weld travel of 4 in/min and initiate weld current upslope.

- Upslope current in 4 seconds to main weld current level of 140 amps; after 3 seconds of upslope, increase plasma gas flow rate from pilot level of 2 cfh to main weld level of 5 cfh. Keyhole is established "on the fly" as the current approaches 140 amps.

Several combinations of initial current, travel start delay time and upslope time were tried, with best results obtained at the values noted above. The AVC control was locked out for a period of 7 seconds after transferred arc initiation to allow time for the plasma column to stabilize. (Without this stabilization period, large fluctuations occurred during startup, producing a very uneven surface.) Using this initiation procedure, no residual through-hole was produced, and the excessive reinforcement resulting from puddle sagging was reduced somewhat. However, attempts to further reduce the reinforcement through additional parameter optimization were unsuccessful. This presented an intolerable handicap to the development of an acceptable weld termination procedure, so additional weld initiation development was pursued.

The third and ultimately successful approach to weld initiation was based on the concept of a hole premachined through the canister wall at the joint interface. By aligning the torch with such a hole prior to initating the automatic closure weld sequence, it was possible to establish and propogate a keyhole very quickly, with a minimum of extraneous workpiece heatup and corresponding minimum initial puddle size, and with elimination of the puddle turbulence and splashback associated with the establishment of a keyhole by directly melting through a solid wall with the high velocity plasma column.

Initial development was done with premachined circular holes of 0.12 to 0.25-in dia. having their axes coincident with the plane of the joint interface. The final configuration is a 0.22-in dia. semicircular hole penetrating only the closure lid half of the joint. This is simpler and less costly to machine, requires no matchup between closure lid and canister body, and introduces no discernable penalty in weld initiation procedure complexity or in acceptability of weld bead shape in the initiation region.

Figure 11 shows this final premachined hole configuration. (The adjacent interconnected slot is discussed in a subsequent section.) Figure 10(c) graphically shows the optimized initiation procedure developed for use with the premachined hole; it consists of the following steps:

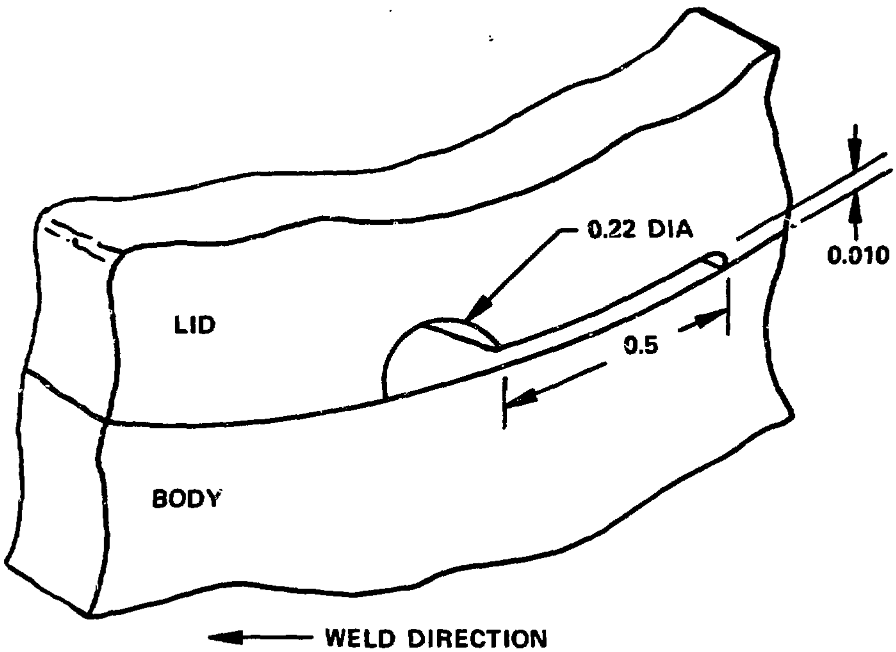

Fig. 11. Premachined keyhole starting penetration and pressure relief slot.

- With torch stationary, switch to transferred arc mode at main weld current level of 140 amps, simultaneously increasing plasma gas flow rate from pilot level of 2 cfh to main weld level of 5 cfh.

- After 6 second delay, initiate weld travel of 4 in/min.

Main Weld

The main weld extends from the point at which a stable, propogating keyhole is established to the point at which weld current downslope is initiated. The welding parameters are held constant during this ∿ 360-degree period (workpiece heatup effects are not sufficient to require compensatory weld current tapering), except for arc gap/arc voltage adjustments made by the AVC unit (when used) to compensate for ovality and/or thermal distortion. The development of a main weld procedure involved the optimization of various parameters, resolution of certain equipment system problems, and choices among alternative procedural strategies, as discussed below.

Weld Travel Speed - Main weld procedures were investigated at travel speeds of 4, 6, 8 and 10 in/min. Equivalent weld heat input levels and bead shapes were obtained using weld currents of approximately 140, 190, 240 and 270 amps, respectively. At speeds of 6 in/min and above, however, "double arcing" was experienced, with the frequency of incidence increasing with increasing travel speed. This is a phenomenon unique to plasma arc welding in which the transferred arc established between electrode and workpiece suddenly becomes diverted and split into two separate arcs, one between electrode and torch orifice and the other between orifice and workpiece. Several resultant effects, all deleterious, make it impossible to produce an acceptable closure weld while double arcing is occurring.

Several approaches to the elimination of double arcing are known; however, those which do not require modifications to the plasma arc torch (such as increasing plasma gas flow rate at a given travel speed and weld current) were tried without success. Accordingly, a travel speed of 4 in/min was adopted for all remaining work. No significant penalty was associated with this decision, as the 10-minute weld time at this speed represents a minor fraction of the time required for the entire encapsulation sequence.

Plasma Torch Characteristics and Performance - Throughout the early phases of the procedure development activity, problems were experienced with lack of reproducibility of weld joints made with nominally identical control system settings, and with the failure of systematic variations in certain settings to produce interpretable results. Many of these difficulties were due to deficiencies in the travel speed control subsystem, the resolution of which was discussed earlier, and to various other minor electrical and mechanical defects which were resolved in a straightforward manner. The problems persisted, however, and a perception developed that the source of these might lie in the plasma arc torch itself; one (of several) reason for this was the periodic observation of the occurrence of greenish coloration of the plasma column accompanied by spitting sounds and plasma column fluctuations, all suggesting that torch cooling water might be leaking into the plasma gas stream.

To investigate the latter possibility, an intensive study of torch characteristics and performance was undertaken. The pertinent torch components and dimensional features are shown schematically in Fig. 12. For study purposes, the workpiece was a water-cooled copper block, and all tests were performed with the torch stationary. A set of 14 orifice bodies, as-received from the manufacturer,

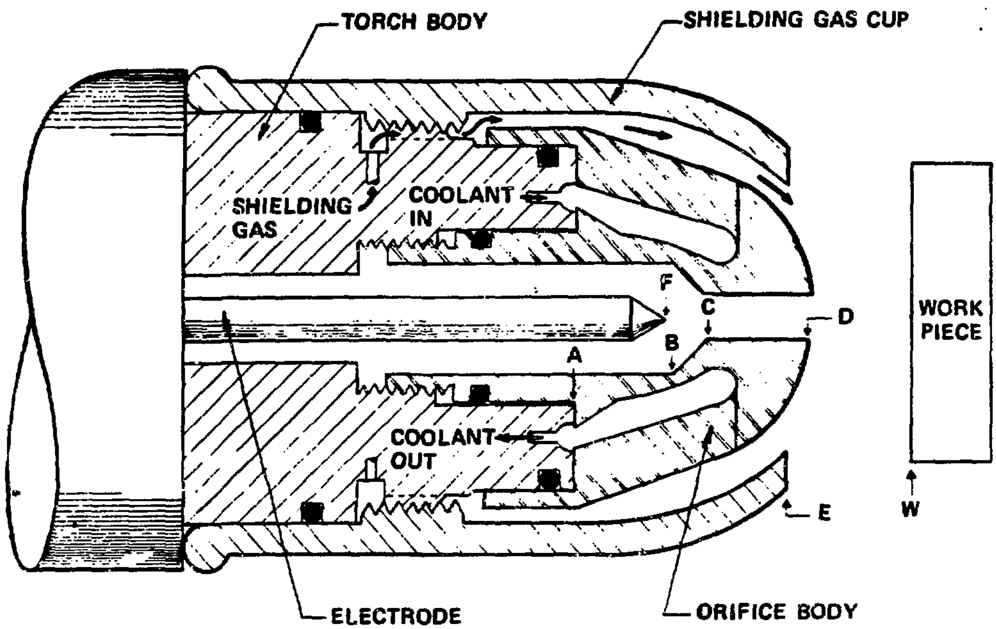

Fig. 12. PAW torch schematic.

was collected for evaluation. Using fixed weld parameters and electrode positions within the torch, it was quickly determined that an unacceptably wide range of arc voltages was obtained over the orifice bodies in the set. Representative test results illustrating this conclusion are given in Table 2. Also, indications of torch coolant leakage into the plasma gas stream were obtained with one orifice body and suspected with others.

