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WELDING AT THE KENNEDY SPACE CENTER

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ABSTRACT

Welding plays a major role in the design, manufacture, and construction of the ground support equipment at the Kennedy Space Center.

Three applications of welding are described, i.e., an example of the structural welding of a girder in a mobile launcher (presently designated mobile launcher platform), an example of the repair welding of crawler/transporter shoes, and an example of the welding of the liquid hydrogen and liquid oxygen storage spheres and vacuum jacketed piping in the propellants system.

This welding technology was developed during the Apollo and earlier programs. It is now being applied to the Space Shuttle.

KSC WELDING SPECIFICATIONS AND PROCESSES

The welding of GSE, at the Kennedy Space Center is specified in the design phase to meet certain engineering requirements. These requirements are stipulated in welding specifications generated in the Design Engineering Directorate of the Kennedy Space Center. A list of Kennedy Space Center (KSC) Welding Specifications is given in Table 1.

Gas tungsten-arc welding is the process most used on the critical piping of the major systems on the launch sites at the Kennedy Space Center. GTAW is used in welding the 36% nickel and stainless steel piping in vacuum jacketed lines in the propellants system. It is used to weld the aluminum alloy piping in the environmental control system. GTAW is used also in welding the high pressure piping in the pneumatic system.

The gas metal arc welding process was used in welding the vessels for liquid hydrogen and liquid oxygen storage in the propellants system.

The shielded metal-arc welding process (SMAW) and the submerged metal arc welding process (SAW) were used extensively on the heavy structural sections of the mobile launcher and the transporter/crawler.

The welding processes now used at the Kennedy Space Center are:

● Shield metal-arc welding (SMAW)
● Gas tungsten-arc welding (GTAW)
● Submerged arc welding (SAW)
● Induction brazing (IB)
● Torch brazing (TB)

WELDING MOBILE LAUNCHER GIRDERS

One typical application of structural welding is the welding of the girders in mobile launchers. There are several large girders in the base of a mobile launcher. One centrally located girder, (G-14), Figure 1, is described as typical. The girder is 135 feet long and 25 feet high. The web is constructed of steel plate 1½ inches thick. The top and bottom flanges are constructed of steel plate six inches thick.

The base metals used in the construction of the girder conform to ASTM A 36 Specification for Structural Steel and ASTM A 441 Specification for High Strength Low Alloy Structural Manganese Vanadium Steel.

The weld filler metal used for manual shielded metal arc welding was AWS A 5.1 Class E7018. The filler metal and flux combined in submerged arc welding were Grade SAW-2 of the American Institute of Steel Construction.

The girder was prefabricated at the contractor's plant in six parts, consisting of two identical end sections and four inner sections. These were massive parts, each weighing approximately 40 tons.

The six prefabricated parts of the girder were shipped to Kennedy Space Center where the field erection was performed at the mobile launcher (ML) parking site adjacent to the Vehicle Assembly Building (VAB). As this was to be the permanent parking site for the mobile launchers, it was covered with a level, hard top, asphalt surface. The geometry for the control of the erection of the mobile launchers was laid out on the asphalt surface of the parking site. The locations and dimensions of the cribbing and blocking needed for their construction were established on this layout.

The G-14 girder was assembled on the ML parking site in the following manner:

1. Initially, the four inner sections of the girder were fitted together on blocking sufficiently heavy to hold the dead weight and to facilitate maintaining the camber. They were braced in the vertical position with steel guy cables. The welds splicing together the four inner sections were made in the sequence 1, 2, 3 shown in Figure 2. This sequence minimized distortion and maintained the beam camber within the 9/16 inch tolerance for the complete girder. Camber was checked by periodic rod readings.

2. After the four inner sections were welded to-

gether on the blocking, the entire inner section subassembly was lifted onto false work supports set up in place at the final erection location of the girder on the parking site. The move was limited to one lift because of extreme weight. The subassembly was hung with its bottom flange at an elevation of approximately 20 feet from the ground. Here it was joined to other girders such as G-3 and G-9 shown in Figure 3. Next the end sections were lifted into place and splice welded in the sequence 4, 5, and 6 shown previously in Figure 2. During the welding of the end sections, they were bolted to the tripod-like mount mechanisms, Figure 3. The mount mechanisms are large screw jacks, permanently installed at the parking site to secure the mobile launchers during parking.

3. During the splicing of the girder, the flange was welded at six locations (Figure 2). These welds were applied in multiple passes using the submerged arc welding process. The joint design and welding data are shown in Figure 4. The flange splice welds were 100% radiographically inspected to UW 51 of the ASME Code.

4. The web was spliced by a total of 3968 inches of welding applied by the shielded metal arc welding process with E7018 electrodes. The joint design was an AWS prequalified type, B-U5 for the horizontal position and B-U3 for the vertical position. These welds were complete penetration groove welds qualified for unlimited thickness. The welding was radiographically inspected by spot-examination to UW-52 of the ASME Code.

5. Joints that bore identical sequence numbers were welded simultaneously.

6. All weld joints of the same sequence numbers were completed before starting joints having higher sequence numbers.

7. Shims 1/8 inch thick were placed between all erection angles at the splices to assure the butt weld root opening and to allow for shrinkage during the welding of web and flange joints.

8. Welded groove joints made without backing were back-gouged to sound metal by the air carbon-arc process before welding the opposite side.

9. Erection angles and runoff bars were removed after the welding was completed.

10. All layers in thick joints, except the first and last layer were allowed to be peened to reduce shrinkage and distortion.

The weld quality was maintained at a high level throughout the construction of the mobile launcher girders. The design specified radiographic inspection of the field splice welds in the girder flanges and girder webs. The requirement was radiographic inspection in accordance with UW-51 of the ASME Code for the girder flange splice welds and UW-52 for the web splice welds.

Fillet welds were inspected visually for size, contour and conformance to the acceptance standards specified in the design, (AWS D1.1), Bridge Code.

Certain large groove welds in heavy sections were inspected for cracks using the magnetic particle method of inspection.

The welding of girder G-14 is typical of the welding of the largest girders in the mobile launchers at the Kennedy Space Center. The girder was welded in accordance with Kennedy Space Center welding specification KSC-SPEC-Z-004, and AWS D1.1, Structural Welding Code, Section 9, Bridges. The girder is unique in its role of providing major support to loads in one of the largest existing mobile structures. The methods of welding, joint designs, and inspection methods are described.

As a final item of data of general interest, the total linear inches of welding on girder G-14 are tabulated in Table 2. Weld sizes and types range from ⅛ inch fillet welds to six inch thick butt welds in flange splices and column connections. The linear inches of welding of all types total 76,254 inches, or well over a mile of welding in the G-14 girder.

REPAIR WELDING OF CRAWLER TRANSPORTER SHOES

Crawler/transporter shoes are shown laid out for a periodic maintenance inspection in Figure 5.

Worn areas of the roller paths of shoes are rebuilt with weld metal, then machined to their original dimensions. Also, cracks particularly in lug areas are repaired by welding. The lugs function to retain connecting pins when the shoe is coupled into a belt. As part of the refurbishment, the bores of worn lugs are provided with hardened steel sleeves pressed into the lugs.

