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Advanced Ultrasupercritical (AUSC) Tube Membrane Panel Development

FINAL TECHNICAL REPORT

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ABSTRACT

Alstom Power Inc., a wholly owned subsidiary of the General Electric Company (GE), has completed the project “Advanced Ultrasupercritical (AUSC) Tube Membrane Panel Development” under U.S. Department of Energy (DOE) Award Number DE-FE0024076. This project was part of DOE’s *Novel Crosscutting Research and Development to Support Advanced Energy Systems* program. AUSC Tube Membrane Panel Development was a two and one half year project to develop and verify the manufacturability and serviceability of welded tube membrane panels made from high performance materials suitable for the AUSC steam cycles, defined as high pressure steam turbine inlet conditions of 700-760°C (1292-1400°F) and 24.5-35MPa (3500-5000psi).

The difficulty of this challenge lies in the fact that the membrane-welded construction imposes demands on the materials that are unlike any that exist in other parts of the boiler. Tube membrane panels have been designed, fabricated, and installed in boilers for over 50 years with relatively favorable experience when fabricated from carbon and Cr-Mo low alloy steels. The AUSC steam cycle requires membrane tube panels fabricated from materials that have not been used in a weldment with metal temperatures in the range of 582-610°C (1080-1130°F).

Fabrication materials chosen for the tubing were Grade 92 and HR6W. Grade 92 is a creep strength enhanced ferritic Cr-Mo alloy and HR6W is a high nickel alloy. Once the materials were chosen, GE performed the engineering design of the panels, prepared shop manufacturing drawings, and developed manufacturing and inspection plans.

After the materials were purchased, GE manufactured and inspected the tube membrane panels, determined if post fabrication heat treatment of the tube membrane panels was needed, performed pre- and post-weld heat treatment on the Grade 92 panels, conducted final nondestructive inspection of any heat treated tube membrane panels, conducted destructive inspection of the completed tube membrane panels,and performed simulated shop repairs on the panel fabricated using Grade 92.

GE executed the program as the prime contractor under the direction of Principal Investigator Mr. James Pschirer. Other participants in this project included GE Boiler Engineering, GE Chattanooga Manufacturing, GE Materials Technology Center, GE Rocky Mountain Service Center, and a Technical Consultant from Electric Power Research Institute (EPRI).

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EXECUTIVE SUMMARY

Alstom Power Inc., a wholly-owned subsidiary of the General Electric Company (GE), has completed a development program with the objective to develop and prove the manufacturability of welded tube membrane panels made from high performance materials suitable for the Advanced Ultra Supercritical (AUSC) steam cycles of a fossil-fired boiler. The overall goal of the Advanced Ultra Supercritical (AUSC) materials program is to develop high performance materials technology to enable higher efficiency fossil energy power plants to realize +10% points increase in efficiency above today's state-of-the-art boiler steam cycles. These high performance materials (operating at higher temperatures and pressures) can support future transformational power technologies including AUSC oxy-combustion, supercritical CO_2 cycles, nuclear power, concentrating solar power and more efficient natural gas combined cycle units as targeted by the High-Performance Materials and Modeling Research Initiative of the U.S. DOE/NETL Cross-Cutting Research Technology Program Plan.

This final technical report contains results of GE's AUSC Tube Membrane Panel Development project, under U.S. DOE/NETL Cooperative Agreement No. DE-FE0024076. The objective of this project is to develop and prove the manufacturability of welded tube membrane panels made from high performance materials suitable for the AUSC steam cycles (greater than 1300°F / 4000psi) of a fossil-fired boiler. In developing the technology, GE leveraged its long-term involvement with the AUSC Consortium of U.S. boiler and turbine manufacturers, an unincorporated consortia, to further the preliminary efforts needed for undertaking a pre-competitive full scale AUSC Component Test (AUSC ComTest) program and ultimately the commercial realization of this technology.