Dimensional and shape measurements were made to assess the physical similarity of the orifice bodies. The results indicated large variations in features which were judged to be critical to the reproducibility of plasma gas flow characteristics and of the electrode to orifice body relationship. The "As-Received" columns of Table 3 indicate these variations for the dimensions AB and AD. Others included a range of ~0.030 in for the orifice length CD, several mils of variation in orifice diameter, a noncoplanar condition between the inner and outer contact surfaces at plane A, and nonperpendicularity between the contact surfaces A and the orifice body mounting thread axis.

To bring the set of orifice bodies into a reasonably standard configuration, a hand forging die was designed and fabricated. Each body was then forged to make the inner and outer contact surfaces at A coplanar to within 0.001 in. The effect of this operation on the AB and AD dimensions is shown in the "After Forging" columns of Table 3. Machining operations were then performed to bring the AB and AD dimensions to the "After Machining" values shown in Table 3, and to standardize the orifice length CD and the orifice diameter.

TABLE 2 Test results illustrating nonreproducible performance obtained with as-received torch orifice bodies

Orifice Body Number	Plasma Gas Supply Pressure (psig)	Plasma Gas Pressure (in H_2O) Before Initiating Transferred Arc	After Initiating Transferred Arc	Arc Voltage (volts)
01	29.2	24	34	27.0
02	29.2	24	35	27.5
03	29.2	24	35	28.0
04	29.2	24	34	27.5
05	29.2	24	37	28.5
06	29.3	24	36	27.5
07	29.4	24	35	28.0
08	29.3	24	35	27.2
09	29.3	24	36	29.0
10	29.3	24	34	28.0
11*	-	-	-	-
12*	-	-	-	-
13*	-	-	-	-
14*	-	-	-	-

*Not tested prior to modification

TABLE 3 Critical plasma torch orifice body dimensions before and after modification

Orifice Body Number	Dimension AB* (in) As-Received	After Forging	After Machining	Dimension AD* (in) As-Received	After Forging	After Machining
01	0.303	0.292	0.312	0.464	0.459	0.456
02	0.320	0.303	0.311	0.500	0.458	0.456
03	0.320	0.306	0.312	0.500	0.467	0.456
04**	0.294	0.285	0.286	0.453	0.435	0.434
05	0.305	0.294	0.310	0.480	0.457	0.456
06	0.303	0.292	0.311	0.480	0.453	0.452
07**	0.300	0.286	0.286	0.480	0.450	0.434
08**	0.321	0.318	0.332	0.508	0.490	0.464
09	0.310	0.306	0.311	0.480	0.472	0.456
10**	0.325	0.316	0.332	0.495	0.465	0.464
11	0.303	0.298	0.311	0.474	0.464	0.457
12**	0.314	0.305	0.311	0.474	0.465	-
13	0.306	0.294	0.311	0.474	0.448	0.449
14	0.305	0.303	0.311	0.453	0.449	0.449

*Dimensions defined in Fig. 12.
**As modified configuration judged unacceptable for further use.

With these modifications completed, it was possible to proceed with a systematic study and optimization of electrode to orifice body relationship. Listed below are the final standardized and/or optimized* orifice body dimensions and electrode position relationships, with pertinent comments regarding the establishment of each. As indicated in Table 3, five of the 14 orifice bodies were disqualified from further use due to excessive variations from these standardized/optimized values.

- Electrode stickout, dimension AF: Optimized value is 0.300 ± 0.001 in. Values from 0.280 to 0.320 in were investigated.
- Dimension AB: Standardized value is 0.311 ± 0.001 in.
- Electrode tip to edge of orifice entry angle, dimension FB: Standardized value is 0.010 $^{+0.001}_{-0.000}$ in. The study showed the following:
  - Values in the optimum range of 0.010 to 0.020 in produce stable, predictable arc voltages with no discernable electrode tip erosion.
  - At values greater than 0.020 in, rapid tip erosion occurs.
  - If the electrode is advanced so that the tip falls within the orifice entry angle region BC, unstable arc voltage behavior is observed.
- Orifice entry angle, region BC: Standardized value is 118° (included), the as-received value.
- Orifice length, dimension CD: Standardized value is 0.100 ± 0.003 in. For a fixed arc gap FW, arc voltage increased slightly as CD was varied from 0.095 to 0.103 in.
- Orifice diameter: Standardized value is 0.125 ± 0.001, established by reaming each as-received orifice body.
- Dimension AD: Standardized value is 0.457 $^{+0.000}_{-0.005}$ in.

  As a result of standardizing dimensions AF and AD, the arc gap FW can be conveniently established during setup by

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*Note that this "optimization" applies only for the complete set of dimensions arrived at here. Other "standardized" dimensions could have been established, and corresponding different "optimized" values developed, that would produce equally satisfactory results.

fixing the externally determinable dimension DW (or, as was done on this program, the externally determinable dimension EW with the interrelating dimension ED under close control).

Table 4 gives representative test results indicating the performance repeatability among the (usable) members of the orifice body set following modification and standardization. Orifice bodies conforming to this standardized configuration were used exclusively through the balance of the program.

TABLE 4 Test results illustrating reproducible performance obtained with modified, standardized orifice bodies and optimized electrode-orifice relationship

Orifice Body Number	Orifice Length (in)	Plasma Gas Supply Pressure (psig)	Plasma Gas Pressure After Initiating Transferred Arc ($in\ H_2O$)	Arc Voltage (volts)
01	0.101	29.7	32.5	25.0
02	0.102	29.7	33.0	25.0
03	0.101	29.7	33.0	25.0
05	0.103	29.7	33.0	25.0
06	0.098	29.8	33.0	24.9
09	0.102	29.8	33.0	25.1
11	0.103	29.8	33.5	24.9
13	0.095	29.7	33.0	24.6*
14	0.095	29.7	33.0	24.6*

*The reduced arc voltages for 013 and 014 are a direct consequence of their shorter orifice lengths, as predicted by earlier test results.

Assembly Ring Configuration and Joint Venting - To mitigate concerns regarding internal pressure buildup which might lead to weld puddle blowout, considerable attention was devoted to the geometric configuration of the assembly ring and to venting of the weld joint. The final assembly ring configuration, shown previously in Fig. 2, is a 0.50-in radial thickness member containing a 0.30-in deep x 0.60-in high relief groove directly behind the joint interface. This configuration evolved from the initial design configuration, a 0.125-in radial thickness strip containing a 0.050-in deep x 0.250-in high relief groove, as a result of experiencing occasional weld puddle blowouts with the latter configuration late in the development program.

The concern over internal pressure buildup led to an experimental setup transition from the lid/body mockup assembly resting on a baseplate penetrated only by purge gas inlet and purge gas outlet/pressure relief ports, to the mockup assembly gasket-sealed to a flange of a "full volume" simulator. The latter is simply an evacuable/backfillable tank whose internal volume is approximately equal to the net free internal volume of a canister loaded with a spent PWR fuel assembly (less the internal volume of the lid/body mockup). This allowed a more realistic assessment of the magnitude of internal pressure buildup effects due to the continuous injection of hot plasma gas into the assembly ring relief groove as closure welding progressed. Provision for an internal heater also allowed an assessment of the additive effect of heat generated by the canister contents.

Results of weld experiments made with the simulator indicated that puddle blowout near the end of the main weld (or during the weld termination sequence) was a credible possibility. To alleviate this, a 0.5-in long x 0.010-in high venting slot, located at the end of the main weld travel and interconnected with the semicircular keyhole starting hole, was incorporated into the closure lid weld preparation. (This slot was illustrated previously in Fig. 11.) Approximately 20 complete closure welds were made on the simulator with mockups containing this venting slot, with no blowouts being experienced.

Automatic AVC vs. Fixed Arc Gap - Through most of the program, automatic AVC was used to maintain constant arc voltage as the main weld progressed. As discussed earlier, the AVC control was locked out until a stable, propogating keyhole was established (using a preset initial arc gap). It was then automatically switched on, and functioned to increase or decrease the arc gap in response to workpiece ovality, thermal distortion or other geometric perturbations as required to maintain arc voltage at the preset value. At the point of weld current downslope initiation, the AVC control was automatically switched off, allowing weld termination to proceed under (final) fixed arc gap conditions.

Excellent results were obtained with the use of the AVC system in this manner, and it appeared that the system could adequately compensate for much larger geometric perturbations than were allowed or experienced in the canister closure hardware. Late in the program, however, it became necessary to abandon its use. As described further in a later section, this resulted from the unsuccessful attempt to develop a completely autogenous keyhole closure procedure, and the subsequently determined necessity for adding filler wire prior to the initiation of current downslope.