The shoes are manufactured of cast AISI86B30 steel. This is a quenched and tempered steel of relatively high tensile strength. The welding of this type of steel requires the use of special procedures, including a preheat and postheat treatment. The chemical analysis of the shoes is shown in Table 3.

The original heat treatment performed on each shoe was as follows:

1. Normalized at 1750°F for four hours and air cooled.

2. Draw at 1150°F.

3. Cleaned and shotblasted. Magnetic particle inspected.

4. Quenched and tempered. 1700°F for four hours and water quench. 1180° for four hours and water quench.

5. Shotblasted.

6. Magnetic particle inspected.

7. Repair welding necessary. If repair welded

then stress relieved at 1150° for four hours and water quenched.

The mechanical properties of the shoes are given in Table 4.

The need for a preheat treatment is illustrated by reference to an isothermal transformation diagram for the steel, Figure 6. An isothermal transformation diagram is a plot on cartesian coordinates of temperature versus time depicting the various metallurgical structures resulting from differerent cooling rates for a particular steel. The diagram shows that the weld and heat affected zone in this steel when cooled rapidly (1 minute or less) from above 1600°F to below 300°F will transform from the high temperature gamma iron or austenite phase to a hard, brittle martensite. The brittle martensite can cause the weldment to be low in impact properties and highly susceptible to cracking, obviously undesirable properties.

In contrast, if the weld is cooled more slowly or held sufficiently long above the martensite completion temperature, it will form a more ductile metallurgical structure, such as that consisting of a fine perlite and tempered martensite. In any case, the final metallurgical structure existing at room temperature is a function of the cooling rate. In general, the slower the cooling rate, the more ductile is the resulting metallurgical structure. This increase in ductility is associated with some reduction in strength. Therefore, it is desirable to determine the optimum metallurgical structure; i.e., one with adequate strength and good ductility. At this point, the logic of applying a preheat becomes apparent, because by means of a preheat, we can retard the cooling rate in the weld and thereby control the resulting metallurgical structure and associated weld properties.

Design Engineering initiated instructions that provided the guidelines for investigating a welding procedure for the repair welding of crawler/transporter shoes. By use of the isothermal transformation diagram, a range of preheat was established at 300°F to 500°F. Immediately after the completion of welding, the repaired shoe was raised in temperature to 600 ± 50°F, and maintained at this temperature for a minimum of two hours, then cooled at the rate of 100°F per hour to a temperature of 200°F after which it was cooled to ambient temperature with no further monitoring. The latter, postheat treatment was performed to diffuse out hydrogen that had been inducted by welding. The preheat and postheat control for welding was maintained by use of electrical resistance heating elements in a specially designed heat treatment oven shown in Figure 7. Electrical timers permitted the control of preheating overnight so that welding could begin at the start of the day shift. An AWS E-14018 type of self consuming welding electrode was applied to perform the welding using the manual shielded metal arc welding process. This electrode was developed under a Navy contract for welding HY 130 steels used in constructing nuclear submarine/pressure hulls. This electrode produces weld metal of 140,000 psi tensile strength that

matched the mechanical properties of the cast steel base metal in the shoe.

Welding electrodes are received in hermetically sealed containers to assure that their hygroscopic coatings do not absorb hydrogen in the form of water vapor. Immediately after opening the container, electrodes must be placed in a holding oven maintained at 250°F. Small portable holding ovens are located at the welding site for individual dispensing of electrodes. Each welder must not remove more than 20-minute supply of electrodes. Electrodes exposed to the atmosphere for more than 20 minutes must be rebaked at 750° ± 25°F for one hour in a vented forced air furnace with adequate temperature control. Electrodes must be placed in a holding oven immediately after rebaking and not rebaked more than one time. Electrodes that come into contact with grease, paint, water, or other contaminants must be discarded.

During the welding of quenched and tempered steels, the heat input must be carefully controlled to assure that the metallurgical structure of the weld is not adversely affected. If the weld structure is adversely affected by an incorrect heat input, the reaction is not reversible by heat treatment, and cracking may result. To control the heat input during welding, it is necessary to monitor the welding amperage, the welding voltage and the welding travel speed. Because of the importance of energy input, it is monitored in conjunction with preheat during the welding of quenched and tempered steels. It is measured in watt seconds or Joules per inch. For convenience, a simple formula can be used, as given:

$$\text{Energy Input} = \frac{\text{Amps x Volts x 60}}{\text{In. per Min (Weld Travel Speed)}}$$

The energy input limit is not as critical for thick sections as it is for thin sections. It was found not to pose a problem in the repair welding of the crawler shoes. To determine the affect of the welding parameters, including the preheating and postheating, trial welds were made and tested. The results of these tests showed that the properties of the weld metal and the weld fusion zone were good and the heat affected zone was acquiescent so that satisfactory mechanical properties were obtained. Welding in progress is shown in Figure 8. This procedure gave satisfactory results in the repair welding of crawler/transporter shoes. Results of weld metal mechanical property tests are shown in Table 5.

Three methods are used for inspecting shoes for cracks and other defects. They are the dye penetrant inspection, magnetic particle inspection and radiographic or x-ray inspection methods. A shoe being prepared for radiographic inspection is shown in Figure 9 on the turn table of the 20 million volt betatron x-ray facility. The betatron is capable of penetrating 16 inches of steel. It was used originally for x-raying solid rocket motors.

After the repair weld is built up on the roller path of a crawler shoe, the roller path is machined on a horizontal mill to its original contour

tolerances as shown in Figure 10.

Worn lug bores are repaired by press fitting sleeves into the lugs and reboring them to fit the pins. These sleeves are AISI 4340 steel of approximate 330 Bhn hardness. The addition of hard sleeves strengthens the bore and increases its resistance to wear.

The pins that attach shoes together to form the belt are of AISI 4130 steel. At present a study is being considered to investigate the metal spraying of the pins to hard surface them.

Finally the shoes are machined and ground around the lug areas to assure that adequate tolerances exist for clearance of moving parts without binding during the operation of the crawler belt.

PROPELLANTS SYSTEM WELDING

Typical examples of welding in the propellants system are the welding of the liquid hydrogen and liquid oxygen storage spheres, and the welding of vacuum jacketed piping. The plates for both storage spheres were cut to templates and dished to the proper spherical radii prior to their erection and welding in the field. The design of each plate allowed for shrinkage to permit each finished weld to blend at the joint to the overall spherical contour of the tank. In general, a transverse shrinkage of 3/32 inches was allowed for a weld seam. Each storage tank consisted of an inner sphere of Type 304 stainless steel and an outer sphere of carbon structural steel. The welding process used was gas metal arc welding (GMAW) with argon shielding gas. The weld filler metal used on the inner sphere welding was 0.045 inch diameter, E-308L stainless steel wire. A carbon steel filler metal was used for welding the outer sphere.

Liquid Hydrogen Tank

The liquid hydrogen system consists of a storage area, a transfer system and a venting system. The 850,000 gallon storage sphere has a 70 foot diam. outer shell of carbon structural steel, and an inner shell of Type 304 stainless steel. A four foot annular space between the inner and outer shells is filled with expanded perlite (volcanic glass) insulation and evacuated to a pressure of 50 microns of mercury absolute. The inner sphere is hung by stainless steel rods extending between the spheres at the equator. This design of support minimizes heat transfer. A photograph of the liquid hydrogen storage tank and some of its piping with a space vehicle in the background is shown in Figure 11.

