WELDED REPAIR OF FILL AND DRAIN HOLES IN HIGH-CARBON STEEL GAS STORAGE CYLINDERS

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Y-12 PLANT
Oak Ridge, Tennessee

UNION CARBIDE CORPORATION
NUCLEAR DIVISION

Operating the
OAK RIDGE GASEOUS DIFFUSION PLANT
OAK RIDGE Y-12 PLANT

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Y-12 PLANT

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Oak Ridge, Tennessee
July 13, 1964
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ABSTRACT

Stress calculations based on the ASME Code requirements for a 1500-psig working pressure indicated that 63 gas storage cylinders would be operating at or above the yield point of the base metal adjacent to their 3/4-inch fill and drain holes which are located in the head knuckle radius. They would be subject to catastrophic failure since they are operating below their NDT, as shown by drop-weight tests on the base material.

The cylinders were forged from steel having a nominal composition of 0.50% carbon and 1.60% manganese. Due to the composition of the metal and the fact that the plug-type repair would be accessible from one side only, a specialized welding procedure was developed to effect a full-penetration weld.

Material used in the investigation was taken from a cylinder that was made available for the test. All test weldments received complete nondestructive inspection after fabrication in addition to the standard guided-bend test recommended by the ASME Boiler and Pressure Vessel Code. Tensile, hardness traverses, metallography, drop weight, and impact tests were also utilized in the evaluation.

With proper welding procedures it was demonstrated that the cylinders could be welded to withstand the pressure allowed by the ASME Code Case 1205-4. The stress-relieved sections of the cylinders containing the plug welds shifted the Charpy V-notch transition curve about 100°F lower than the normalized-only (no temper) base material. The integrity and safety of the repaired cylinder exceeds that of the existing normalized cylinder with holes, as shown by the fracture resulting from the burst test of the test cylinder.
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INTRODUCTION

The Y-12 Plant helium-argon gas storage facility contains 62 cylinders that are 24 inches OD by 38 to 40 feet long and have a 1/2-inch wall thickness. The cylinders are located on above-ground structural supports.

These cylinders were fabricated to military Specification MIL C-7127-1 dated March 23, 1951, normalized only, and YS-1196. The chemical composition of the forged steel is equivalent to SA372 Type IV. They were hydrostatically tested to 2800 psig prior to drilling and tapping 3/4-inch ips fill and drain holes in the knuckle radius of each cylinder head.

Stress calculations(1) based on ASME Code requirements for a 1500-psig working pressure indicated the vessels would be operating at or above the yield point of the base metal adjacent to the holes. When the wall thickness and the stress at the holes were considered, a maximum allowable working pressure of only 400 psig could be allowed. Thus, the cylinders could not be considered the equivalent of ASME Code vessels and safe to operate without a large reduction in working pressure.

In July 1962 a proposal by the Engineering Division(2) was made to investigate and develop a full-penetration, plug-type welding procedure for repair of the existing fill and drain holes. As an interim safety measure the working pressure of the cylinder was set at 1000 psig.

A close study of the ASME Code Section VIII Part UF entitled "Requirements for Un-fired Pressure Vessels Fabricated by Forging" indicates that welded repair of base metal defects and welded attachments to vessels during fabrication is permissible if the requirements outlined in the following paragraphs are fulfilled.

Par UF-5 (General)

"(b) The ladle analysis of forgings to be fabricated by welding shall not exceed 0.35 percent carbon. When the welding, however, involves only minor non-pressure attachments, as limited in Par UF-32; or repairs, as limited in Par UF-37, the carbon content shall not exceed 0.50 percent by ladle analysis. When, by ladle analysis, the carbon content exceeds 0.50 percent, no welding is permitted."

Par UF-32 primarily provides for certifying the welding procedure and operator in accordance with Section IX and also defines the inspection requirements of the completed weld for material exceeding 0.35 percent carbon.

Par UF-37 provides for and defines the type of repair permissible in two classes of base materials depending on carbon content. Since the cylinders exceed 0.35 percent carbon, Par UF-37(b) is quoted as follows:
"(b) Thinning to remove defects beyond those permitted in Par UF-30 may be repaired by welding, only after approval by the inspector. Defects shall be removed to sound metal as shown by acid etch or any other suitable method of examination. The welding shall be as outlined below:

(2) Material having carbon content over 0.35 percent (by ladle analysis).

(a) Welding repairs shall conform with Par UF-32(c) except that if the maximum weld depth exceeds 1/4 inch, radiography, in addition to magnetic particle inspection or liquid penetrant shall be used."

From this information it can be seen that the proposed repair does not fall within the scope of the fabrication requirements of the code for two reasons:

1. The carbon content of the cylinder base materials exceeds 0.35 percent. Repairs to base metal defects only or nonpressure attachments are permitted above this range.

2. The cylinders are existing and permanently installed, therefore repairs would be under the jurisdiction of the local inspection agency and would be subjected to their approval per National Board of Boiler and Pressure Vessel repair rules.

Since the proposed repair would not meet the established parameters for welding forged material, as outlined in the ASME Code, the welding procedure investigation and repair procedure would have to establish criteria that would equal or exceed the code requirements and permit approval of the repaired cylinders.

These criteria have been established with good results as shown in this study and demonstrated by burst tests of the cylinder.

Welding of high-carbon manganese steels is not new. However, on pressure vessels, welding has been limited to nonpressure-type seal weldments or structural attachments. During welding the steels are susceptible to cracking if high-carbon untempered martensite is allowed to form. As this report will show, cracking can be successfully avoided by the proper selection of weld filler metals, joint design, and welding procedure. In arriving at the joint design used for repair and evaluation of the test cylinder, the following objectives and problems were investigated:

1. Since access for welding was from one side only (the outside), the weld joint design had to be a single "V" or "U" configuration.

2. Joint preparation and welding was to be done in place under "field" conditions.

3. The 3/4-inch threaded holes required drilling or reaming to a larger size in order to provide a weld joint and to remove all contaminants used in attempts to seal the threaded plugs.
4. Cleanliness of the cylinder had to be maintained to insure high gas purity and to prevent the malfunction of valves or instruments by such foreign matter as drill chips, weld slag, and scale.

5. The completed weldment had to be the equivalent of a double butt-welded joint; i.e., full uniform penetration and be free of objectionable defects such as cracks and stress risers.

6. The strength, ductility, and impact properties of the weld and heat-affected zones had to meet or exceed the minimum properties of the normalized and stress-relieved base material.