The filler wire feed unit is fixed to the plasma torch mounting bracket, and consequently is fixed to the AVC drive unit. The wire feed nozzle thus moves in concert with the torch as the AVC system functions. During the main weld, observations indicated that a continuous small, cyclic variation in keyhole size occurred as the weld progressed, and that the AVC system responded to this variation by producing a small, cyclic variation in arc gap. The effect of this variation on the shape and acceptability of the autogenous weld bead was completely negligible; however, its effect on filler wire placement proved to be intolerable.

Because of this, rather than design and implement an alternate wire feed unit mounting scheme or attempt to reduce the cyclic arc gap variations thorugh procedure parameter adjustments, the decision to abandon use of the AVC system was made. No significant problems were introduced by this decision for the subject application. The main weld procedure was shown to be tolerant to arc gap variations of ± 0.125 in from the specified nominal value, whereas maximum canister hardware ovality is of order 0.020 in and the thermal distortions measured during welding were 0.005 in at most. The final main weld procedure is thus based on a fixed initial arc gap, and automatic AVC is not used.

Base Metal Chemistry Variations - In the course of main weld procedure development, it was determined that small but vital adjustments were required in certain critical parameters to accommodate the differences in melting temperature and weld puddle viscosity and surface tension among the various canister body and closure lid base metal combinations investigated. Table 5 gives the parameter variations required to yield acceptable main weld beads for three base metal combinations. Based on these results, it appears necessary to separately qualify a detailed welding procedure for each base metal combination allowed in the canister design and, quite possibly, to qualify on a material heat basis if substantial heat-to-heat chemistry variations are encountered.

Table 5. Main weld parameter variations required for various base metal combinations

Closure Lid/ Canister Body Base Metals	Weld Current (amp)	Arc Voltage (volts)	Torch/Work Separation (in)	Plasma Gas Flow Rate (cfh)
A515 Grade 70/ A106 Grade B	130-135	25.5	0.19	∿ 5 @ 40 in H_2O
A516 Grade 70/ A106 Grade B	145	27.0	0.38	∿ [illegible] @ 35 in H_2O
A516 Grade 70 A53 Tp. S Gr. B	140	26.0	0.25	∿ 5 @ 38 in H_2O

Base Metal Temperature - Heatup of the closure lid and canister body before and during welding will result from three sources: decay heat generated by the canister contents, normal weld heat buildup in the joint region, and the continuous injection of hot plasma gas into the assembly ring relief groove as the weld progresses. Test results on preheated mockups indicated that a given main weld procedure produces acceptable results over an initial weld joint temperature range from room temperature to 150°F. Higher temperatures were not investigated, but it appeared that a reduction in weld heat input would be required for preheat temperatures much above 150°F.

Final Main Weld Procedure - The final main weld procedure, as qualified for the A516 Grade 70/A53 Type S Grade B base metal combination, is summarized as follows:

- Shielding Gas Supply Pressure: 30.0 psig*
- Shielding Gas Flow Rate: 36 cfh*
- Plasma Gas Supply Pressure: 29.8 psig*
- Plasma Gas Console Pressure: 38 in H_2O
- Plasma Gas Flow Rate: 5 cfh
- Torch/Work Separation: 0.250 in*
- Arc Gap: 0.466 in*
- Arc Voltage: 26.0 volts
- Weld Current: 140 amp
- Weld Travel Speed: 4 in/min

As noted earlier (see Table 5), appropriate adjustments in weld current and plasma gas (console) pressure would be made for the other allowed base metal configurations. Figure 13 illustrates the appearance of a typical mockup welded using one of these main weld procedures.

Weld Termination

Three basic approaches to closure weld termination were investigated, only one of which yielded acceptable results. These are described and discussed in the following sections.

Continguous Autogenous Termination - The simplest and most desirable termination procedure would be a contiguous continuation of the main weld procedure in which some optimum combination of weld current, plasma gas flow rate and/or travel speed downslope (or, conceivably, upslope) would produce an autogenous closure of the keyhole and a final solidified closure region bead which meets all of the previously stated acceptance criteria. A large number of trial terminations was performed in which these parameters were

* These values also used for weld initiation and termination procedures.

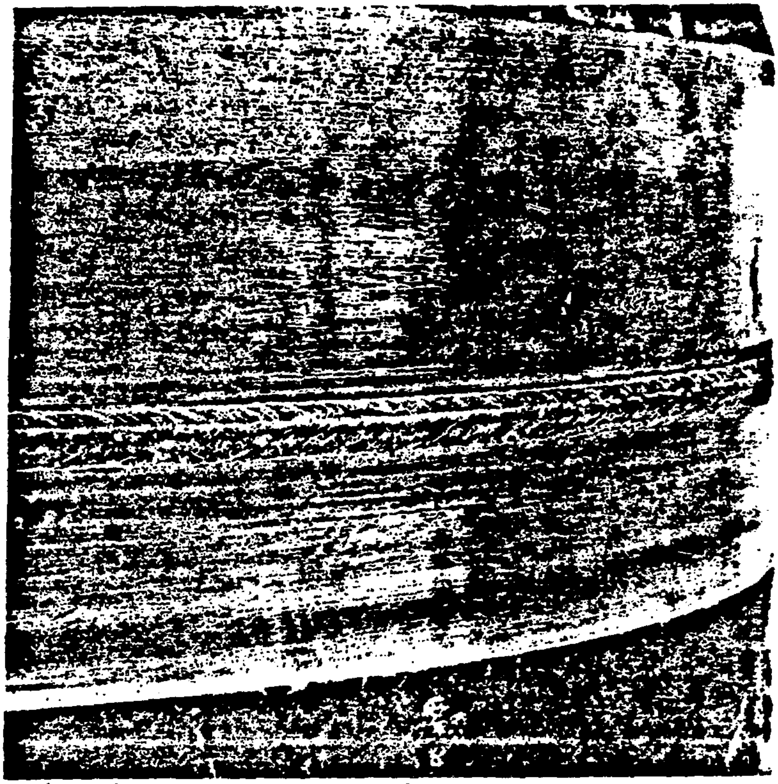

Fig. 13. Appearance of typical closure welded mockup.

varied and their interrelationships studied. Two main effects were observed to work in opposition to achievement of the objective:

- After initiation of current downslope, as soon as the keyhole closed (which closure always initiated at the root side of the weld), the weld puddle changed from a stable, conical layer to a turbulent, closed-bottom pool agitated by the incident plasma gas. In most cases, this turbulence resulted in the development of unacceptable porosity during final solidification.

- Due to the conical shape of the keyhole (small end at the root side), and the root-to-face direction of solidification during termination, a certain amount of face-side undercut (actually, underfill) was inevitably present after solidification was complete.

The most successful attempt at a termination of this type was performed using the procedure shown graphically in Fig. 14. The termination region was free of porosity, but the face-side undercut remained excessive. At this point, schedular requirements dictated

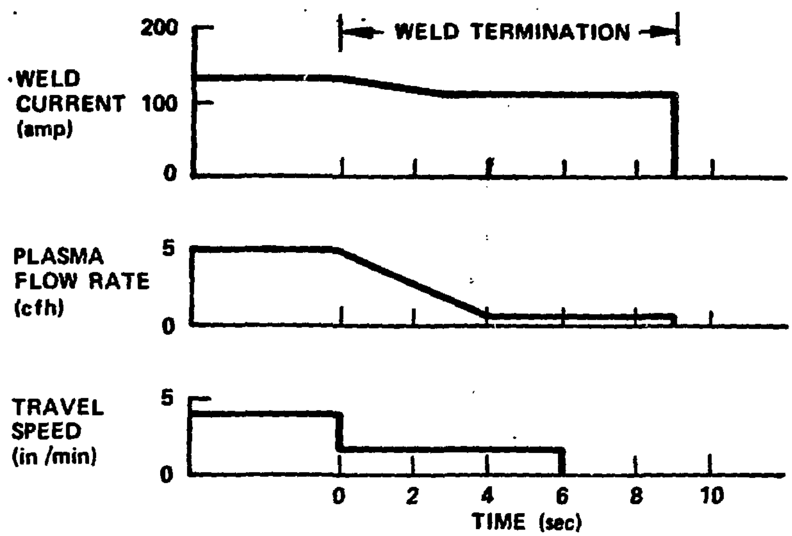

Fig. 14. Contiguous autogenous weld termination procedure.

that another termination approach be investigated, as discussed in the next section.

Contiguous Termination with Filler Addition - The next level of procedural complication was the incorporation of a filler metal addition into the keyhole closure region during termination. In this way, it was envisioned that an undercut condition such as that just discussed could be overcome in the most expedient manner.