The storage tank is designed to contain liquid hydrogen at 90 psig. The design also provides for the differential pressure resulting from the vacuum in the insulated space between the inner and outer spheres. The liquid hydrogen is low in density; consequently, its pressure and not its weight is the controlling factor in the design of

the tank. The thickness of the inner stainless steel sphere wall is 1.16 inches. A typical joint design is shown in Figure 12.

The 70 foot diam. outer sphere is of structural steel 11/16 inches thick. A typical weld joint design of the outer structural steel sphere shell is shown in Figure 13.

Liquid Oxygen Tank

The liquid oxygen system consists of the necessary facilities for the storage of liquid oxygen and for the transfer of liquid oxygen to the stages of the space vehicle.

The storage tank has a capacity of 900,000 gallons and consists of an outer sphere 70 feet in diam. of carbon structural steel, and an inner sphere of Type 304 stainless steel. The annular space between spheres is filled with perlit insulation and with nitrogen at a pressure slightly above atmospheric. The sphere is charged through a six inch fill manifold from self-unloading highway transports. Five inlet ports are provided on the fill manifold for this purpose. A partial view of the 900,000 gallon liquid oxygen (LOX) tank is shown in Figure 14.

The LOX storage tank is designed to contain liquid oxygen at 10 psig. Because liquid oxygen is relatively high in density, its weight becomes a significant factor in the design of the tank. The total weight of the liquid oxygen is equivalent to an additional calculated 30 psig. For this reason, the wall thickness of the inner sphere is graduated in four zones, Figure 15, with thinner plates at the top and thicker plates at the bottom. Joint designs for various plate thicknesses are shown in Figure 16 where the joints are referred to Table 6 which summarizes the joint design details.

The 70 foot diam. outer sphere of the liquid oxygen tank is made of structural steel 11/16 inches thick. A typical joint design used for this vessel is shown in Figure 17.

Fabrication of the liquid hydrogen and liquid oxygen storage spheres was performed in accordance with the ASME Boiler and Pressure Vessel Code, including procedure and operator qualification in accordance with Section IX. The welds in the liquid hydrogen and liquid oxygen storage tanks were radiographically inspected. The inner spheres of both the liquid hydrogen and liquid oxygen storage tanks were 100% x-rayed in accordance with paragraph UW 51 of Section VIII of the Code. The outer spheres of both tanks were spot checked by x-ray inspection in accordance with paragraph UW 52 of Section VIII of the Code.

After radiographic inspection, the storage tanks were leak tested and hydrostatically tested, then cold shocked. The leak testing of the liquid hydrogen tank was performed using a helium mass

spectrometer type of leak tester. The inner sphere was pressurized to 90 psig with a 20% helium-air mixture with a "full" vacuum in the annular space. The operating pressure for the liquid hydrogen inner sphere is 60 psig. The helium sensing pick-up was located in the annular space during the test which permitted a maximum leak rate of 10^{-7} atmospheric cubic centimeters per second. Subsequent to the helium leak testing, the inner sphere of the liquid hydrogen tank was hydro-pneumatically tested at 1¼ times the operating pressure. During the test, the inner sphere was partially filled with water to 1/16 capacity to simulate the weight of a full tank of liquid hydrogen. It was not possible to fill the tank full of water because the weight of a full tank of water would cause an excessive load on the inner tank supports and the column supports. Water is approximately 16 times heavier than liquid hydrogen. After hydro-pneumatic testing, the liquid hydrogen storage tank was cold shock tested with liquid nitrogen.

The liquid oxygen tank was leak tested by pressurizing the inner sphere with nominal pressure of gaseous nitrogen and applying a soap bubble test to the weld areas. Subsequent to the leak test, the inner sphere of the liquid oxygen tank was hydrostatically tested at 1⅓ times the design pressure of 18 psig. After hydrostatic testing, the liquid oxygen storage tank was cold shock tested with liquid oxygen prior to being placed in service.

Welding Vacuum Jacketed Piping

A sketch of a straight section of vacuum jacketed piping is shown in Figure 18. The inner pipe is Invar, an allow of iron containing 36% nickel. The principal property of Invar is its low coefficient of expansion in the operating range from ambient to minus 423 F. By specifying Invar to be in contact with the cryogenic fluid, the design engineer economizes on the use of expansion joints in the system.

The outer jacket is austenitic stainless steel pipe, AISI Type 304. Sections of VJ piping are fabricated in the shop. A minimum number of welds are made in the field. Sections are sometimes safe-ended with stainless steel to eliminate the need to weld Invar in the field because of the higher level of skill required.

The inner pipe is procured in random lengths to a specification that covers seamless or welded pipe, but it is usually supplied as lengths of welded pipe made from rolled Invar sheet. The longitudinal weld seam in this pipe can introduce a problem in making girth welds for spool pieces. It is advantageous to specifiy a filler metal of a modified chemistry described later for the longitudinal weld seam to minimize hot short cracking tendencies. The chemical composition of the Invar sheet is shown in Table 7 and the mechanical properties are shown in Table 8.

The 8 and 10 inch diam. sizes in Schedule 10 Invar pipe are the sizes used for the majority of the cross-country piping in the propellants systems. The permissible variation in diameter is 0.063 inches for this size range. The minimum wall thickness accepted is 12.5% under the nominal wall thickness specified. Ovality is maintained within 0.5% of the nominal diameter. The pipe is descaled but pickling in nitric-hydrofluoric acid is not permitted.

Type 304 stainless steel pipe for the outer jacket of VJ piping is procured to ASTM-A-312, which covers seamless or welded pipe. The pipe is pickled free from scale. Mechanical properties of the pipe are shown in Table 9.

The welding of vacuum jacketed piping is done in accordance with a KSC specification. An important item specified in the welding of Invar is the use of Invar filler metal of modified chemistry. Past experience at the Kennedy Space Center has shown that Invar can be hot short and can crack in the weld under some conditions of heat input and stress. A particular example was noted during the fabrication of girth welds in Invar pipe for the original Apollo ground support equipment. A crack sometimes occurred when the girth weld traversed the existing longitudinal seam weld in the Invar pipe.

This cracking occurred in the heat-affected zone of the girth weld and was located in the grain structure of the longitudinal seam weld. The cracking was intergranular in nature, and it was found to be associated with low melting point phases existing in the longitudinal seam weld grain structure. The condition was more pronounced when the longitudinal seam weld had been made with little or no filler metal added. The longitudinal seam may or may not have been planished after welding. Planishing obliterated any appearance of a seam and served to compound the problem by adding stress. To repair this type of cracking, it was found necessary to remove a portion of the longitudinal seam weld and reweld it, using a modified Invar filler metal before completing the girth weld.

To alleviate this hot short cracking condition caused by low melting point, grain boundary phases, a filler metal of modified Invar chemistry was developed. This "modified" Invar filler metal contains additives such as manganese and titanium that act as malleablizers. The composition of the modified filler metal, as shown in Table 10, is verified by mill certificate. Chemical analysis checks are made on Invar filler wire clippings at the Kennedy Space Center. Also, chemical analyses are made of weld metal pads to verify their specified chemistry.