The four joint designs considered for repairing the cylinders, as shown in Figure 1, had the objective of providing relative economical joint preparation, easy fit up and alignment of the plug, full uniform root pass penetration, and controlled shrinkage by minimizing the number of weld passes. Design C proved to be the most satisfactory and met all inspection and test requirements.

![Figure 1. PROPOSED JOINT DESIGNS.](image-url)
SUMMARY

Fill and drain holes for hydrostatic pressure tests were drilled and tapped into the head knuckle radius of forged-steel gas storage cylinders. These cylinders had a nominal composition of 0.50% carbon and 1.60% manganese and dimensions of 24 inches OD by 40 feet long and a wall thickness of 1/2 inch.

Due to the location of the holes they were considered serious stress risers. Stress calculations based on ASME Code requirements for a 1500-psig working pressure indicated that the cylinders would be operating at or above the yield point of the base material adjacent to the holes.

In the interest of safety the operating pressure was set at less than 1000 psig, and an investigation was initiated to develop a full penetration plug-type welding procedure for repairing the holes.

A close study of the ASME Code rules for fabrication indicated that the proposed repair would not meet the established parameters for welding forged material. Therefore, the welding procedure investigation would have to establish criteria that would equal or exceed code requirements and permit approval of the repaired cylinders.

To establish these criteria, an existing cylinder was made available for use as base material in a four-phase investigation:

1. The base material was evaluated to determine its properties as (1) normalized, (2) stress relieved at 1100°F, and (3) stress relieved at 1150°F. Charpy V-notch impact specimens, tensile tests, and drop-weight tests were utilized in this evaluation.

2. Standard welding procedure qualification tests were conducted to assure a good match in the physical properties of the base material and the filler metal. In addition to the standard guided side-bend test (as recommended by the ASME Boiler and Pressure Vessel Code), tensile, hardness traverse, metallography, radiography, and magnetic particle tests were also utilized.

3. Joint qualification tests were also utilized although not required by ASME Code rules. Standard guided side-bend tests, radiography, magnetic particle tests, and metallography were utilized in this evaluation.

4. A proof test cylinder was fabricated and tested to destruction to establish the safety and integrity of the repair.

The results of this investigation can be summarized as follows:

1. Based on the drop-weight tests of the cylinder base material used in developing the welding procedure, the nil ductility temperature (NDT) of the normalized
material is 120° F. It is, therefore, logical to assume that all cylinders would be operating below their NDT and could result in a catastrophic failure at ambient temperatures.

2. The 1150° F stress-relief treatment shifted the transition curve 100 degrees lower than the as-received (normalized only) base material. The NDT in the 1150° F stress-relieved condition is 20° F.

3. Tensile, bend, drop-weight, and Charpy V-notch tests have shown that the welding procedure developed for this material plus proper preheat and postheat treatment have provided a good match in the physical properties of the base material and the filler metal.

4. Full-penetration, plug-type welds equivalent to a double butt-welded joint can be accomplished satisfactorily from one side only—the outside.

5. Although ASME Code Case 1205-4 allows a maximum design stress of 1/3 the minimum tensile value for steel of this analysis, it forbids welding and also limits the placement of holes no larger than 3/4 inch in areas that are not stressed above 1/6 of the minimum tensile value. Using the welding procedure established by this investigation it was demonstrated that the fill and drain holes in the cylinders could be eliminated by welding, and the repaired cylinders would withstand the maximum working pressure allowed by the ASME Code and Case 1205-4.

6. The integrity and safety of the repaired cylinder exceeds that of the normalized cylinder with holes, as shown by a proof (burst) test of the cylinders.
INVESTIGATION OF THE WELDING PROCEDURE

MATERIALS AND APPARATUS

Base Materials

Since base material that conformed to the requirements, as specified for the fabrication of the cylinders, was not available for weld procedure investigation, an existing cylinder was used for fabricating the test plates and proof testing the cylinder. The chemical analyses and physical properties of the steel, as certified by mill test report, are given in Table 1.

Stress relieving temperatures of 1100 and 1150°F for one hour were applied to sections of the cut-up cylinder. Tensile and Charpy V-notch impact test specimens were machined from: (1) the as-received, normalized-only material; (2) the 1100°F stress-relieved sections, and (3) the 1150°F stress-relieved sections. The minimum yield strength requirement on the original specification was 80,000 psi. Table 1 also includes the results of the material as received, 1100°F stress relieved, and 1150°F stress relieved. It will be noted that the 1150°F stress relieved gives the lowest yield strength but is still above the 80,000-psi minimum. The as-received material had the highest yield strength.

Figure 2 shows the Charpy V transition curves for the three conditions of the steel, i.e.: (1) as received, (2) 1100°F stress relieved, and (3) 1150°F stress relieved. The most striking thing about these curves is the dramatic shift to lower temperatures as a result of the stress-relieving treatments. As can be seen, the 1150°F stress-relief treatment experienced a 100-degree lower shift; the 1100°F stress-relief treatment about an 80-degree shift.

Drop-weight tests were made on the as-received and 1150°F stress-relieved material. The hard surface bead was deposited on the specimens without any preheat being used. The results, shown in Figure 3, compared favorably with the Charpy curves, and the NDT(3, 4) was established to be 120°F for as-received and 20°F for 1150°F stress-relieved material.

Weld Filler Metals

Table 2 summarizes the chemical analysis of the welding rod and electrodes used. The MIL 11018 electrode conforms to ASTM A316-58T, E110-18G. The remaining rod and electrodes are manufacturers' grades and are not classified to AWS ASTM Specifications.

To prevent moisture pick up, the MIL 11018 electrode was stored in the manufacturer’s container in an oven at 125°F until used.
Equipment

To meet the quality requirements established for repairing cylinders, the root pass is made by the inert gas-shielded, tungsten-arc (TIG) process. In addition, the back side or internal surface of the weldment was blanket ed with inert gas. A fixture was fabricated from a section of the available cylinder to restrain the test plates and to provide gas coverage to the back or bottom side during welding.

The power supply used for welding was a 200-ampere selenium rectifier equipped with a high-frequency unit to initiate the tungsten arc, and a foot-operated remote-control unit and micro switch for extinguishing the tungsten arc.

A standard water-cooled, inert gas-shielded torch was used for making the tungsten-arc portion of the welds.

A portable 400-cycle, 30-kw induction stress-relieving machine was used for the preheat and postheat treatments. The motor-generator unit was equipped with all controls necessary for programming the complete preheat and stress-relieving cycle.