Again a large number of trial terminations was performed in which the previously discussed parameters plus filler wire feed rate and wire feed position were varied and their interrelationships studied. The most successful procedural approach of this type is shown graphically in Fig. 15. Simultaneously weld travel was terminated and weld current was reduced in a step change (as opposed to a downslope). Also, at the same point, plasma gas downslope was initiated at the maximum rate allowed by the control system, and filler wire feed was initiated. This approach minimized the problem of weld pool turbulence, but the undercut problem persisted. The general results of this approach can be summarized briefly: when porosity was eliminated, undercut was excessive; and when undercut was controlled, unacceptable internal porosity was invariably detected. Accordingly, this approach was also abandoned in favor of the technique discussed in the next section.

Two-Pass Termination with Filler Addition - The final, successful approach to weld termination was developed by Westinghouse AESD/Nevada personnel after the author's participation in the project had ended. This and other later aspects of the program will be reported separately from this paper.

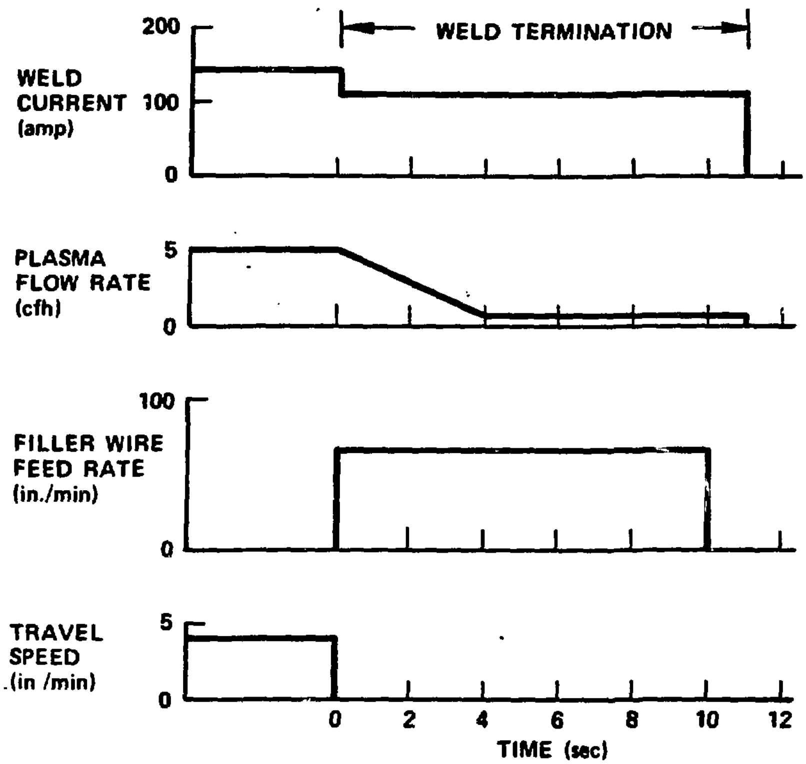

Fig. 15. Contiguous weld termination procedure with filler addition.

The final termination procedure consists of the following steps:

- Stop torch travel, and simultaneously initiate plasma gas flow rate downslope, weld current downslope and filler wire feed. Pulsed weld current (a capability not described in this paper) is used to help minimize heat input.

- The above results in a closed keyhole region free of porosity but having excessive undercut.

- Back the torch $\sim$ 0.5 in (circumferentially) along the weld travel path.

- Perform a second, $\sim$ 0.5-in long melt-in filler pass to build up the undercut region to an acceptable level.

Although this approach is operationally more complex than the contiguous approaches described previously, it enabled a successful overall procedure qualification to be performed on the A516 Grade 70/A53 Type S Grade B base metal combination in accordance with program requirements.

WELD EVALUATION

At various points in the program, complete welded mockup assemblies were selected for comprehensive evaluation. Following visual examination and x-ray radiography, each assembly was sectioned in accordance with a detailed sampling pattern, and converted into appropriate specimens for tensile and bend testing, hardness measurements and metallographic examination. Results of the evaluation of two typical assemblies will be described here; these are representative of results obtained on all other mockups evaluated throughout the program.

Tensile and Bend Tests

Tensile and bend test specimens were machined to (essentially*) the procedure qualification configurations specified in Section IX of the ASME Code. The curved (closure lid) portion of each transverse tensile specimen was flattened with a press prior to machining; since this portion was part of a grip section of the final specimen, the strain hardening introduced by flattening had no effect on the test results.

Each transverse tensile specimen was scribed with a 1.25-in gage length and then tested (at room temperature) to failure in a Wiedemann tensile machine using a constant crosshead speed of 0.05 in/min. The strength and elongation values calculated from the test results are given in Table 6, together with the corresponding minimum values allowed for the closure lid and canister body base metals in their respective material specifications.

All specimens tested fractured in the canister body material section, at yield and ultimate strength values well in excess of the specification minimums for that material. The results are thus in conformance with the qualification acceptance criteria of Section IX of the ASME Code. The variations among individual test results are typical for welded steels of these general types. The reduced elongation values (as compared to the base material specification minimums) reflect the weld fusion zone hardening effects described below. These elongation values do not affect the acceptability of the tensile test results with respect to the Code criteria.

Bend test specimens were tested in a die/punch bending fixture mounted on a Wiedemann tensile machine. A crosshead speed of 1.0 in/min was used for all specimens. The results are compiled in Table 7, and the surface appearance of four representative specimens after bending is shown in Fig. 16. No cracks were seen in any specimen, so the results are in conformance with the Section IX qualification acceptance criteria.

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*Some bend test specimen widths deviated slightly.

Table 6. Transverse tensile results and base material specification minimums for typical welded mockups

Specimen Number	Yield Strength (psi) 0.2 pct. Offset	Ultimate Tensile Strength (psi)	Elongation in 1.25 in (pct.)
55T3	47,800	66,800	18.3
55TT67*	50,100	66,500	14.1
55T7	58,100	67,900	18.8
88T1	57,300	67,100	17.1
88T5	51,000	71,400	14.0
88TT67*	50,900	69,000	16.4
Base Material Specification			
Canister Body A106 Grade B	35,000 min	60,000 min	27.0 min
Closure Lid A516 Grade 70	38,000 min	70,000 min	21.0 min

*Specimen located in tack weld region.

Table 7. Bend test results for typical welded mockups

Specimen Number	Type of Bend Test	Test Results
55B1	Transverse face bend	No cracks
55B2	Transverse root bend	No cracks
55BT45	Transverse face bend	No cracks
55B6	Transverse root bend	No cracks
88B2	Transverse root bend	No cracks
88BT45	Transverse face bend	No cracks
88B6	Transverse root bend	No cracks
88B8	Transverse face bend	No cracks
88LB34	Longitudinal root bend	No cracks