In the weld puddle, manganese and titanium react to remove iron sulfides from grain boundaries, and with carbon they control nitrogen and oxygen in the melt. The experience at the Kennedy Space Center has been that the use of the modified Invar filler metal reduces hot short cracking tendencies and thereby improves Invar weld properties and enhances the performance of Invar welds.

Invar pipe is welded using the gas tungsten-arc

process with direct current, straight polarity. The welding current is limited to 70 A maximum to maintain a low rate of heat input to the base metal. The interpass temperature is limited to 250 F maximum. These limits are set to minimize any tendency toward hot short cracking. Argon gas is used as a shielding and purging gas, procured to MIL-A-18455. The girth welds in the 8 and 10 inch diam. pipe sizes are welded in two stringer passes. A consumable insert, 1/8 inch size MIL-I-23413, Group E, Type MIL-82, Class 1 is applied for the root pass. This insert is a nickel alloy of the following chemical composition (wt. %): 0.10 C, 2.50-3.50 Mn, 3.00 Fe, 0.015 S, 0.50 Si, 0.50 Cu, 67.0 Ni, 0.75 Ti, 18.0-22.0 Cr, 2.0-3.0 Cb. Modified Invar filler metal of the composition shown in Table 10 is used in the cover pass.

In the qualification of welding procedures, Invar pipe in the 8 and 10 inch diam. sizes, Schedule 10 is used as most representative of the propellant system pipe size requirements. The qualification is performed in the presence of a welding inspector. To be approved for all positions of welding, the procedure is qualified in the horizontal fixed and in the vertical fixed pipe positions. The Invar and the stainless steel pipe weld joint designs are shown in Figure 19.

Pipe sizing by metal removal is permitted if the wall thickness is not reduced more than 12.5%. External alignment clamps may be used in the assembly of the pipe for qualification tests during the fitting of the insert. The test coupon is shown in Figure 20 with the alignment clamps in place. After tack welding, the alignment clamps are removed prior to welding the test piece in the horizontal and vertical fixed positions.

The weld joint is cleaned by solvent cleaning using methyl ethyl ketone (MEK) followed by mechanical scraping and brushing with an austenitic stainless steel wire brush. The weld joint and two inches on each side of the weld joint are cleaned prior to welding. The welding rods and insert ring also must be clean. The welding inspector verifies the quality of cleaning and the preweld setup including pipe end preparations, alignment, groove dimensions and fitup tolerances of the weld test joint.

The pipe is purged and backed up with argon gas flowing at 10 cfh for 30 minutes prior to welding. Welding is performed using a 1/16 to 3/32 inch diam 2% thoriated tungsten electrode, The torch shielding gas is argon at a flow rate of 18 to 25 cfh.

Joints are inspected after each pass to assure that they are properly cleaned and free of defects. When welding in the horizontal fixed position, the weld beads are laid so as to overlap two inches at the bottom and at the apex. To keep the heat input low, stringer beads are used for all passes in all welds. After the completion of the test weld, the weld ripples are removed from the weld surface on the face and root by mechanical process to a surface finish of 125 rms. The test welds in Invar pipe are inspected using dye penetrants for surface cracks, then the welds are 100% x-ray in-

spected to determine if they meet the radiographic acceptance standards specified.

After radiographic inspection, the Invar test welds are cut into specimens for tensile and bend tests and metallographic examinations. The tensile test must give results equal to or better than the properties shown in Table 8. Typical tensile and bend test specimens are shown in Figure 21.

The welding of Invar to Type 304 stainless steel is qualified in the same manner as Invar to Invar joints, except that the filler metal specified for the cover pass is a nickel alloy, MIL-E-21562, Class 2, Type MIL-RN-82.

The welding of Type 304 stainless steel pipe for the outer jacket is qualified with the joint design shown in Figure 19, using Type 308 filler metal. The qualification test procedure requirements are similar to those required for fillet welds. The horizontal fixed and vertical fixed test joints combined qualify the procedure for all position welding.

It is apparent that Invar has some tendency to develop hot cracks that may go undetected. During the installation of the ground support equipment for the Apollo program, a test was devised to determine if existing cracks present in Invar welds would propagate under cyclic cold shock. A mockup consisting of a section of VJ pipe was manufactured, Figure 22. This mockup contained duplicate Invar-to-Invar pipe welds and duplicate Invar to stainless steel pipe welds in 8 inch diam. piping. Certain designated welds were defect-free and others contained "built-in" cracks and other defects.

One hundred cold shock cycles were applied to the mockup using liquid nitrogen as the shocking fluid. Accurate measurement of crack lengths were made before, during, and after completion of the testing. Examination revealed that no new cracks developed and that existing cracks did not propagate during cold shock testing. The fact that cracks did not propagate is attributed to the low coefficient of expansion of Invar and the thin wall of the 8 inch Schedule 10 pipe. The thermal stress is correspondingly low. these results increased the level of confidence in the Invar welds and indicated that long time cryogenic service would be satisfactory.

Techniques for fabricating vacuum jacketed piping have been developed at KSC over the span of years since this piping was first introduced into the early launch sites. Current design practice is to specify the reuse of materials that exist in spool pieces and lines available on the launch complex when modifying systems to reconfigure for new programs.

A sketch from a typical design calling for the reconfiguration of an existing spool piece to a new shape reusing the materials in the existing spool piece is shown in Figure 23. This sketch shows a sequence of welding, numerically called-out, step by step, to facilitate the reassembly welding to

the new design configuration. Working to such design "road maps", the shop has adopted techniques of cutting into existing spool pieces or lines to be modified, disassembling them into basic components, which then are reassembled into new configurations. This has evolved into a unique capability for designing, fabricating and installing VJ lines of various shapes and sizes.

When an existing section of VJ piping is to be reconfigured to a new design, it is first disassembled by cutting it into appropriate parts. This may be a single cut dividing it in two or it may be multiple cuts separating it into several sections as required by the new design. The cutting can be done using an abrasive cutting wheel or a portable saw or by using a dry running band saw. The outer jacket can be cut while the inner pipe remains intact, if desired, by restricting the depth of the cut.

Disassembly can be accomplished in the field, although it is preferable to bring the pipe section into the shop. Care must be exercised to avoid cutting into existing teflon spacers or getter material in the annulus. During the disassembly, the aluminum foil or aluminum mylar insulation near the saw cuts becomes frayed and contaminated with particles, and it must be cut back several inches with a sharp knife before replacement during the reassembly operation. If the outer jacket is removed from a section of VJ pipe, the aluminum insulation may be unwrapped from the inner pipe and stored on a commercially clean spool that is then sealed in a polyethylene bag for reuse during reassembly.

The first step in the reassembly procedures is to prepare the inner pipe for butt welding by milling bevels on the pipe ends. The inner pipe is Invar in most cases, but in some lines, it is Type 304 stainless steel. A specially fabricated internal plug and external ring clamp are installed to maintain the thin walled pipe end circular during machining until the pipe is tack welded to an adjoining section to facilitate the fitting operation. Welding is performed by applying the approved procedures previously described for the girth butt welding of Invar pipe.