Induction heating coils used on all work, with exception of the plug weldments in the test cylinder, were hand wound on the work piece. A special coil with attached ceramic insulation was designed and fabricated for use on the ends of the test cylinder, as shown in Figure 4. This arrangement permitted fast and economical installation and removal of the coil.

To prepare the weld joint in the cylinder, an electromagnetic base drill with a clamp-on fixture was used, as shown in Figure 5. Drill and counter sink tool bits were fabricated from standard carbon steel drill stock. A variac was used to control the revolutions per minute of the drill.

To provide adequate gas coverage to the root or inside surface of the plug weldment and to eliminate complete purging of the cylinder, a purge fixture was utilized.

EXPERIMENTAL INVESTIGATION

Procedure Qualification

Since the dimensions of the welding groove are not essential variables for procedure qualification, eight single-but type test joints were prepared with the standard 75-degree included angle and 1/16-inch-thick lands. Assembled test plate dimensions were 1/2 by 7 by 12 inches with the 12-inch-long weld joint being in the circumferential axis of the cylinder base material. Test plates were sandblasted and degreased to remove all scale and foreign material and then were spaced and clamped in the welding fixture to provide a minimum root gap opening of 1/8 inch before tack welding. The test plate was covered with ceramic insulation and the induction heating coil wrapped to provide access for welding the joint. The welding groove was
Table 1
CHEMICAL ANALYSIS AND PHYSICAL PROPERTIES OF THE BASE MATERIAL

<table>
<thead>
<tr>
<th>Part(1)</th>
<th>Cylinder Number</th>
<th>Heat Number</th>
<th>Heat Code</th>
<th>C (%)</th>
<th>Mn (%)</th>
<th>Mg (%)</th>
<th>P (%)</th>
<th>S (%)</th>
<th>Si (%)</th>
<th>Chemical Analysis</th>
<th>Ultimate Strength(2) (psi)</th>
<th>Tensile Strength (psi)</th>
<th>Elongation(3) (%)</th>
<th>Reduction in Area (%)</th>
<th>Ratio of Yield Strength to Tensile Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>33</td>
<td>24339</td>
<td>112</td>
<td>0.48</td>
<td>1.57</td>
<td>0.24</td>
<td>0.021</td>
<td>0.26</td>
<td>0.18</td>
<td>Ladle</td>
<td>83,900</td>
<td>129,300</td>
<td>16.5</td>
<td>24.8</td>
<td>0.649</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Check</td>
<td>0.51</td>
<td>1.57</td>
<td>0.23</td>
<td>0.021</td>
<td>0.25</td>
<td>0.20</td>
<td>Flatening Test to 5.4 Inches - Satisfactory</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Part(1)</th>
<th>Cylinder Number</th>
<th>Heat Number</th>
<th>Heat Code</th>
<th>C (%)</th>
<th>Mn (%)</th>
<th>Mg (%)</th>
<th>P (%)</th>
<th>S (%)</th>
<th>Si (%)</th>
<th>Chemical Analysis</th>
<th>Ultimate Strength(2) (psi)</th>
<th>Tensile Strength (psi)</th>
<th>Elongation(3) (%)</th>
<th>Reduction in Area (%)</th>
<th>Ratio of Yield Strength to Tensile Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Some Chemical Analysis</td>
<td>92,800</td>
<td>133,400</td>
<td>17.7</td>
<td>0.703</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Some Chemical Analysis</td>
<td>89,900</td>
<td>116,800</td>
<td>20.3</td>
<td>0.770</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Some Chemical Analysis</td>
<td>85,000</td>
<td>115,000</td>
<td>21.3</td>
<td>0.739</td>
<td></td>
</tr>
</tbody>
</table>

(1) A. Data provided by certified mill test report.
B. Mechanical properties of Cylinder 33 in the normalized condition - by UCC-ND.
C. Mechanical properties of Cylinder 33 in the 1100°F stress-relieved condition - by UCC-ND.
D. Mechanical properties of Cylinder 33 in the 1150°F stress-relieved condition - by UCC-ND.

(2) 0.2% offset value in UCC-ND tests.
(3) In two inches in Part A, in one inch for UCC-ND tests.

Table 2
CHEMICAL ANALYSIS AND MECHANICAL PROPERTIES OF THE FILLER ROD AND ELECTRODE

<table>
<thead>
<tr>
<th>Electrode Classification</th>
<th>Size (in)</th>
<th>Heat Number</th>
<th>C (%)</th>
<th>Cr (%)</th>
<th>Cu (%)</th>
<th>Mn (%)</th>
<th>Mo (%)</th>
<th>Ni (%)</th>
<th>Fe (%)</th>
<th>Chemical Analysis</th>
<th>Ultimate Tensile Strength (psi)</th>
<th>Tensile Strength (psi)</th>
<th>Elongation (%)</th>
<th>Reduction in Area (%)</th>
<th>Charpy Impact Value</th>
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<tbody>
<tr>
<td>MIL 11018</td>
<td>1/8</td>
<td>2D178(1)</td>
<td>0.04</td>
<td>0.08</td>
<td>1.58</td>
<td>0.38</td>
<td>2.07</td>
<td>0.02</td>
<td>0.02</td>
<td>0.32</td>
<td>0.22</td>
<td>0.00</td>
<td>99,300(2)</td>
<td>118,500</td>
<td>23</td>
</tr>
<tr>
<td>AS16</td>
<td>3/32</td>
<td>9515(1)</td>
<td>0.14</td>
<td>-</td>
<td>1.95</td>
<td>0.53</td>
<td>-</td>
<td>0.010</td>
<td>0.015</td>
<td>0.040</td>
<td>-</td>
<td>-</td>
<td>103,800(3)</td>
<td>116,500</td>
<td>24</td>
</tr>
<tr>
<td>Inco 82</td>
<td>3/32</td>
<td>7864(1)</td>
<td>0.03</td>
<td>0.06</td>
<td>19.86</td>
<td>0.03</td>
<td>1.60</td>
<td>2.70</td>
<td>72.80</td>
<td>0.008</td>
<td>0.30</td>
<td>0.11</td>
<td>0.42</td>
<td>-</td>
<td>40,000(4)(5)</td>
</tr>
<tr>
<td>Inco 182</td>
<td>1/8</td>
<td>5732(1)</td>
<td>0.02</td>
<td>0.04</td>
<td>16.19</td>
<td>0.04</td>
<td>6.60</td>
<td>2.34</td>
<td>71.45</td>
<td>0.007</td>
<td>0.12</td>
<td>3.14</td>
<td>-</td>
<td>45,000(4)(5)</td>
<td>80,000</td>
</tr>
<tr>
<td>Inco-Weld A</td>
<td>1/8(4)</td>
<td></td>
<td>0.10</td>
<td>0.50</td>
<td>13.00</td>
<td>0.50</td>
<td>6.00</td>
<td>1.00</td>
<td>0.50</td>
<td>1.00</td>
<td>0.50</td>
<td>-</td>
<td>40,000(4)(5)</td>
<td>80,000</td>
<td>30(4)</td>
</tr>
</tbody>
</table>

(1) Certified analysis and properties.
(2) As welded.
(3) Heat treated.
(4) Manufacturer's typical analysis and properties.
(5) 0.2% offset.
sealed with glass tape so that the gas purge could escape only through the weld joint and at one end of the fixture.