The AUSC ComTest program is a U.S. initiative envisioned to demonstrate pressure part components operating at high temperature, high pressure steam conditions up to 38.5MPa/730°C/760°C (5500 psi/1350°F/1400°F) in a fossil-fired power plant. The welded tube membrane panel is one component of the AUSC ComTest program and needs development prior to commercial realization. The starting point for the engineering design and fabrication of the welded tube membrane panel was provided by the work of the "Boiler Materials for Ultra Supercritical Coal Power Plants" by the AUSC Consortium that started in 2001. The specific program objectives are:

1. Down select candidate materials, ferritic, austenitic, or nickel alloys, for the AUSC steam cycle considering the design pressure and temperatures, also considering the corrosives in the gas and deposit conditions. Several materials such as T91, T92, HR6W, CCA617, and VM12 show promise to fulfil the requirements needed to meet the challenges of a membrane wall in the AUSC steam cycle.
2. Complete detailed engineering design of tube membrane panels using the identified candidate materials following rules defined from prior work and in-line with proposed governing ASME Code.
3. Develop manufacturing procedures to fabricate and repair the tube membrane panels utilizing the selected materials.
4. Develop detailed design drawings of the tube membrane panels that can be used by a manufacturer for fabrication of a prototype panel.
5. Develop a non-destructive test plan that will be used by the fabricator to measure and inspect the fabricated prototype tube membrane panels.
6. Fabricate and test prototype tube membrane panels to demonstrate the fabrication viability. The initial plan for testing the prototype membrane panel will be Non-Destructive Examinations (NDE). Depending on the findings of the NDE further destructive examination such as macro sectioning will be performed.

The GE Project Team conducted a Survey of Material Information on already commercialized high temperature materials and identified suitable candidates in product forms, including weld consumables, required for a tube membrane panel to meet the AUSC steam cycle requirements. The candidate materials showing the highest potential for successful fabrication were chosen by GE Boiler R&D Engineering, using its many years of design experience for USC boilers, to specify a tube membrane panel specification that will be representative of a full scale utility boiler wall.

The specification required the development of arrangement drawings with all details necessary to fabricate the prototype membrane panels, plus the development of manufacturing and inspection plans for the prototype tube membrane panels for use by GE's manufacturing facility in Chattanooga, Tennessee, to ensure the highest chance for successful fabrication.

The non-destructive inspection plan for these prototype panels was based on ASME Code requirements, existing shop procedures, and contains “hold points” to gather information and identify possible issues prior to progressing to the next stage of fabrication. The drawings, manufacturing, and test plans for the prototype panels were based on using GE's existing manufacturing and testing equipment currently available in the manufacturing facility. All specifications, plans, and drawings were reviewed by members of the team and the Project Technical Consultants to ensure risk mitigation for the successful fabrication of the panels.

Utilizing a team from GE that includes Boiler R&D Engineering, Welding Engineering, Materials Experts, and an Electric Power Research Institute (EPRI) Consultant, the design of the prototype panels was defined on arrangement drawings with the required detail to fabricate the prototype membrane panels. The non-destructive test plan was based on GE's extensive experience and risks identified during the design to ensure an early detection of potential failure mechanisms that will inhibit successful completion of the objective.

The fabrication and non-destructive examination were completed in the GE Chattanooga Manufacturing facilities. This facility, with state of the art equipment, is an industry leader in the manufacturing of boiler components and its quality team employs a number of ASME qualified inspectors. Local oversight of the manufacturing and inspections was completed by GE's Welding Engineers and Material Experts.

The AUSC tube membrane panels are designed and fabricated to operate at higher temperatures than tube membrane panels in conventional USC or SC units. The purpose of this project was to develop and verify the manufacturability of welded tube membrane panels made from high performance materials such T92 or HR6W suitable for the AUSC steam cycles to reduce the risk of early life issues.

Prototype panels were successfully fabricated from T92 tube material with Grade 91 membrane material and from HR6W tube material with Alloy 617 membrane material. Several weld filler materials were used during fabrication. The T92 panel also has a “Dutchman” repair successfully done to simulate shop repair of a fabricated panel. This report includes details on material downselection, prototype panel design and fabrication, prototype panel nondestrictive and destructive testing, and fabrication and welding procedure development.

1 INTRODUCTION

Alstom Power Inc., a wholly-owned subsidiary of the General Electric Company (GE), has completed a development program with the objective to develop and prove the manufacturability of welded tube membrane panels made from high performance materials suitable for the Advanced Ultra Supercritical (AUSC) steam cycles of a fossil-fired boiler. AUSC steam conditions are defined as greater than 1300°F and 4000 psi main steam outlet conditions. The welded tube membrane panels are typically fabricated in the shop and then assembled in the field to form the welded furnace walls, which is the current practice for materials used in tube membrane panel on commercial boiler installations.