A section of VJ piping is shown in Figure 24 during an early stage of its reassembly. An oxygen analyzer is being applied to check the oxygen content of the purged inner pipe during a welding operation. This instrument is used as an adjunct to the qualified procedure in the welding of Invar pipe. Although not a requirement, an oxygen content of 1% or lower is considered to be good practice in the production of welds of satisfactory quality.

All welds in the inner pipe are 100% radiographically inspected. The x-rays are made using a contact shot technique. Six exposures are made around the circumference of the 8 inch diam. inner pipe. The 100 kV x-ray equipment used is portable. It is mounted on a two wheeled cart similar to the type used for portable single unit oxyacetylene outfits. Radiographs were made of the Invar pipe welds using 90 kV, 8mA, and 1½ min exposures.

In addition to radiographic inspection, each weld is leak-tested using a helium mass spectrometer. The inner pipe containing the weld to be tested is sealed by applying aluminum plates against rubber gaskets coated with vacuum grease to each end of the pipe and evacuating the section as shown in Figure 25. A clear plastic hose coming from the vacuum pump on the leak tester is attached to a fitting in one of the aluminum plates. The inner pipe is evacuated to 50 microns. Helium gas is applied to the external face of the weld by means of a nozzle and hose attached to a bottle of helium gas. The leakage tolerance permitted at the weld is 10^{-9} standard (atmospheric) cubic centimeters per second of helium gas detection.

The weld is cleaned, and oxidation is removed using an austenitic stainless steel wire brush. Grease, oil and dirt, if present, are removed from the completed weld and pipe using Freon and a clean cloth.

The next step in the reassembly operation is the application of the insulation in areas where it had been removed during the disassembly. Because cleanliness is important, fabrication personnel are required to wear neoprene gloves. The insulation is trimmed back two inches on each side of the weld using a sharp clean knife or a razor blade. The trim line is then tapered from the surface of the pipe to the last layer of insulation for an additional two inches on each side of the weld, creating a beveled channel eight inches wide into which new insulation is applied. Aluminum foil insulation is applied by wrapping the first layer 30 deg to the right of vertical, and the second layer 30 deg to the left of vertical and continuing with alternate layers until the newly applied insulation is level with the existing insulation.

Teflon block spacers mounted in stainless steel straps are installed over the aluminum foil insulation at intervals to provide uniform spacing between the inner and outer pipes.

Next the outer jacket is fitted over the teflon spacers to mate with existing jacket ends. Sections of the outer pipe or jacket are joined by fillet welding a strap or sleeve slipped over the pipe ends, as shown schematically in Figure 23. This technique permits fitting and welding the jacket without the necessity for close tolerances in each length as required when butt welding. The welds in the outer jacket are 100% dye penetrant inspected.

After the completion of the welding of the outer jacket, a helium mass spectrometer vacuum leak test is conducted on the annulus similar to the one conducted on the inner pipe Invar welds. No leak detection of helium is allowed using a sensitivity of 10^{-9} SCC/second.

After the completion of the helium mass, spectrometer vacuum leak test, a hydrostatic proof test of the inner line is conducted at 1½ times the working pressure of the cryogenic line.

A cold shock test is performed by flowing liquid nitrogen through the inner pipe of the completed spool piece as shown in Figure 26. During the initial stages, a vapor discharges from the vent line. Cold flow is continued until liquid nitrogen is observed coming from the discharge end of the transfer line. The level of the vacuum in the annular space is recorded. The pressure must be less than 500 microns at this stage of fabrication.

The inner pipe of the spool piece is then cleaned in the cleaning facility in accordance with KSC specifications. A sequence of trichorethylene degreasing and phosphoric acid cleaning procedures are used.

After the spool piece has returned to ambient temperature, a hot gaseous nitrogen purge is applied to the annulus. Gaseous nitrogen at 180 F and 5 psig is flowed through the annular space for 20 h to dry it out.

A final vacuum pumpdown is applied to the annulus. During this step, hot gaseous nitrogen at 180 F and 10 psig is flowed through the inner pipe to provide a heat source for enhancing the vacuum pumpdown. The annulus is evacuated to 10 microns of mercury absolute pressure and sealed by closing the VJ pipe vacuum port valves. The hot gaseous nitrogen flow is terminated. A vacuum decay test is conducted. Absolute pressure in the annulus must measure below 10 microns of mercury after a 72 hour holding period.

Finally, all VJ pipe ports and end flanges are sealed with polyethylene sheet and bags until the spool piece is installed in the system. A positive purge pressure of gaseous nitrogen is maintained in the inner pipe during storage.

A heat loss determination has been made on fabricated spool pieces. This consists of flowing liquid nitrogen through the inner pipe while measuring heat loss by means of a heat loss sensor (calorimeter) attached to the outer jacket.

Vacuum jacketed piping was installed on the mobile launchers and on launch pads 39A and 39B for the Apollo/Saturn program. A view of a straight run of cross country VJ pipine is shown in Figure 27 extending from the liquid hydrogen storage tank to the launch pad on 39A and up the mobile launcher to the several swing arms servicing the space vehicle. The line branching off at approximately midway to the pad is a section of the hydrogen vent line that returns hydrogen gas boiled off from venting the space vehicle liquid hydrogen tanks during fueling. This goes to a hydrogen burn pond.

Liquid hydrogen and liquid oxygen piping installed at the base of a mobile launcher is shown in Figure 28. The liquid hydrogen lines are the three larger lines at the left hand center of the photograph, running horizontally to the center and up the mobile launcher. The middle line is the liquid hydrogen fill line. The bottom line is the line that vents the fuel tanks of the space vehicles second and third stages. The top line is the

vent from a helium heat exchanger wherein helium is cooled prior to pressurizing the space vehicle tanks for launch.

The liquid oxygen lines run in a configuration similar to the liquid hydrogen lines but are located on the mobile launcher at the right hand center of the photograph. The middle line is the 14 inch liquid oxygen fill line. The top line is the tank replenishing or topping-off line. The bottom line is the liquid oxygen tank vent line which goes to a dump basin on the pad where the vented liquid oxygen is disposed of by boiling it off to the atmosphere. A portion of the astronaut emergency egress chute can be seen at the right side of the photograph.

After several years of service during the Apollo/Saturn program, a modification was made to the VJ piping in the liquid hydrogen storage sphere fill line on launch pad 39B. This modification was necessary to avoid the recurrence of fatigue failures in expansion bellows in the outer jackets of the VJ piping in the liquid hydrogen transfer lines. A failure that is typical of the fatigue cracking experienced is shown in Figure 29. The design modification consisted of removing this type of expansion bellows from the system and replacing it with a new design using a larger convolate in the bellows. Whenever possible, the welding had to be done in the shop.

However, much of the welding had to be done in the field. For field welding, either a tarpaulin or plastic screen is set up to shield the weld from the wind. A weld being made in the overhead position with limited accessibility is shown in Figure 30.