Joint Qualification

As pointed out earlier, selection of the joint design for repairing the cylinders was based on economical joint preparation, easy fit up and alignment of the plug for welding, full uniform root pass penetration, and controlled shrinkage by minimizing the number of weld passes.

Of the four designs proposed for the repair, as shown in Figure 1, Designs B and D were disqualified prior to machining test plates for two reasons, i.e.: (1) machining cost of the plug would be high, and (2) maintaining the land thickness necessary for root-pass penetration and uniformity was impossible due to the curvature or radius of the cylinder shell. Design A was disqualified prior to machining the test plates since the angle of the joint in the shell would have to be approximately 50 to 60 degrees to permit proper access for welding and controlled penetration. Fusion would also be difficult on the straight side of the plug, and shrinkage stresses in the shell side of the joint would probably be hard to control.

Five test plates measuring 7 by 10 inches were removed from the cylinder and were prepared for welding by machining Design C (Figure 1). In the first test plate, the hole simulating that to be used in the cylinder was drilled to 1 1/4-inch diameter. The joint was beveled to $37^\circ_{2}^0$ degrees with a $1/16^+_0^1/64^-$ inch land. A one-inch-diameter plug was removed from the cylinder base material and machined to the same angle and land dimensions as the hole in the plate. Test plates and plugs were
cleaned and set up for welding in the same manner as that used for the procedure qualification test plates with the exception of the fit up and alignment of the plug. This step proved to be a problem since it was desired to maintain a 1/8-inch root gap for control of first-pass penetration and crater cracks. Misalignment of the plug with respect to the inner and outer surfaces of the cylinder would also introduce notches or stress risers. The problem was solved by using the fixture shown in Figure 6. The plug was press fitted into the fixture and the complete assembly dropped into the hole for a satisfactory fit up. The assembly was then preheated, the plug tack welded, and the fixture removed for completion of the weld joint.
WELDING DETAILS OF THE TEST JOINTS

Procedure Qualification

All welding was performed by a welder who was certified for both the manual tungsten-arc welding process and the shielded metal-arc welding process for carbon and austenitic stainless steels.

Seven test joints were welded to completion according to the welding procedure test data given in Table 3. Preheat and postheat treatments were used on all test weldments with exception of Test Plate 3. To eliminate all possible arc strikes on the base material, a high-frequency unit was used to initiate the arc for all inert-gas, tungsten-arc-weld passes.
Test Plate 1 - After the preheat temperature reached 500° F, the induction heat was turned off and the test plate demagnetized prior to depositing three 1/2-inch-long tack welds in the joint. These welds were located at each end and at the center of the joint. Root gap spacing after tack welding was maintained at 1/8 +0.32 inch. The first pass was deposited with a 3/32-inch Inco 82 bare rod. Filler metal was added in short jabs to the front edge of the molten weld pool at an angle of 20 to 30 degrees. Weld Passes 2 through 11 were completed with the 1/8-inch Inco 182 electrode. The standard "T" start with the arc being initiated on the deposited weld metal was used with the coated electrode. No difficulty was experienced with either filler metal during welding.

Test Plate 2 - The welding procedure for this joint was modified from that used in Test 1 by lowering the preheat to 450° F and using the 3/32-inch AS16 filler metal for the first pass. The addition of filler metal was accomplished by the drag technique; ie, the rod is never withdrawn from the molten weld pool and is added to the pool at an angle of 5 to 15 degrees. Weld Passes 2 through 12 were completed with the 1/8-inch Inco 182 electrode. The AS16 filler metal tended to be viscous and some trouble with porosity was experienced.
Test Plate 3 - The procedure for this plate was modified from that used in Tests 1 and 2 in that no preheat was applied and no purge gas was used on the root side of the joint. The first pass was deposited using the 3/32-inch AS16 filler metal. Both techniques for the addition of bare rod filler metal, as described under Tests 1 and 2, were used. The plate was rejected after the first pass due to excessive porosity and oxidation.

Test Plate 4 - The procedure used for this plate differed from that used in Test 2 in that the preheat temperature and welding amperage were increased slightly and the dip-type technique for the addition of filler metal was used. Deposition characteristics of the AS16 filler metal improved since it tended to provide a better flow or wash for the joint sides.