Welded furnace walls, which are frequently referred to as waterwalls, provide the enclosure around a combustion chamber. These welded walls form the gas seal and provide structural support. The drawing in Figure 1-a shows how the tube and membrane bar (sometimes called a fin bar) are joined. In the upper section of the combustion chamber of an AUSC boiler, the tube membrane panels are part of the superheat circuit. These upper furnace panels experience the highest metal temperatures of any waterwalls in a coal-fired AUSC boiler and are the subject of this tube membrane panel development project.

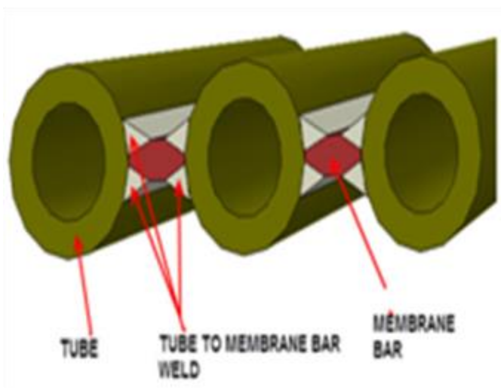

Figure 1-a Tube Membrane Panel Schematic

Tube membrane panels have been designed, fabricated, and installed in boilers for over 50 years with relatively favorable experience when fabricated from carbon and Cr-Mo low alloy steels. The tolerance of the "traditional" alloys for abusive conditions, whether during manufacturing or during service, has contributed significantly to the favorable service experience.

With no firm base of boiler operating experience with membrane-welded walls fabricated from the more advanced alloys and operating in superheater mode at the pressures and temperatures of the AUSC steam cycle, it is imperative that issues associated with the fabrication, construction, and installation of membrane-welded panels fabricated using advanced alloys be investigated so that potentially disruptive problems can be identified and technically feasible resolutions of those problems developed. A typical tube membrane subpanel is shown in Figure 1-b.

Figure 1-b Typical Tube Membrane Panel

The Scope of Work for this project included the selection of tubing and plate/bar materials from commercially available materials suited for AUSC steam cycles and the fabrication of laboratory test panels. These identified materials and experience gained from the laboratory panels were then used to design and fabricate prototype tube membrane panels. Careful consideration by the engineers has been given to such details as welding, joint configurations, typical boiler membrane panel features such as openings, repair of a shop defect, and handling of the completed panels by shop and field equipment. The Scope of Work was executed utilizing the GE's resources in Connecticut (Engineering offices in Windsor and Clean Energy Center test facility in Bloomfield), Tennessee (Materials Testing Center or MTC Laboratory and the Boiler Manufacturing facility in Chattanooga) and Colorado (Rocky Mountain Service Center in Denver) to perform the material survey, engineering design, fabrication and simulated repair of the tube membrane panels. Technical advice for this project is provided from the Electric Power Research Institute (EPRI).

The following work outline was defined to prove the manufacturability of welded tube membrane panels made from high performance materials suitable for the AUSC steam cycles of up to 760°C (1400°F) and 35 MPa (5000psi).

Task 1.0 Project Management and Reporting

Within this task GE managed and directed the project in accordance with the Project Management Plan to meet all technical, schedule and budget objectives and requirements. GE coordinated activities between different execution centers in order to effectively accomplish the work.

Task 2.0 Tube Membrane Panel Design and Fabrication Development

Within this task and its subtasks, GE developed an overall project specification, selected two candidate materials, designed the prototype membrane panels, developed manufacturing procedures, developed drawings for manufacturing the prototype panels, and developed the Manufacturing Inspection and Test Plan (ITP).

Task 3.0 Prototype Fabrication and Inspection

GE procured the materials needed to fabricate the prototype tube membrane panels. GE used the design drawings to fabricate the prototype tube membrane panels, then conducted Non-Destructive Inspection based on the ITP, performed Heat Treatment of Prototype Panel of the membrane panels (if required), and performed a final Non-Destructive Inspection.

2 RESULTS AND DISCUSSION

Provided below is a description of each technical task from the Statement of Project Objectives (SOPO) along with the results and discussion of each subtask.