The welds in the inner pipe were 100% radiographically inspected. An inner pipe weld being radiographically inspected in the field is shown in Figure 31. The isotope source is mounted on a tripod and focused on the weld at the proper focal distance. The film in a black cassette is taped to the back side of the weld. A penetrameter can be seen taped to the near side of the weld. The lead box container with part of the remote control cable and radiation counters are in the foreground. While this type of radiograph is being made, the immediate area is roped off and monitored by the Safety Office to protect personnel from hazardous radiation. Upon completion of the exposure time, the isotope is remotely cranked back into the lead container by the inspector, who then retrieves the exposed film for development and viewing. The welds in the outer jacket are inspected using dye penetrants.

After radiographic testing is completed, the welds are helium mass spectrometer vacuum leak tested in the field. Next, the system is hydrostatically tested at 1½ times the working pressure, cleaned, and then tested in an initial cold flow test prior to service.

Another application of a weld repair occurred when it became necessary to replace a damaged spool

piece in the liquid oxygen VJ piping on pad A. The spool piece was brought into the shop so that the damaged section of the inner pipe could be replaced. The damaged section was sawed out. A close view of the damage is shown in Figure 32. This crack was due to inadvertantly applying nitric acid instead of phosphoric acid during a pipe cleaning operation on the spool piece. The reduction of wall thickness in the vicinity of the crack resulting from the action of the nitric acid on the Invar pipe was visually apparent in a cross section. A new section of Invar pipe was welded into the spool piece in the shop, and, after inspection, the unit was hydrostatically tested. The spool piece is shown in Figure 33 undergoing a final machining operation while being vacuum leak tested with a helium mass spectrometer leak tester. Finally, the repaired spool piece was reinstalled in the propellants piping system.

To change from the Apollo/Saturn to the Skylab program, one mobile launcher was reconfigured to accommodate an S-IB type of launch vehicle. This required a modification to the liquid oxygen VJ lines on this mobile launcher. Existing VJ pipe sections and spare spool pieces were used to the maximum extent practicable in this modification. They were cut and reassembled in the shop into the modified configurations using the fabrication techniques previously described. Much of the work on individual sections was done in the shop. Completed sections and spool pieces were delivered to the Vehicle Assembly Building where they were installed on the mobile launcher undergoing modifications. Welding on this installation is shown in Figure 34, with safety nets and scaffolding deployed at weld stations. For this modification, it was required to maintain the interpass temperature below 150 F for certain welds. A welding inspector is shown in Figure 35 checking the interpass temperature of a weld on vacuum jacketed piping with a portable hand pyrometer.

Some areas on the mobile launcher are extremely limited in accessibility. One such area on an elevated platform on the mobile launcher is shown in Figure 36. Flanged fittings welded to VJ piping can be seen where a portion of the outer jacket has been removed temporarily to provide access for welding.

All welds on the inner pipe where sections of VJ pipe were joined together at the weld stations on the mobile launcher were 100% radiographically inspected in the field. A weld marked for radiographic inspection is shown in Figure 37. After the completion of welding on the modified liquid oxygen system, the sytem was hydrostatically tested and cold shock tested prior to putting the system into service for the Skylab program.

Some development work has been done on the automatic welding of vacuum jacketed piping at the Kennedy Space Center. A vacuum jacketed spool piece being fabricated in the shop using an automatic pipe welding process is shown in Figure 38. This and other piping such as piping for the hydraulic steering mechanism on the transporter/crawler have

been fabricated using an automatic welding process. However, due to the variety of the welding encountered, the more versatile manual welding takes precedence over automatic setups, which are better adapted to a more routine production line type of welding.

SUMMARY

Over the years spanning the implementation and growth of the space program, the Kennedy Space Center has developed a unique capability to design and fabricate ground support equipment. This has resulted in advancing the industrial technology in a number of areas including the area of welding technology. Welding specifications are established for ground support equipment and welding procedures have been qualified and proven for numerous applications, too voluminous to include in a single paper.

The applications described represent an attempt to provide some depth of coverage to the description of the welding of ground support equipment. However, the preponderance of additional material available must be omitted due to a limitation in writing space.

The welding technology developed during the Mercury, Gemini, Apollo, unmanned launches, and other programs is now being applied to design and fabricate the ground support equipment and facilities required for the Space Shuttle.

REFERENCES

(1) Clautice, W. E., "Welding at the Kennedy Space Center," Welding Journal, Vol. 52 (6) June, 1973, pp 364-371.

(2) Clautice, W. E., "Brazing at the Kennedy Space Center", Welding Journal, Vol. 53 (10) October, 1974, pp 612-622.

(3) Clautice, W. E., "Welding Vacuum Jacketed Piping at the Kennedy Space Center", Welding Journal, Vol. 54 (7) July, 1975.

TABLE 1 – KSC WELDING SPECIFICATIONS

KSC-SPEC-Z-0001	Invar Pipe, Specification
KSC-SPEC-Z-0002	Welding, Aluminum Alloy Pipe, Tubing and Associated Fittings, Specification
KSC-SPEC-Z-0003	Welding, Stainless Steel and Invar Pipe, and Associated Fittings, Specification
KSC-SPEC-Z-0004	Welding, Structural, Carbon Steel, Stainless Steel, Low Alloy Steel, and Aluminum Alloys, Specification
KSC-SPEC-Z-0005	Brazing, Steel, Copper, Aluminum, Nickel and Magnesium Alloys, Specification
KSC-SPEC-Z-0006	Induction Brazing, Aerospace Tubing Fittings, Specification
KSC-SPEC-Z-0010	Welding, High Yield Strength, Quenched and Tempered Alloy Steels, Specification
KSC-SPEC-Z-0016	Automatic Welding, Stainless Steel Pipe and Tubing, Invar 36 Pipe, Carbon Steel Pipe, Aluminum Pipe, Specification
AWS D1.1	Structural Welding Code
AWS A2.0	Welding Symbols Standard
AWS A3.0	Welding Definitions
ASME	Boiler and Pressure Vessel Code
ANSI B31.1	Pressure Piping Code
AISC	Manual for Steel Construction
KSC	Safety Manual

TABLE 2 LINEAR INCHES OF WELDS USED ON G-14

SUMMARY OF WELD LENGTHS

TYPE	LENGTH (INCHES)
TOTAL FILLET WELDS	61,966
TOTAL SINGLE GROOVE WELDS	6,867
TOTAL DOUBLE GROOVE WELDS	7,421
TOTAL WELDS IN G-14	76,254

FILLET WELDS

SIZE (INCHES) (FILLET LEG)	LENGTH (INCHES)
1/4	6,834
3/8	4,055
1/2	13,841
5/16	33,482
3/4	3,554
1	200
TOTAL:	61,966

SINGLE GROOVE WELDS

SIZE (INCHES) (DEPTH OF CROSS SECTION)	LENGTH (INCHES)
1/2	411
3/4	92
11/16	60
7/8	24
1	2,270
1-1/2	2,400
3	61
3-3/4	453
6	1,096
TOTAL:	6,867

DOUBLE GROOVE WELDS

SIZE (INCHES) (DEPTH OF CROSS SECTION)	LENGTH (INCHES)
1/2	72
5/8	52
3/4	1,721
1	1,608
1.1 4	3,968
TOTAL:	7,421

Table 3 — Composition of Shoes

Element	Wt. Percent
Carbon	0.27 to .033
Manganese	1.00 to 1.30
Phosphorous	0.043 Max.
Sulfur	0.043 Max.
Silicon	0.20 to 0.35
Chromium	0.50 to 0.80
Nickel	0.60 to 0.90
Molybdenum	0.25 to 0.35
Boron	0.0005 Min.