Test Plate 5 - This plate was welded to completion using the 3/32-inch Inco 82 rod for the first pass and 1/8-inch Inco "A" electrode for Passes 2 through 12. No difficulty was experienced with either filler metal during welding.
<table>
<thead>
<tr>
<th>Test Plate</th>
<th>Pass</th>
<th>Filler Metal</th>
<th>Preheat (°F)</th>
<th>Polarity</th>
<th>DC Current</th>
<th>Tungsten Electrode Size (in)</th>
<th>Torch Cup Size (in)</th>
<th>Argon Flow (cft)</th>
<th>Postheat (°F)</th>
<th>Pass Sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Inco 82</td>
<td>500</td>
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<td>75</td>
<td>3/32</td>
<td>6</td>
<td>25</td>
<td>None</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2-11</td>
<td>Inco 182</td>
<td>500</td>
<td>Reverse</td>
<td>85</td>
<td>-</td>
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<td>-</td>
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</tr>
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<td>2</td>
<td>1</td>
<td>AS16</td>
<td>450</td>
<td>Straight</td>
<td>75</td>
<td>3/32</td>
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<td>25</td>
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</tr>
<tr>
<td></td>
<td>2-12</td>
<td>Inco 182</td>
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<td>Reverse</td>
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<td>3/32</td>
<td>-</td>
<td>-</td>
<td>None</td>
<td>1150</td>
</tr>
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<td>AS16</td>
<td>None</td>
<td>Straight</td>
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<td>3/32</td>
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<td>25</td>
<td>None</td>
<td>Joint Reverted on First Pass</td>
</tr>
<tr>
<td></td>
<td>2-12</td>
<td>Inco 182</td>
<td>480</td>
<td>Reverse</td>
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<td>3/32</td>
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<td>-</td>
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<td>2-12</td>
<td>Inco 182</td>
<td>480</td>
<td>Reverse</td>
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<td>3/32</td>
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<td>480</td>
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<td>3/32</td>
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<td>-</td>
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</tr>
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<td>460</td>
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<td>130</td>
<td>3/32</td>
<td>-</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
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<td>MIL 11018</td>
<td>460</td>
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<td>140</td>
<td>3/32</td>
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<td>-</td>
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<td>25</td>
<td>60</td>
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</tr>
<tr>
<td></td>
<td>2</td>
<td>MIL 11018</td>
<td>500</td>
<td>Reverse</td>
<td>130</td>
<td>3/32</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Same as TP 2</td>
</tr>
<tr>
<td></td>
<td>3-12</td>
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<td>Reverse</td>
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<td>3/32</td>
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<td>25</td>
<td>60</td>
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<tr>
<td></td>
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<td>MIL 11018</td>
<td>500</td>
<td>Reverse</td>
<td>95</td>
<td>3/32</td>
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<td></td>
<td>3-13</td>
<td>MIL 11018</td>
<td>500</td>
<td>Reverse</td>
<td>145</td>
<td>3/32</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>Same as TP 2</td>
</tr>
</tbody>
</table>
Test Plates 6, 7, and 8 - The procedure used for welding all three of these plates was essentially the same except for variations in the preheat and postheat, in the purge gas volume, and the addition of one more tungsten arc and coated electrode weld pass in Pass 8.

Joint Qualification

All welding was performed by the same welder who performed the procedure qualification tests.

Five test joints were welded to completion as shown by the joint qualification test data in Table 4.

Test Plate 11 - After the fixture was removed from the tack-welded plug, both tack welds were feather ground on each end to aid in uniform fusion and penetration during the pass to the tack weld. The first pass was deposited counterclockwise using the 3/32-inch AS16 filler metal in two steps; i.e., tack weld to tack weld 180 degrees and repeated on the opposite side. The second pass was deposited in the same manner but the start and stop locations were rotated 90 degrees from those used in the first pass. Passes 3 through 13 were completed using the MIL 11018 electrode.

The 75-degree included-angle joint design proved to be unsatisfactory for two reasons: (1) the volume of weld deposit that was required to fill the joint resulted in excessive shrinkage (the inner surface of the plug was approximately 1/8 inch below the test plate surface after completion of the weld), and (2) interpass temperature was excessive since the plug mass was too small for the heat input.

Test Plate 12 - The angle of the plug was reduced from the 37 +2 degrees used in Plate 11 to 15 degrees. This change resulted in an included angle joint design of 52 +2 degrees. The first two passes were deposited with the AS16 filler metal with no apparent difficulty. Passes 3 through 6 were completed with the MIL 11018 electrode. The change in joint design reduced the number of weld passes that were required to complete the joint and also solved the shrinkage and interpass temperature problems.

Test Plates 13, 14, and 15 - These were completed with the same joint design as used in Test 12. With the exception of the number and thickness of the passes, the procedure was the same.

All bare rod filler metal passes were run with a short arc maintained at all times. The first or root pass was of the stringer type, and where a second pass was used it was a modified-weave type and did not exceed 1/4 inch in width. Where the drag technique was used with the bare AS16 wire, porosity was encountered. Slight agitation of the molten weld pool by the dip technique eliminated this problem. Each pass was wire brushed and irregularities and craters were hand ground with a Carboloy steel burr in an air-operated tool grinder.
<table>
<thead>
<tr>
<th>Test Plate</th>
<th>Pass</th>
<th>Filler Metal</th>
<th>Preheat (°F)</th>
<th>DC Current</th>
<th>Tungsten Electrode</th>
<th>Torch Cup Size</th>
<th>Argon Flow (cfm)</th>
<th>Postheat (°F)</th>
</tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Polarity</td>
<td>Amperes</td>
<td>Volts</td>
<td>Size (in)</td>
<td>Torch Backup</td>
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<td>1</td>
<td>A-5-16</td>
<td>470</td>
<td>Straight</td>
<td>100</td>
<td>12</td>
<td>3/32</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>A-5-16</td>
<td>470</td>
<td>Straight</td>
<td>130</td>
<td>14</td>
<td>3/32</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>3 - 13</td>
<td>MIL-11018</td>
<td>470</td>
<td>Reverse</td>
<td>140</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>A-5-16</td>
<td>440</td>
<td>Straight</td>
<td>100</td>
<td>12</td>
<td>3/32</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>A-5-16</td>
<td>440</td>
<td>Straight</td>
<td>130</td>
<td>14</td>
<td>3/32</td>
<td>6</td>
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<tr>
<td></td>
<td>3 - 6</td>
<td>MIL-11018</td>
<td>440</td>
<td>Reverse</td>
<td>140</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>A-5-16</td>
<td>520</td>
<td>Straight</td>
<td>100</td>
<td>12</td>
<td>3/32</td>
<td>6</td>
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<td>500</td>
<td>Straight</td>
<td>130</td>
<td>14</td>
<td>3/32</td>
<td>6</td>
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<td></td>
<td>3 - 6</td>
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</tr>
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<td>14</td>
<td>1</td>
<td>A-5-16</td>
<td>470</td>
<td>Straight</td>
<td>85</td>
<td>12</td>
<td>3/32</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2 - 9</td>
<td>MIL-11018</td>
<td>470</td>
<td>Reverse</td>
<td>140</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>15</td>
<td>1</td>
<td>A-5-16</td>
<td>450</td>
<td>Straight</td>
<td>90</td>
<td>12</td>
<td>3/32</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>A-5-16</td>
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<td>Straight</td>
<td>120</td>
<td>13</td>
<td>3/32</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>3 - 7</td>
<td>MIL-11018</td>
<td>450</td>
<td>Reverse</td>
<td>130</td>
<td>20</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
A close arc was maintained at all times with the coated electrodes. Weld passes were both stringer and weave types; however, the maximum width of weave did not exceed four times the electrode diameter. The MIL 11018 electrode had exceptionally good operating characteristics and was virtually self cleaning if the weld passes were deposited properly. After removal of the slag, all passes were wire brushed. All craters and surface irregularities were hand ground with a Carboloy steel burr in an air-operated tool grinder.