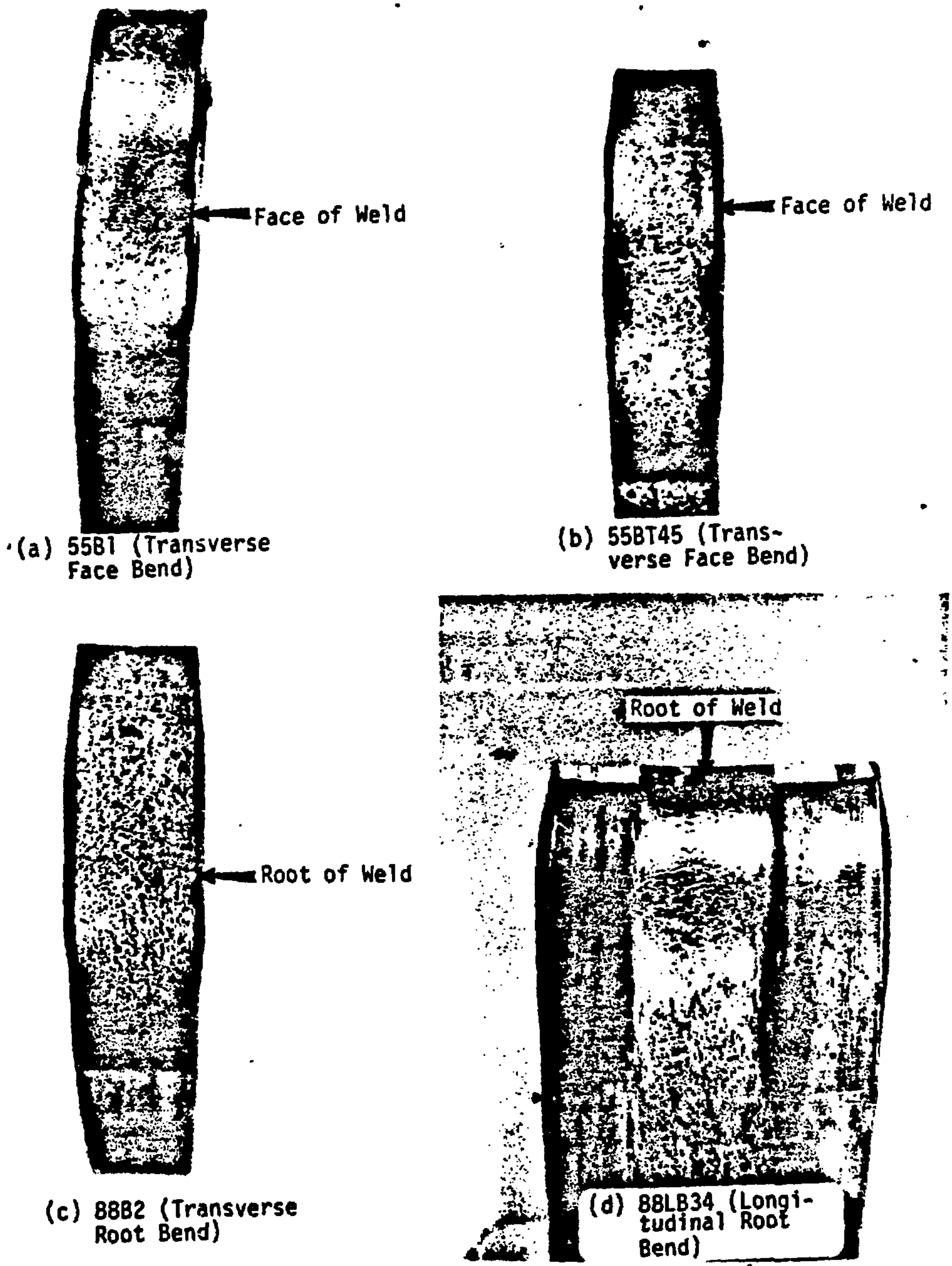


Fig. 16. Appearance of typical as-tested bend specimens.

Hardness Measurements

Diamond Pyramid (Vickers) hardness measurements were made on specimens from both assemblies to characterize the softening/hardening effects of the plasma arc welding process on the canister materials. The Diamond Pyramid technique permits the determination of accurate hardness values and the mapping of hardness gradients through the relatively small transition zones found in welded structures of this type. The test specimens were metallographically polished and etched, and hardness traverses made along the prepared surfaces beginning in the canister body base metal and proceeding through the body heat-affected zone, weld fusion zone, closure lid heat-affected zone and lid base metal.

Plots of the resultant hardness profiles are shown for four representative specimens in Fig. 17. In each case, the weld fusion zone hardness values are at or near the highest level in the weldment; this reflects a combination of alloying effects (the body and lid base metal compositions are somewhat different, as indicated previously in Table 1), microstructural effects and hardening due to phase transformations during weld cooling. The body base metal is the softest region in each case; this follows directly from the minimum strength specification values given previously in Table 6, and the fact that hardness and tensile strength are closely correlated in steels of this type. The hardness gradient in the body heat-affected zone forms a monotonic transition between the low-hardness body and high-hardness weld fusion zone; the hardening in this region is due to transformation effects, as evidenced by the fact that the gradient increases sharply as the weld fusion zone boundary (where welding-induced temperature levels and subsequent cooling rates are highest) is approached.

The hardness gradient in the lid heat-affected zone is similar to that in the body side of the weldment, and a similar transformation effects explanation seems appropriate. The difference in closure lid hardness levels between the two assemblies is within the range expected from a combination of heat-to-heat chemistry variations and differences in detailed fabrication/processing parameters during ellipsoidal lid manufacture. No significant differences were observed between hardness profiles in tack welded versus non-tack-welded regions within a given assembly.

Although the details of the hardness measurement results are of considerable interest from the viewpoint of characterization and understanding of the metallurgical effects and resultant properties produced by the welding operation, the hardness variations observed are of no consequence in evaluation of the acceptability of the weld joint. All of the conditions described above are acceptable from the mechanical, metallurgical and ASME Code criteria viewpoints.

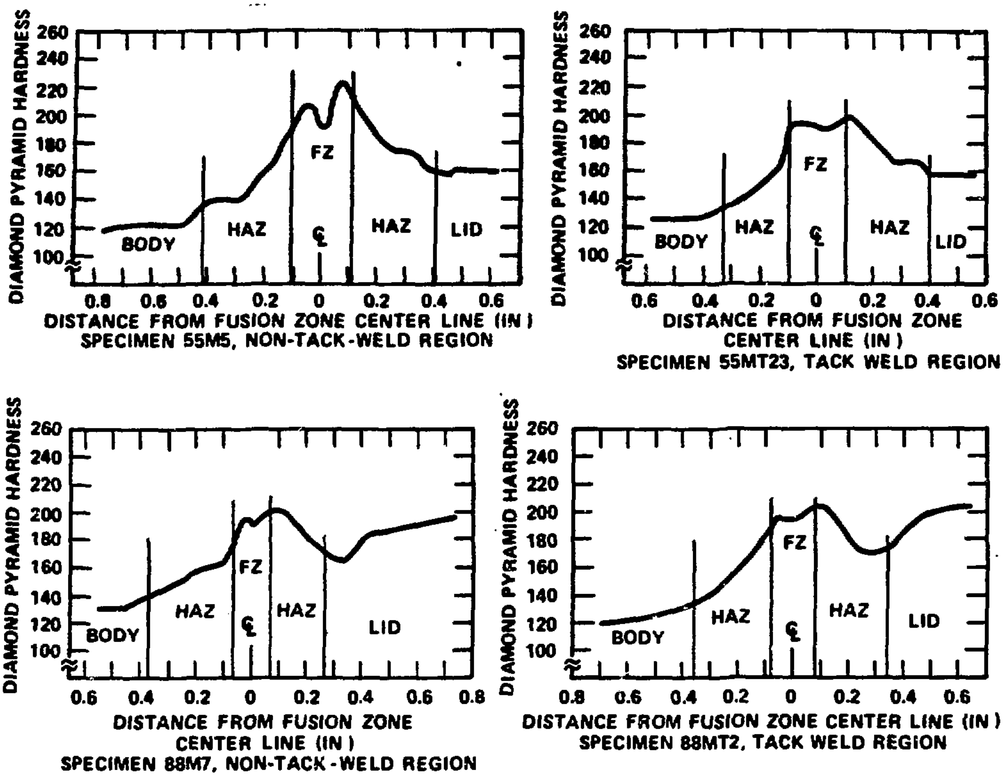


Fig. 17. Hardness profiles across typical closure weld joints.

Metallographic Examination

Prior to making hardness profile measurements, metallographic examination was performed on specimens taken from each assembly. The specimens were metallographically polished, etched to display the microstructures of the various weld zones, and examined by optical microscopy at various magnifications.

The cross-sectional features of a typical weld section are shown in Fig. 18. The weld bead face of all specimens examined exhibited slight reinforcement toward the canister body (lower) material, and most exhibited slight undercut toward the closure lid (upper) material. All of the reinforcement and undercut conditions seen in all of the specimens examined fall within the allowable limits specified in the Code.

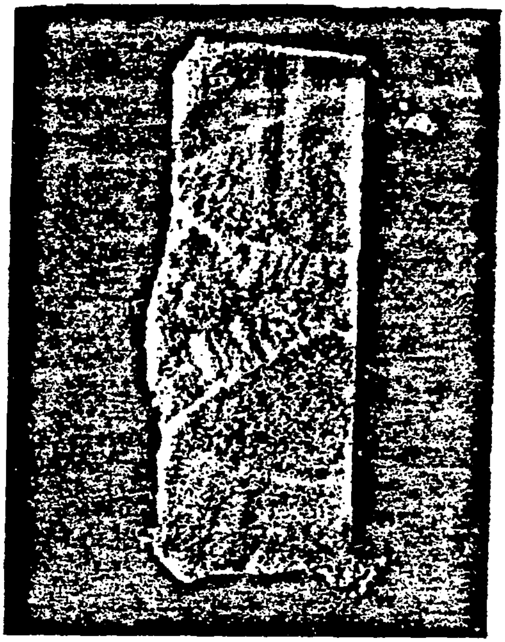


Fig. 18. Cross-sectional features of typical closure weld joint.

The microstructures of the base metals, heat-affected zones and weld fusion zones in typical specimens are shown in Fig. 19. No significant differences were seen either between assemblies or between tack welded and non-tack-welded regions within a given assembly. No porosity, weld-created inclusions or other undesirable microstructural features were seen in any of the specimens examined; all were judged to be metallurgically sound and completely acceptable for this application.

REMOTE ENCAPSULATION PROCESS SEQUENCE

An aerial view of the experimental encapsulation facility ("E-MAD" Facility) at the Nevada Test Site is shown in Fig. 20. This facility, built in the 1960's as part of the NERVA (nuclear rocket engine) program, is currently operated for the U.S. DOE by Westinghouse AESD/Nevada Operations. An appreciation of the scale of the hot bay interior may be gained from Fig. 21, which shows a canistered spent fuel assembly (from an earlier program) being remotely loaded into a shielded storage cask for an above ground dry storage demonstration. The canister closure welding station is shown in Fig. 22, where a spent fuel assembly is being remotely loaded into an earlier design canister prior to closure welding.