Table 4 — Mechanical Properties of Shoes

Tensile Strength	130,000 psi
Yield Strength	100,000 psi
Elongation	12%
Reduction of Area	25%
Impact Strength	15 ft lbs, Charpy V-Notch at −400°F
Hardness	285 to 331 Bhn

Table 5 — Weld Mechanical Properties

Preheat	Strength, PSI Tensile	Strength, PSI Yield
300–400°F	136,000	118,000
400–500°F	135,500	117,000

TABLE 6 — PLATE ORIENTATION DATA LIQUID OXYGEN INNER SPHERE

PLATE LOCATION	DESIGN LOAD	EQUIVALENT PRESSURE (PSIG)	EQUIVALENT PRESSURE KN/m^2	PLATE THICKNESS (INCHES)	PLATE THICKNESS (METERS)	JOINT DESIGN (See Figure 12)
Top	Retains 10 psig pressure	10	68.95×10^3	0.250	6.35×10^{-2}	A
Top to Middle	–	–		0.250 to 0.380	9.65×10^{-2}	Transition A to B
Middle	Retains 10 psig plus 1/2 pressure of 900,000 gallons LOX, 30/2 or 15 psig	25	17.24×10^4	0.380		B
Middle to Equator	–	–		0.380 to 0.538		Transition B to C
Equator	This is the area of attachment for structural loading. These plates take the reaction forces for the entire load so are the heaviest.	N/A Load based upon reaction forces.		0.538	13.67×10^{-2}	C
Equator to Bottom	–	–		0.538 to 0.425		See Note (a)
Bottom	Retains 10 psig + 30 psig pressure due to total weight of 900,000 gallons LOX or 40 psig.	40	27.58×10^4	0.425	10.79×10^{-2}	C

NOTE: (a) The transition joint design for joining equator plates to bottom plates is the same as the transition joint design B to C for joining middle plates to equator plates; that is, a double beveled scarf with 3 to 12 ratio reduction of the thicker plate.

Table 7 — Chemical Composition of Invar Sheet

Elements	Percent by weight
Carbon, max	0.10
Manganese, max	0.50
Phosphorus, max	0.025
Sulfur, max	0.025
Silicon, max	0.35
Nickel	35.0 — 37.0
Chromium, max	0.50
Molybdenum, max	0.50
Cobalt, max	0.50
Iron	Remainder

Table 8 - Mechanical Properties of Invar Sheet

Tensile strength, min, ksi (MN/m²)	65 (448)
Yield strength, min, ksi (MN/m²)	35 (241)
Elongation, min, percent	30

Table 9 - Mechanical Properties of Type 304 Stainless Steel Pipe

Tensile strength, ksi (MN/m²)	75 (517)
Yield strength, ksi (MN/m²)	30 (207)
Elongation, percent	35

Table 10 - Modified Invar Filler Metal Composition

Element	Percent by weight
Nickel	35.0 — 37.0
Manganese	2.0 — 3.0
Titanium	0.7 — 1.2
Carbon, max	0.10
Silicon, max	0.20
Iron	Remainder

FIGURE 2: FIELD ASSEMBLY AND WELDING SEQUENCE OF GIRDER G-14

FIGURE 3 - HANGING GIRDER G-14
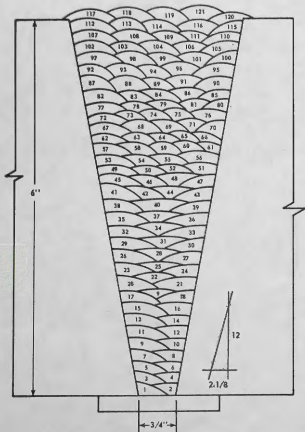
UMBILICAL TOWER
(REMOVED FOR RECONFIGURATION
FOR THE SPACE SHUTTLE)

MOBILE LAUNCHER

GIRDER G-14

FIGURE 1 - ORIENTATION OF GIRDER G-14 IN THE MOBILE LAUNCHER BASE

FIGURE 4 – WELDING DATA AND JOINT DESIGN
FOR THE FLANGE SPLICE WELDS

FIGURE 6 – ISOTHERMAL TRANSFORMATION DIAGRAM FOR 86B30
STEEL (U.S. STEEL ATLAS)

FIGURE 5 – CRAWLER SHOES LAID OUT FOR INTERIM INSPECTION

FIGURE 7 – HEAT TREATMENT OVEN USED FOR CRAWLER SHOE REPAIR WELDING

4-92

FIGURE 8 - REPAIR WELDING A CRAWLER SHOE

FIGURE 11 - LIQUID HYDROGEN STORAGE SPHERE
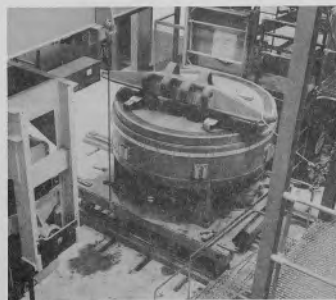
FIGURE 9 - RADIOGRAPHIC (X-RAY) INSPECTION OF A CRAWLER SHOE
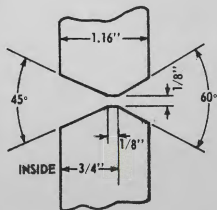
FIGURE 12 - TYPICAL JOINT DESIGN LIQUID HYDROGEN INNER SPHERE

FIGURE 10 - MACHINING A CRAWLER SHOE AFTER WELDING
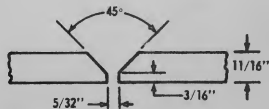
FIGURE 13 - TYPICAL JOINT DESIGN LIQUID HYDROGEN OUTER SPHERE

FIGURE 14 - LIQUID OXYGEN STORAGE SPHERE

JOINT A

TRANSITION JOINT A TO B

JOINT B

Transition Joint B to C

Joint C

FIGURE 16 - TYPICAL JOINT DESIGNS LIQUID OXYGEN INNER SPHERE

TOP PLATES

MIDDLE PLATES

42'-44'

RADIUS 31'- 4 7/16"

EQUATOR

EQUATOR PLATES

9 Ft.

BOTTOM PLATES

__INSIDE SPHERE ELEVATION__

FIGURE 15 - PLATE ORIENTATION ELEVATION, LIQUID OXYGEN INNER SPHERE

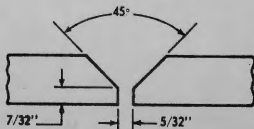FIGURE 17 - TYPICAL JOINT DESIGN LIQUID OXYGEN OUTER SPHERE

NOTES:

1. THE INNER PIPE IS INVAR CONFORMING TO KSC-SPEC-Z-0001, 6 INCH, SCHEDULE 5 (0.109" WALL THICKNESS)
2. THE OUTER JACKET IS STAINLESS STEEL PIPE, AISI TYPE 304, 8 INCH, SCHEDULE 5, ASTM A312.
3. WELDING IS AS SPECIFIED IN KSC-SPEC-Z-0003.
4. STAINLESS STEEL END CAPS ARE REMOVED AFTER LEAK TESTING AND HYDROSTATIC TESTING.
5. THE ANNULUS IS MAINTAINED AT 50 MICRONS OF MERCURY ABSOLUTE PRESSURE TO INSULATE INNER PIPE CONTAINING CRYOGENIC FLUID FROM CONDUCTING AND CONVECTION HEAT FLOW FROM THE ATMOSPHERE AT AMBIENT TEMPERATURE.
6. THE INNER PIPE IS INSULATED FROM RADIANT HEAT BY ALUMINUM FOIL, ALUMINZED MYLAR OR SIMILAR MATERIAL WRAPPED AROUND THE O.D. OF THE INVAR PIPE. TEFLON SPACERS ON STAINLESS STEEL STRAPS ARE USED TO POSITION THE INNER PIPE CONCENTRICALLY FROM THE OUTER PIPE.
7. GETTER MATERIAL IS INSTALLED IN THE ANNULUS TO ALLEVIATE OUTGASSING.