Each test weldment was preheated and maintained at a temperature of 400 to 500° F, as indicated by thermocouple and recorders and surface pyrometer. The induction heat was turned off and the plate demagnetized prior to welding. After welding was completed and prior to stress relieving all weld reinforcement, arc strikes and other imperfections were removed and ground flush and smooth with the test plate surface.

After grinding was completed, the stress-relieving cycle was started. The heating and cooling rates were approximately 200° F/hr. Weldments were held at the stress-relieving temperature for approximately one hour per inch of metal thickness. The heating coil and insulation was removed after the temperature had dropped to 200° F on the cooling cycle.

TEST RESULTS

Inspection and Test Requirements

The quality requirements established for the test weldments were as follows:

1. The root pass "push through" or reinforcement could not exceed 3/32 inch in height and must be uniform in contour.

2. Defects such as cracks, incomplete penetration or fusion, and undercutting was not permitted.

3. Porosity, slag, or other inclusions greater than size fine for plate thickness from 1/4 to 1/2 inch, or in excess of half the amount permitted by the ASME porosity standards for this thickness, were not permitted.

To meet these requirements: (1) each pass was visually inspected under low-power magnification, (2) each test weldment was magnetic particle tested after grinding and stress relieving, and (3) each completed test plate was radiographed per requirements of Par UW-51, ASME Code Section VIII.

Procedure Qualification

Of the eight procedure qualification test plates that were started, Test Plate 3 failed to pass visual inspection due to gross porosity in the first pass and was not completed.
Plates 1 and 2 also contained porosity in the first pass but were repaired satisfactorily and completed. The remaining seven test plates all passed the magnetic particle test with no cracks or subsurface defects noted.

All plates with exception of Plate 2 passed the X-ray requirements with no defects or only minute porosity noted. Plate 2 was rejected due to a slag inclusion approximately 1/4-inch long, but was subjected to other tests for informational purposes. Figure 7 shows a radiograph of completed Test Weldment 7. Note the size and depth of the base metal defects in relation to the porosity size in the weld deposit.

![Radiograph of Test Joint 7](image)

**Figure 7. RADIOGRAPH OF TEST JOINT 7.**

**Joint Qualification**

Of the five joint qualification test plates started, Plate 11 failed to pass visual inspection due to excessive shrinkage during welding. The remaining four plates passed the magnetic particle test requirements.

Plate 12 failed to pass the X-ray requirements due to gross porosity at the weld-to-tack weld interface. This area was transverse to the weld axis and was approximately
1/4-inch long. Plate 13 was classed as borderline due to scattered porosity, Plate 14 passed with only minute scattered porosity, and Plate 15, as shown in Figure 8, passed with no defects.

![Figure 8. RADIOGRAPH OF TEST JOINT 15.](image)

Bend Tests

Standard transverse side-bend coupons (3/8" x 1/2" x 7") were removed from the seven completed procedure qualification test plates for the standard guided bend test. Typical specimens, as bent, are shown in Figure 9.

**Test Plate 1** - Of six specimens tested, five were bent 180 degrees and were free of defects. One specimen failed by complete fracture after bending approximately 20 degrees. No defects were noted in the fracture but the test weldment was rejected because the yield strength of the weld metal was too low.

**Test Plate 2** - Of six specimens tested, all were bent 180 degrees and were free of defects. The AS16 root pass filler metal was almost completely removed during the machining of the side-bend specimens; however, the specimens were not under tolerance for the bend test. As in Test Plate 1, the yield strength of the weld metal was too low.
Figure 9. TRANSVERSE SIDE-BEND SPECIMENS FOR PROCEDURE QUALIFICATION.

Test Plate 4 - Of six specimens tested, five were bent 180 degrees and were free of defects. One specimen failed by complete fracture after bending approximately 150 degrees. No defects were noted in the fracture but the yield strength of the weld metal was again too low.

Test Plate 5 - Of five specimens tested, four were bent 180 degrees and were free of defects. One specimen failed by complete fracture after bending approximately 85
degrees. No defects were noted in the fracture but the weld metal yield strength was too low.

Test Plate 6 - Of six specimens tested, all bent 180 degrees with none free of defects. One specimen had a defect measuring 3/64 inch. The remaining three specimens had from one to two defects measuring less than 1/64 inch in length. Although all specimens met the bend-test requirements, the yield strength and elongation did not meet the minimum requirements.

Test Plate 7 - Of five specimens tested, all bent 180 degrees with none free of defects. The remaining three specimens had one defect each with the largest not exceeding 1/16 inch in length. The AS16 root pass section of these specimens was interesting since the metal appeared to kink. This property was attributed to the difference in yield strengths of the base material and the two filler metals. All specimens met the bend-test requirements and, for the first time, all physical requirements were met.

Test Plate 8 - Of seven specimens tested, all were bent 180 degrees with none free of defects. The remaining three specimens had one defect each with none exceeding 1/64 inch in length. All specimens met the bend-test requirements and all physical requirements were met.

Although the ASME Code rules do not require that the joint design be qualified by bend tests, standard transverse-guided side-bend coupons (3/8" x 1/2" x 7") were removed from three of the joint qualification test plates for testing. Typical specimens, as bent, are shown in Figure 10.

Test Plate 12 - Three specimens were bent 180 degrees with none free of defects. One specimen contained one defect measuring less than 1/64 inch. Another specimen taken from the area of gross porosity, as noted on X-ray, failed completely after bending approximately 70 degrees. The orientation and alignment of the defects were favorable for fracture.

Test Plate 13 - Three specimens were bent 180 degrees with none free of defects. One specimen had four minute defects and one measured approximately 1/16 inch. The third specimen had an aligned defect similar to that in Test Plate 12, but orientation was not favorable for complete failure of the coupon. Each of the five defects opened to approximately 1/64 inch. The plug in the center of the coupon had a groove weld on either side of the plug. The heat-affected zone in the base metal measured approximately 3/16 inch at the top surface and approximately 3/8 inch at the bottom or root surface of the weldment.

Test Plate 14 - Two specimens were bent 180 degrees with none free of defects. One specimen contained six defects with the largest not exceeding 3/32 inch. Two of the defects were on the edge of the coupon and were caused by minute slag inclusions. In this specimen the heat-affected zone stood out in relief. The width of the zone measured approximately 3/16 inch.
Figure 10. TRANSVERSE SIDE-BEND SPECIMENS FOR JOINT QUALIFICATION.