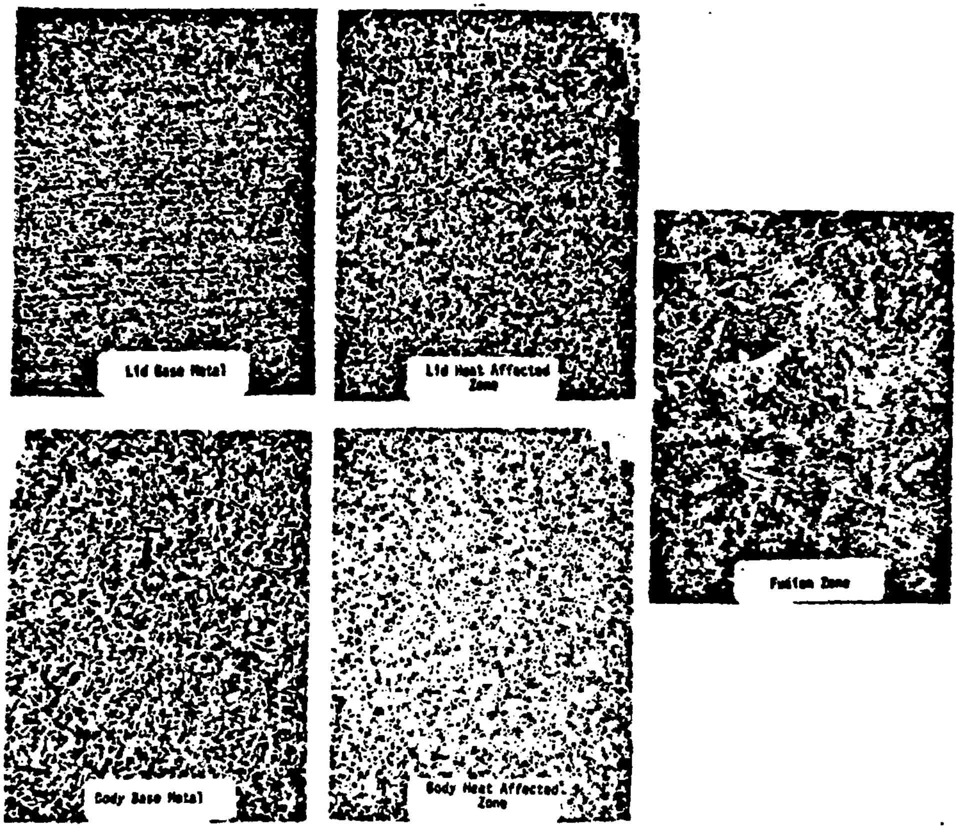


Fig. 19. Microstructural features of typical closure weld joints.

The remote encapsulation process sequence for the canister and plasma arc closure welding system described in this paper is shown in Fig. 23(a) through 23(l). A brief description of each illustrated item or step is given below:

23 (a). Weld pit general arrangement, with adapter for the canister described in this paper.

23 (b). Canister body subassembly installed in weld pit.

23 (c). Evacuation/backfill collar installed on canister body.

23 (d). Photograph of evacuation/backfill collar.

23 (e). Spent PWR fuel assembly remotely installed into canister body subassembly.

23 (f). Automatic welding head/closure lid assembly remotely installed onto canister body.

23 (g). Evacuation/backfill collar remotely positioned and attached to backfill system. (Canister is then

evacuated and backfilled with helium, after which collar is deactivated and stripped down away from closure weld joint.)

23 (h). Automatic plasma arc closure weld made remotely.

23 (i). Automatic welding head removed remotely from welded canister.

23 (j). Evacuation/backfill collar removed remotely from welded canister.

23 (k). Vacuum chamber hood remotely installed. (Chamber is then evacuated through mass spectrometer leak detector to perform helium leak inspection of welded canister.)

23 (l). (After remotely removing vacuum chamber hood), welded canister is removed remotely from weld pit and transferred to shielded storage or transport cask.

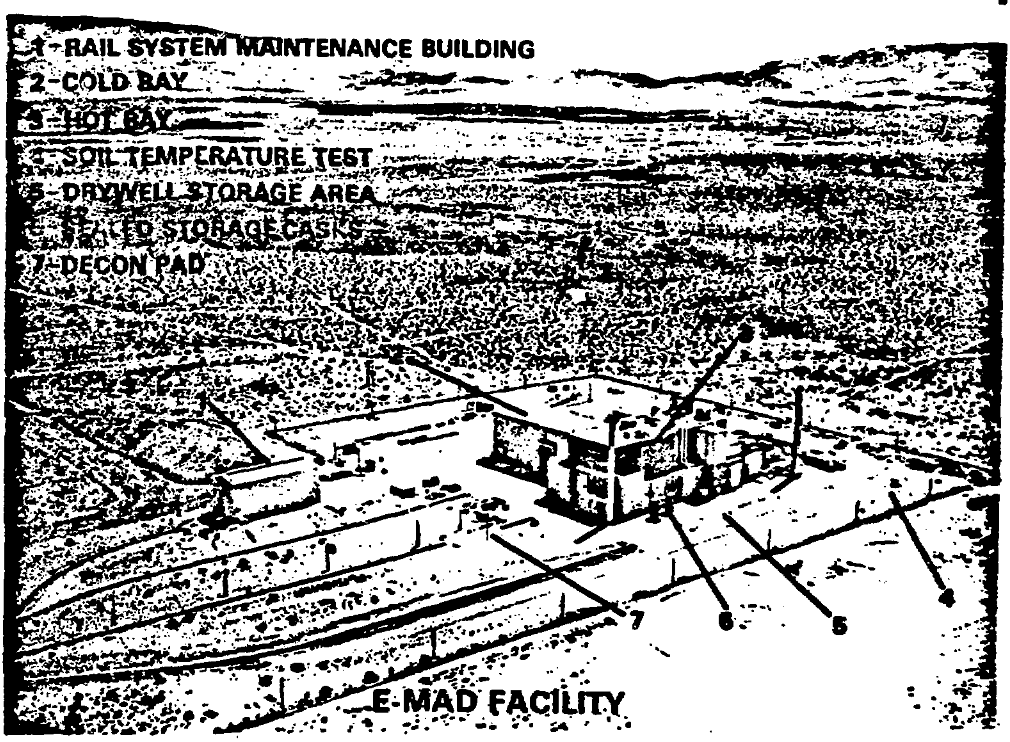


Fig. 20. Experimental encapsulation facility.

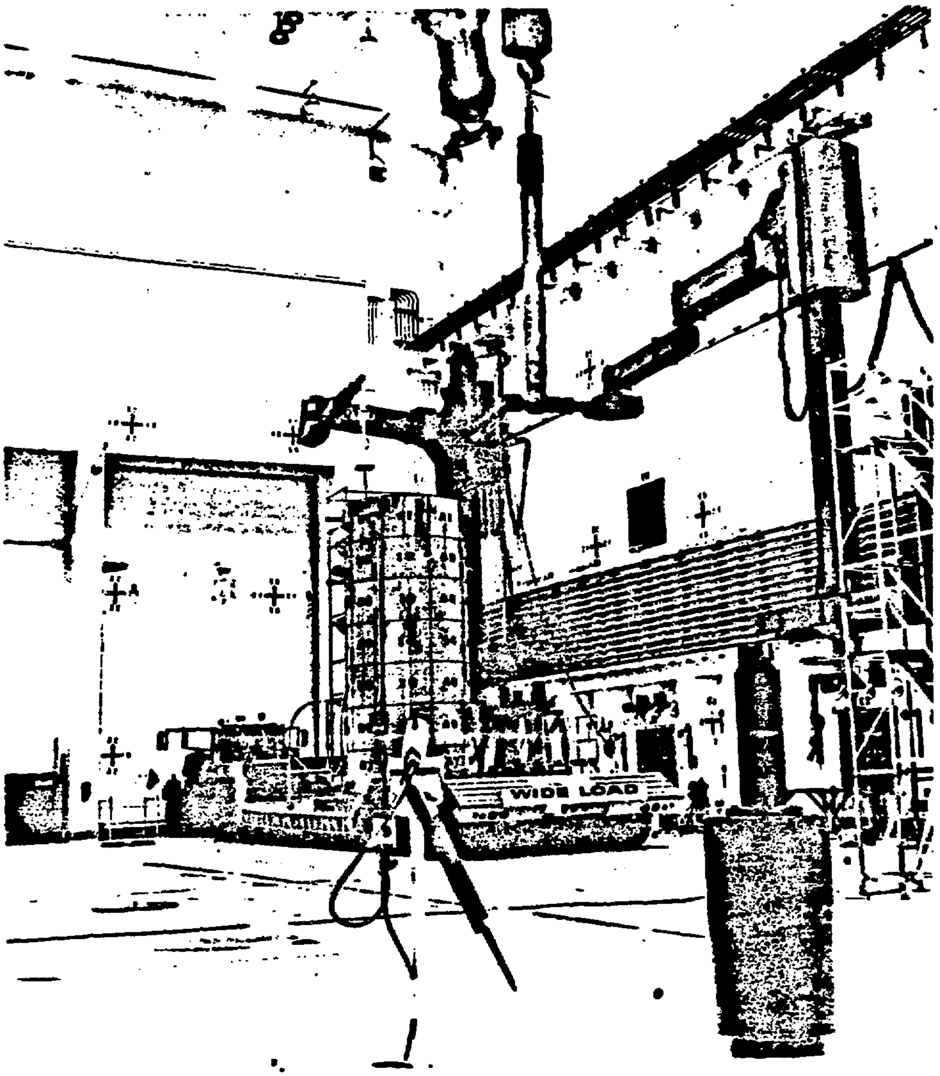


Fig. 21. Hot bay interior.