FIGURE 18 – VACUUM JACKETED PIPING – STRAIGHT SECTION

INNER PIPE – INVAR BUTT WELD JOINT DESIGN

OUTER JACKET – FILLET WELDS JOINING SECTIONS USING A STAINLESS STEEL BAND
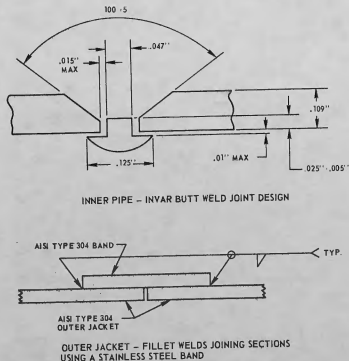
FIGURE 19 – TYPICAL JOINT DESIGNS DEVELOPED FOR WELDING VJ PIPING
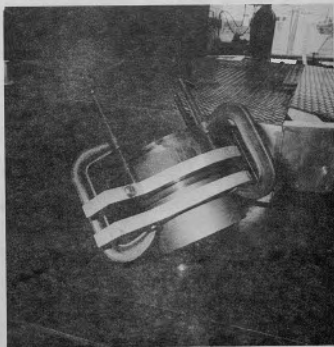
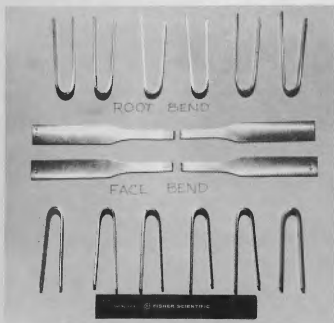FIGURE 20 – ALIGNMENT CLAMPS ATTACHED TO A QUALIFICATION TEST COUPON

FIGURE 21 - TENSILE AND BEND SPECIMENS FROM AN
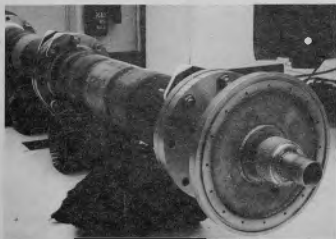INVAR WELD QUALIFICATION TEST

FIGURE 24 - OXYGEN ANALYZER BEING APPLIED DURING AN
EARLY STAGE OF THE FABRICATION OF A VJ SPOOL PIECE

FIGURE 22 - MOCKUP FOR CYCLIC COLD SHOCK TESTING WELDS

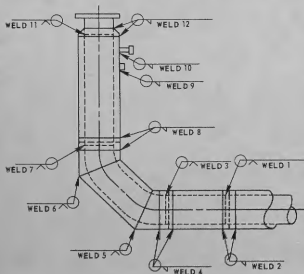
FIGURE 25 - HELIUM MASS SPECTROGRAPHIC LEAK TESTING

FIGURE 23 - TYPICAL WELDING SEQUENCE FOR FABRICATING A
VACUUM JACKETED SPOOL PIECE

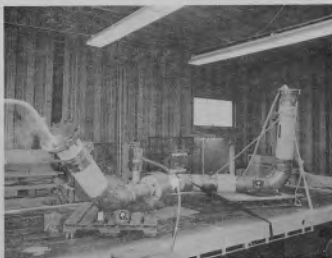FIGURE 26 - COMPLETED VJ SPOOL PIECE UNDERGOING
FINAL COLD SHOCK TESTING

FIGURE 27 - VACUUM JACKETED PIPING INSTALLED IN A
CROSS COUNTRY RUN AT A LAUNCH SITE

FIGURE 29 - FATIGUE CRACK IN THE CONVOLUTE
OF AN EXPANSION BELLOWS IN A VJ PIPE

FIGURE 28 - VACUUM JACKETED PIPING INSTALLED
AT THE BASE OF A MOBILE LAUNCHER

FIGURE 30 - WELDING VJ PIPING OVERHEAD ON THE LAUNCH SITE

FIGURE 31 - FIELD RADIOGRAPHIC INSPECTION OF AN INVAR
PIPE WELD IN VACUUM JACKETED PIPING

FIGURE 33 - VACUUM JACKETED SPOOL PIECE BEING HELIUM MASS
SPECTROGRAPHIC LEAK TESTED DURING FINAL MACHINING IN THE
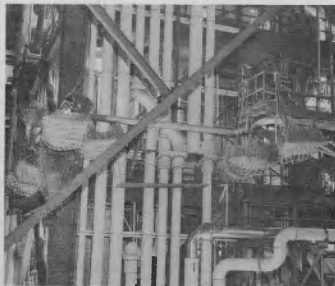LAUNCH EQUIPMENT SHOP

FIGURE 34 - WELDING VJ PIPING TO MODIFY THE LIQUID OXYGEN
PROPELLANTS SYSTEM ON A MOBILE LAUNCHER IN THE VEHICLE
ASSEMBLY BUILDING

FIGURE 32 - SECTION OF DAMAGED INVAR PIPE

FIGURE 35 - INSPECTOR CHECKING THE INTERPASS TEMPERATURE
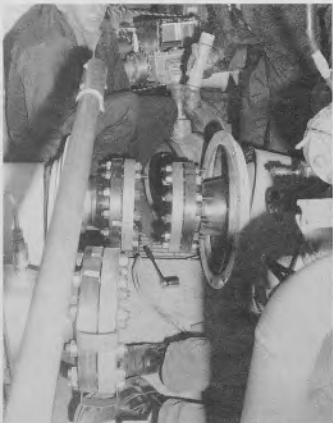ON A WELD IN VACUUM JACKETED PIPING

FIGURE 36 - VACUUM JACKETED PIPING ON A MOBILE LAUNCHER IN AN AREA
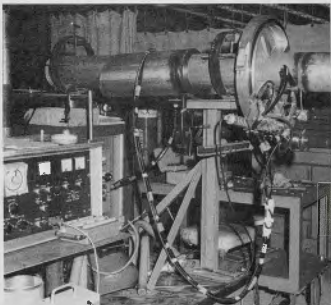OF LIMITED ACCESSIBILITY FOR WELDING

FIGURE 38 - AUTOMATIC PIPE WELDING SETUP ON VJ PIPING IN THE SHOP

FIGURE 37 - INVAR WELD IN VJ PIPING ON A MOBILE LAUNCHER
MARKED UP FOR X-RAY INSPECTION