Tensile Tests

Two standard 0.252-inch tapered shoulder tensile specimens were taken from each procedure qualification test plate. Figure 11 shows the fractured specimens from Test Plates 4 and 7. Note the difference in fracture of the two specimens. This difference was due to the work-hardening characteristics of the two filler metals used. The yield strength of the weld filler metal used in Specimen T-4 was lower than the base metal, while that used in Specimen T-7 matched the base metal. A summary of the mechanical properties of the test specimens is given in Table 5.

Macroscopic Examination

Macrosections were taken from all procedure qualification test weldments for examination with exception of Plates 4 and 5. All were acceptable since no unsatisfactory
defects or unsoundness were found that exceeded those found in the base material or hard untempered martensitic zones or structures.

Figure 12 shows the macrospecimen from Test Plate 7. Note the heat-affected zone in the base metal. This structure compares with that noted on the bend test of coupons from Test Plate 13. Traverse hardness readings taken from the base material through the heat-affected zone and into the MIL 11018 weld filler metal from left to right were 57.5, 61.0, 62.0, 57.0, and 59.0. Diagonally from the AS16 root pass filler metal to the heat-affected zone right-to-left hardness readings were 58.0, 61.0, 62.0, and 63.5. All readings were on the Rockwell "A" scale.

FULL-SCALE TEST EXPERIMENT

Proof Test Cylinder

To establish the procedures necessary for the satisfactory repair of the 3/4-inch fill and drain holes in the cylinder heads while in place in the field, and to evaluate
<table>
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<th>Plate Test</th>
<th>Ultimate Tensile Strength (psi)</th>
<th>Yield Strength (psi)</th>
<th>Elongation (%)</th>
<th>Reduction in Area (%)</th>
<th>Failure</th>
<th>Results</th>
<th>Average Hardness Traverses ($R_A$)</th>
<th>Guided Side Bends</th>
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</tr>
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</tr>
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<td>6</td>
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<td>88,100</td>
<td>19.5</td>
<td>19</td>
<td>Weld</td>
<td>OK</td>
<td>60.4</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>110,400</td>
<td>87,200</td>
<td>18.8</td>
<td>-</td>
<td>Weld</td>
<td>OK</td>
<td>62.6</td>
<td>7</td>
</tr>
</tbody>
</table>

**Procedure Qualification**

**Joint Qualification**

12 2  OK  
13 3  OK  
14 2  OK

(1) Average of two specimens per test plate.
(2) 0.2% offset. Minimum yield strength of 80,000 psi required (ASME Code A372 Class IV requires 65,000 psi).
(3) In one inch.
(4) Specimens required to bend 180 degrees before complete fracture. Fractures exceeding 1/8 inch were rejected.
(5) NG - Rejected.
and prove the integrity and safety of the repaired cylinder, a proof test cylinder was fabricated and tested to destruction.

Fabrication Details - The 24-inch-diameter by 91 3/4-inch-long test cylinder was fabricated from the two end sections of the cylinder that was used as base material in the welding procedure investigation.

The cylindrical ends were machine beveled to the same joint design as used in the procedure qualification test plates. To provide ease of fit up and to assure full penetration of the single-butt-weld girth joint, a 1/8-inch-thick by 2-inch-wide backing ring was rolled and tack welded inside one cylinder end after using a local preheat. The second end section was then fitted over the ring and tack welded to provide a 1/4-inch root gap spacing.

Since turning the cylinder for flat or downhand position welding would be difficult with an induction stress-relieving coil attached, the cylinder was placed in a support fixture and positioned vertically. This direction placed the girth joint to be welded in the horizontal position. After positioning a stress-relieving coil on the cylinder, the joint was preheated to 450° F. Prior to welding, the heat was turned off and the joint demagnetized. The MIL 11018 electrode was used to weld the entire joint without backup or purge gas used. Amperage and such techniques as short arc length and "T" start that were established by procedure were followed closely. Requirements for such operations as interpass grinding of craters and strict cleaning procedures were dropped since the quality required for this joint was not as great as that required in the plug-weld repair.

After all welding was completed, the weld reinforcement and arc strikes were removed by grinding. The joint was stress relieved for 1/2 hour at 1150° F and slowly cooled
to 200° F. For the stress-relieving cycle, the entire cylinder had to be wrapped with an asbestos blanket to reduce the loss of heat by radiation to the air. Due to porosity and a slag inclusion approximately three inches long, the completed weldment did not meet the X-ray requirements. However, repairs were not made since the defects were oriented in the circumferential axis and would not reduce the strength of the joint whereby failure or rupture would occur other than in the longitudinal axis.

Preparation of the Plug Weld Joint

Six repair joints including the two 3/4-inch fill and drain openings were prepared for welding. They were located 120 degrees apart in each head knuckle radius.

Prior to drilling and preparing the test joints in the cylinder ends, test plates cut from the base material were utilized to establish drill and countersink tool speeds. This investigation showed that if the drill speed was too fast, the base material air hardened thus dulling the tools. Too high a speed on the countersink tool would also cause chatter and produce an oblong hole.

Drill speeds were established for four sizes of drill bits in addition to the countersink tool, as follows:

3/8 and 1/2-Inch-Diameter Carbon Steel Drills - 120 rpm at no load; 110 rpm under load.

1 1/8 and 1 1/4-Inch-Diameter Carbon Steel Drills - 110 rpm at no load; 70 rpm under load.

Carbon Steel Countersink Tool - 110 rpm at no load; 60 rpm under load.

Drilling the threaded holes to 1 1/4-inch diameter was accomplished in two operations: (1) 3/4-inch to 1 1/8-inch diameter, and (2) 1 1/8-inch to 1 1/4-inch diameter. Drilling the cylinder to 1 1/4-inch diameter was accomplished in three operations: (1) a 3/8 or 1/2-inch diameter pilot hole; (2) 3/8 or 1/2-inch to 1 1/8-inch diameter, and (3) 1 1/8-inch to 1 1/4-inch diameter. The final weld joint design was accomplished with a 37 1/2-degree beveled countersink tool. All joint preparation was accomplished without coolant.

Cleaning, Purging, and Welding

Since cleanliness of the cylinder had to be maintained for gas purity and to prevent malfunction of such items as valves and controls, the test cylinder was pressured to 10 psig with instrument air. This step minimized the entrance of such contaminants as drill chips, dust, and trimmings into the cylinder during joint preparation and cleaning. A vacuum line was used to pick up contaminants that did get by the air stream and into the cylinder.
Prior to welding, the base metal around the joint was ground to a clean bright metal both internally and externally. A spherical burr was inserted through the 1 1/4-inch-diameter hole to clean and grind the internal surfaces.