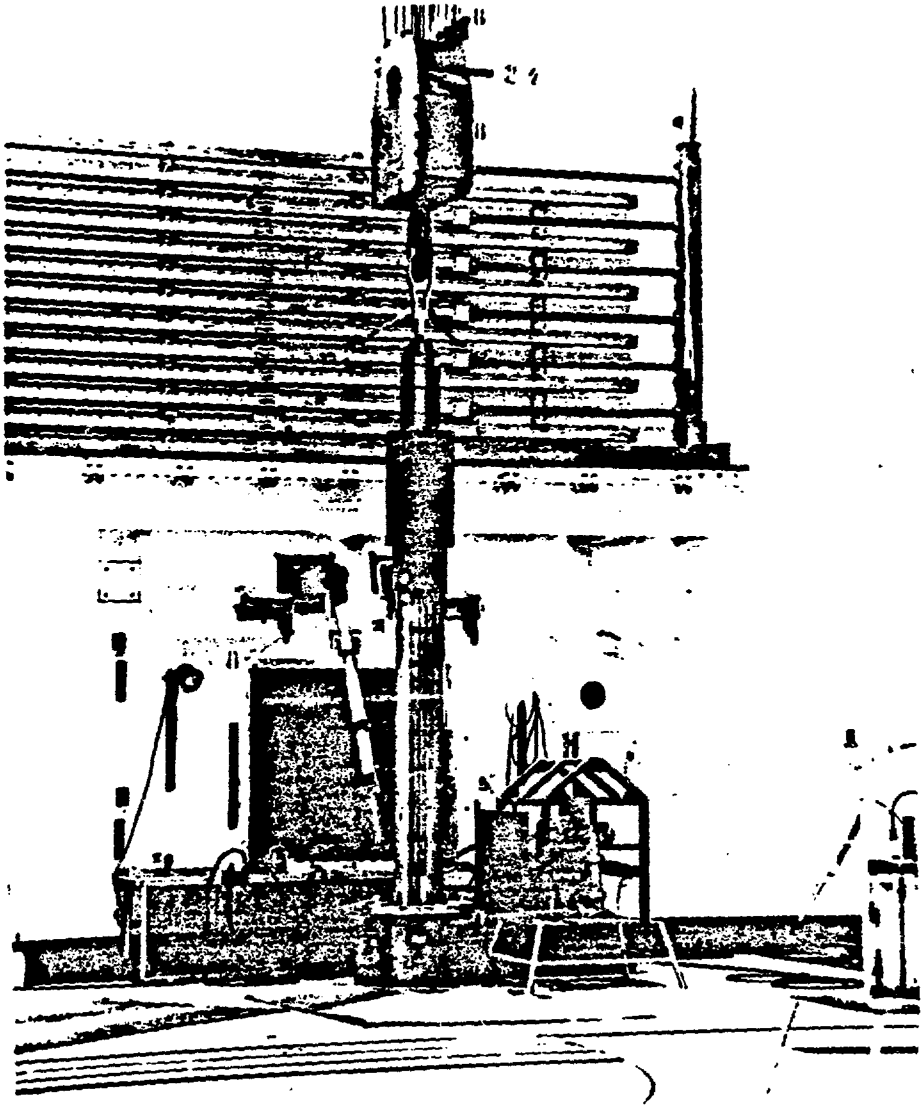


Fig. 22. Hot bay canister closure welding station.

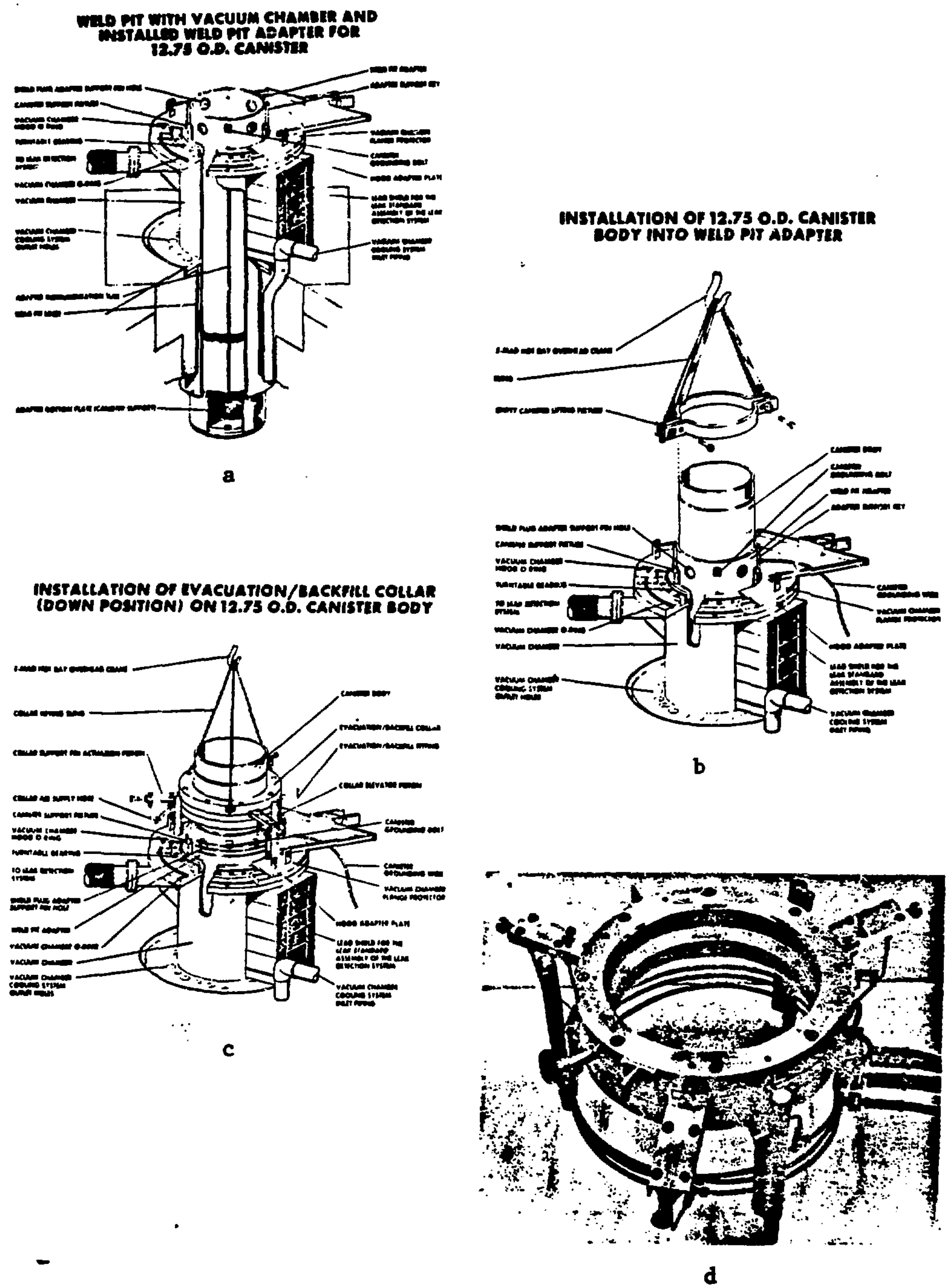


Fig. 23. Remote encapsulation process sequence.