The special purge fixture was inserted through the cylinder head nozzle and positioned directly under and perpendicular to the joint axis, as shown in Figure 13. With the center point in the purge fixture in contact with a center punch mark in the plug, a 1/2-inch spacing from the internal surface to the repair joint was assured. The plug was pressed into the assembly fixture and dropped into the joint for welding.

![Figure 13. PURGE FIXTURE IN POSITION.](113154(U))

All requirements of the welding procedure established by Test Plates 7 and 13 were followed for repair of the six joints, with exception of two. Rigid interpass cleaning requirements were not observed in these two joints so that the effects of porosity and slag during hydrostatic proof test could be evaluated.

**Magnetic Particle Test**

After the stress-relieving cycles were completed, the repair joints were magnetic-particle tested with no defects found.

**Radiography**

A six-curie Ir-192 source was positioned through the cylinder nozzle to provide a source-to-film distance (SFD) of 12 inches. An exposure time of seven minutes with
fine-grain film and lead screens on the outside surface of the cylinder plug weld repair produced gammagraphs well within the requirements of Par UW-51 of the ASME Code. Four repair joints exceeded the requirements with only minute porosity being observed. One joint was classed as borderline and Joint 1 (Figure 14) was classed as unacceptable. Figure 15 shows Joint 6 which was acceptable.

Figure 14. RADIOGRAPH OF PLUG WELD 1.

Hardness Test

Readings taken at random locations ranged from $R_A$ values of 56.5 to 64.5.

Pressure Test

Preparation - The test cylinder was externally sandblasted to remove all scale and positioned vertically in a fixture designed to permit unrestricted expansion during the test. After placing the fixture and cylinder in an isolated concrete test pit, strain gages were applied. The cylinder was filled with water and allowed to stand overnight prior to completing all test connections.

To assure accuracy in pressure readings, four laboratory test gauges were used; two were located on the pump, one on the test cylinder, and one in the pressurizing and fill line. The hydrostatic test pump used to pressurize the cylinder was a standard
pneumatic-operated diaphragm-type pump with a maximum pressure capacity rating of 30,000 psi.

Test Details - On the date of the test, the ambient temperature ranged from 72 to 76° F. Pressure was applied in increments of 200 to 500 psig over a period of approximately eight hours.

As indicated by the test gauge, yielding of the cylinder occurred at 3400 psig. Strain gage readings also indicated yielding between 3000 and 3500 psig. After relieving the pressure, examination of the cylinder disclosed that bulging had occurred at the girth joint on one side of the cylinder. Four base-metal defects were also found adjacent to the bulged area. These defects were laminations of scabs from one to two inches long. The test was resumed with the pressure increments being reduced to 50 psig. The test was terminated by the rupture of the cylinder at 4560 psig. Rupture occurred with a loud report and water from the cylinder was blown completely over the building used to shield the test personnel. Figure 16 shows the test cylinder immediately after failure. Note that the fracture terminated at the strain gages below the plug weld repair.

Examination of the Fracture - The chevrons in the fracture indicated that the source point for the failure was the girth weld joint, as shown in Figure 17. Severe plastic deformation had occurred in this area. No defects were found in the weld and it was
concluded fracture was initiated by plastic overload at the backing ring to the shell interface. The weld metal fractured in a 45-degree shear tear and propagated in the longitudinal axis of the cylinder from both sides of the girth joint, as shown in Figure 18.

From the girth joint down, the fracture progressed through the bottom head and was arrested in the stress-relieved section on the opposite side of the cylinder. From the girth seam up, the fracture progressed approximately 19 inches then turned diagonally for approximately 20 inches and was arrested in the stress-relieved zone approximately five inches below a plug weld repair. Figure 19 shows the fracture with 1/16-inch shear lips in the nonstress-relieved section of the shell. The scabs or laminations noted at the vessel yield point were not of sufficient size to contribute to the failure and did not open or progress to any degree from yield to rupture. Figure 20 shows the fracture surfaces from the nonstress-relieved section to the stress-relieved section.
Figure 17. POINT OF FRACTURE INITIATION.

Figure 18. FRACTURE ALONG THE LONGITUDINAL AXIS.
Figure 19. FRACTURE AT THE NONSTRESS-RELIEVED SECTION.

below the plug weld. The brittle fracture appearance here changes to a tough, ductile-type tear typical of fracture above the NDT. Figure 21 shows the internal surface of the ruptured cylinder and the full uniform root-pass penetration achieved in the second plug weld repair. The repair was located approximately eight inches from the fracture.

Proof Test Results

The proof test demonstrated that the cylinders could be welded to withstand the pressure allowed by the ASME Code and Case 1205-4.

The stress in the cylinder wall at the indicated yield pressure of 3400 psi and rupture pressure of 4560 psi compared favorably with the minimum yield and tensile strength of 80,000 psi and 105,000 psi as follows:

\[
\text{Yield Stress} = \frac{PD}{2T} = \frac{3400 \times 24}{2 \times 0.5} = 81,600 \text{ psi}
\]

\[
\text{Rupture Stress} = \frac{PD}{2T} = \frac{4560 \times 24}{2 \times 0.5} = 109,440 \text{ psi}
\]
Calculations for the maximum allowed working pressure of the repaired cylinder indicate the following values:

1. Based on the bursting pressure: Code allows $1/5$ BP or $1/5$ of $4560 = 912$ psig.

2. Based on the proof test yield: $P = 0.4H$ or $0.4 \times 3400 = 1360$ psig.

3. MAWP at $1/4$ the minimum tensile strength: $P = \frac{SET}{R + 0.6T} = \frac{26250 \times 1 \times 0.5}{11.5 + 0.6 \times 0.5} = 1112$ psig.

4. MAWP at $1/3$ the minimum tensile strength: $P = \frac{SET}{R + 0.6T} = \frac{35000 \times 1 \times 0.5}{11.5 + 0.6 \times T} = 1483$ psig.

The latter pressure is based on Code Case 1205-4, August 14, 1962, with no stress risers—no stamping—no welding.
Rounding off the latter MAWP to 1500 psig, the stress in the shell would be: $PD/2T$ or $\frac{1500 \times 24}{2 \times 0.5} = 36,000$ psi. This is less than one half the stress required for yield of the test cylinder.
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REFERENCES