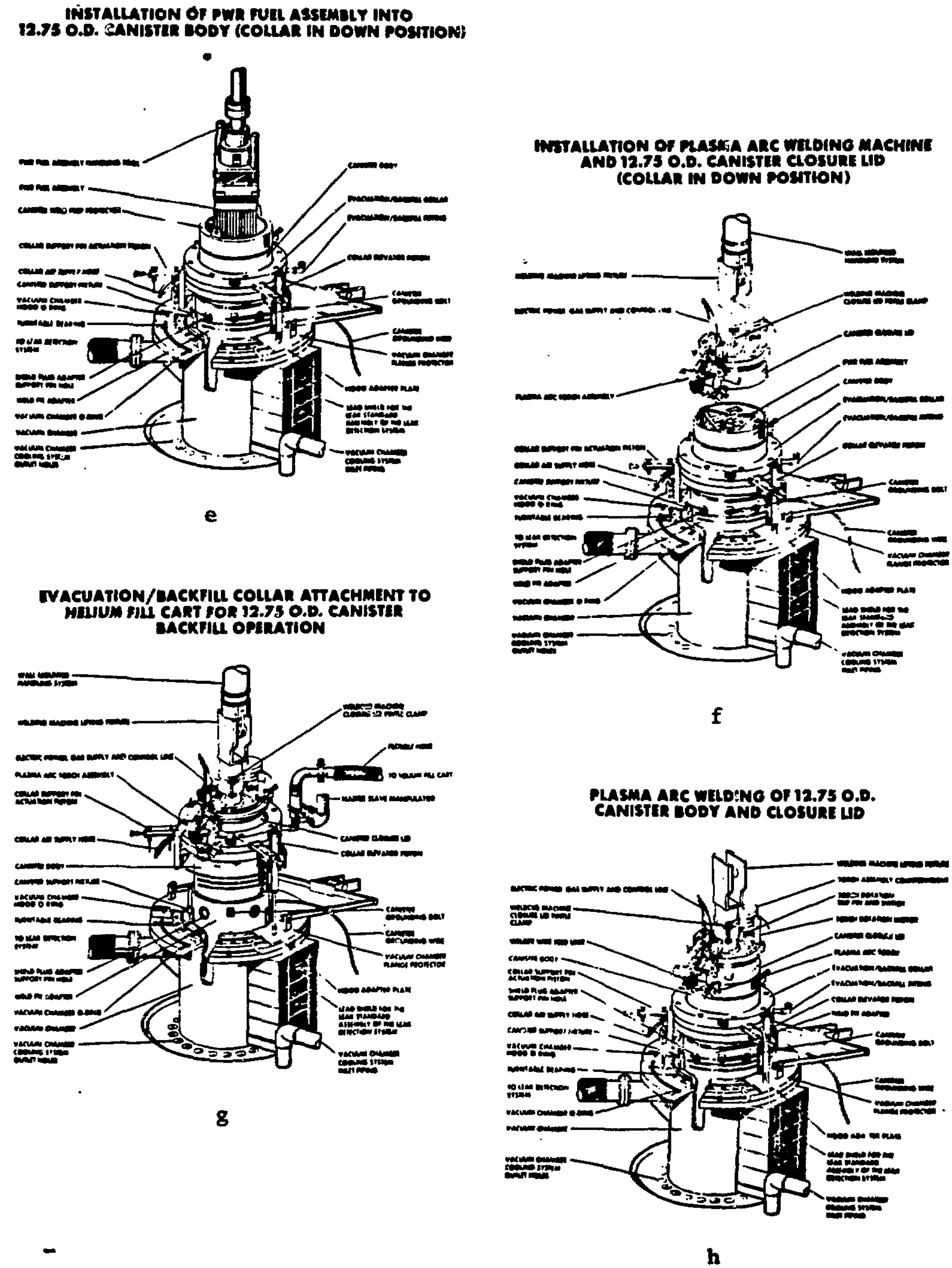
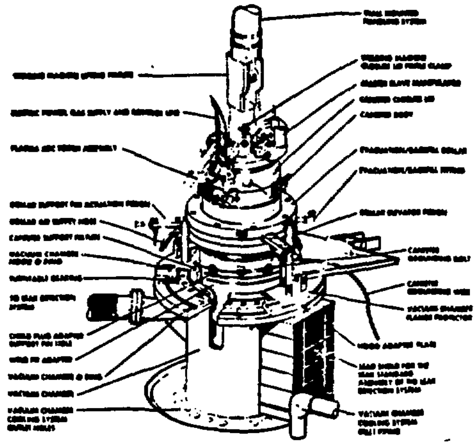


Fig. 23. Remote encapsulation process sequence.

REMOVAL OF PLASMA ARC WELDING MACHINE FROM 12.75 O.D. CANISTER ASSEMBLY



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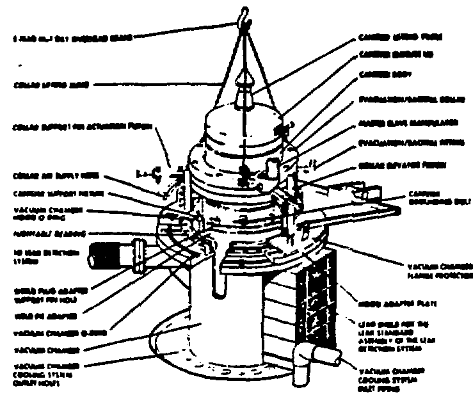
REMOVAL OF EVACUATION/BACKFILL COLLAR FROM 12.75 O.D. CANISTER ASSEMBLY



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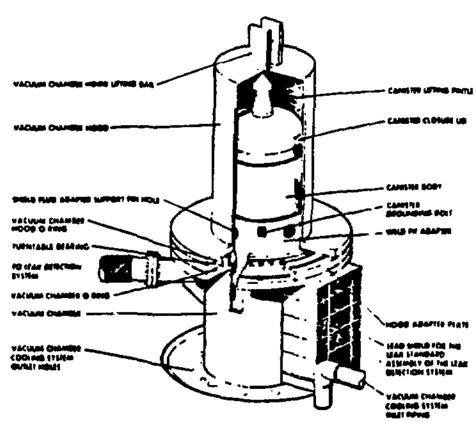
LEAK INSPECTION OF COMPLETED 12.75 O.D. CANISTER ASSEMBLY



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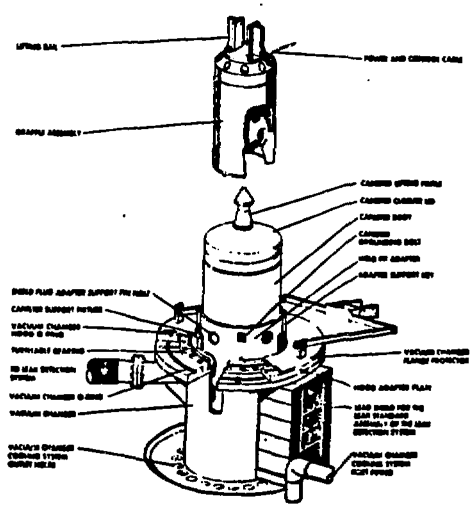
REMOV \L OF COMPLETED 12.75 O.D. CANISTER ASSEMBLY FROM WELD PIT



l

Fig. 23. Remote encapsulation process sequence.

CONCLUDING REMARKS

The selection of plasma arc welding for this remote, automatic closure application has been thoroughly substantiated by the results described herein. The advantages of the single-pass autogenous butt weld made using the keyhole technique are numerous in view of the apparent difficulties in controlling groove shape/volume and filler metal placement with the alternative GMAW and GTAW processes in the 2G position. Much has been learned regarding the equipment and procedural requirements for such a demanding application which would make the design and implementation of a second generation system a more straightforward undertaking. Nonetheless, the only significant disadvantage of the process is the present necessity to use a two-pass, filler-added termination procedure. We feel that a contiguous termination procedure is definitely achievable through further development.

Hardware having much less precisely controlled joint fitup dimensions than described here can definitely be accommodated through the use of automatic AVC, so long as the system is locked out during the transient stages of keyhole initiation and weld termination. In applications where bead shape requirements are less restrictive, the applicability of the process (and of a simpler termination procedure) appears even more favorable.

Although the nominal carbon steel thickness of the subject design is 0.25 in, mockups having up to 0.32-in wall thickness were welded successfully. For significantly heavier thicknesses a two-pass approach would be adopted. Using a part-through groove configuration, an autogenous butt weld would be made for the first pass, thus rigidly fixing the geometry of the remaining groove which would be filled with a second pass using the melt-in filler-addition technique. Similar 2G welding of the other base metals, incuding stainless steels, nickel-base and titanium alloys, appears eminently feasible.

ACKNOWLEDGMENT

The authors wish to acknowledge contributions made by the following personnel to the work described herein: Jane M. Branscomb, M. K. Brechel, D. E. Dickey, L. R. Eisenstatt, H. J. Grubich, D. F. Moran and F. L. Przywarty, Westinghouse AESD/Pittsburgh, PA; and D. B. Casey, J. S. Cummings, H. H. Irby, H. C. Snow and K. N. Stingley, Westinghouse/AESD Nevada Operations.

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