2.1 Tube Membrane Panel Design and Fabrication Development

An internal project specification was developed in order to define the scope of the project and describe the purpose of this project to the project team. This specification was used to ensure the project team stays on task and maintains technical focus on the schedule, subtask requirements, budgets and required deliverables. This specification was incorporated into the internal orders for the project team. The AUSC Tube Membrane Panel Development Project Specification document was issued on January 5, 2015.

The technical goal of this project was to develop the design and manufacturing processes that are required for welded tube membrane panels in power boilers for AUSC steam cycles. The steam cycle defined for this project was 1400°F / 5000 psi main steam conditions. The specified results of the project are to demonstrate fabrication and heat treatment prototype welded tube membrane panels from at least two of the different alloy materials that show promise for successful results. The panels were to be designed and manufactured for long term (30 years or longer) use at the elevated temperatures and pressures of AUSC steam cycles. The results of this project can also be applied to manufacture similar assemblies in other advanced fossil energy technologies operating at elevated temperatures and pressures.

The overall objective was reached by design, analysis, and materials selection; followed with the development of fabrication, heat treatment and inspection procedures to fabricate the prototype tube membrane panels. The alloys used for tubing and plate/bar in the tube membrane panels were selected from available materials that are suitable for use in coal fired Advanced Ultra Supercritical steam cycles. The identified materials were then used to design tube membrane panels for use in boiler walls. Careful consideration was given during the design phase to such details as welding, joint configurations, typical boiler membrane panel features such as openings, repair of a shop or field defect, and handling of the completed panels by shop and field equipment. Tube, bar and plate materials were procured only from approved suppliers.

Manufacturing and inspection procedures were developed, and then prototype tube membrane panels were fabricated. Nondestructive examination of the prototype tube membrane panel was done before and after heat treatment of the fabricated panels, as required.

There were two (2) major technical tasks of this project.

- Task 2 identified and selected the appropriate materials to fabricate the tube membrane panels, perform the engineering design of the panels, prepare shop manufacturing drawings, and develop manufacturing and inspection plans.
- Task 3 purchased materials, manufactured and inspected the tube membrane panels, determined if post fabrication heat treatment of the tube membrane panels was needed,

performed heat treatments if needed, conducted final nondestructive inspection of any heat treated tube membrane panels, and performed simulated shop repairs on the panel fabricated using Grade 92.

Manufacturability and durability considerations included:

- Control of weld penetration to satisfy mechanical and heat transfer requirements
- Control of panel deformation to acceptable tolerances.
- If straightening is required in the workshop after welding and heat treatment, can required dimensional tolerances for successful site installation be met
- A **Creep Strength Enhanced Feritic** (CSEF) steel will be prone to cracking in the coarse-grained heat affected zone (HAZ) due to hydrogen-delayed cracking. The inherent restraint of a membrane-welded panel will magnify the potential significance of this problem.
- Impact of maintaining preheating through the welding process, which could result in handling and shop processing issues that will substantially increase cost

2.2 Down Select Candidate Materials

From the list of candidate materials such as T91, T92, HR6W, CCA617, VM12 and others, GE selected two that showed the highest potential, including weld consumables, to meet the AUSC steam cycle requirements, up to 760°C (1400°F) and 35MPa (5000psi), as defined in the final report produced under Task 1 of the DOE/NETL Cooperative Agreement titled “Boiler Materials for Ultra Supercritical Coal Power Plants”.

Work began on this subtask by confirming the early work from the Boiler Materials for Ultra Supercritical Coal Power Plants Task 1A, Conceptual Design. [1] This early work identified that the upper section of the boiler would not be constructed with one of today’s conventional materials for the boiler membrane walls due to the elevated operating temperatures. Additionally, application of T92 alloy for the construction of waterwalls is technically challenging and requires advanced manufacturing techniques that need to be fully developed.

The chart shown in Figure 2-a was developed using GE Standard Practices for determining predicted temperatures of the membrane wall and the allowable material stress values. Based on this figure, it becomes apparent that there are several materials that are very close to matching the requirements for temperature and stress values and will meet the requirements needed for the membrane wall. There are a number of materials that just meet the requirements needed. Austenitic materials are not permitted by ASME code to be used in a wetted section of the boiler. The possible material selections were evaluated based on this information. The overall serviceability and manufacturability were also considered. Candidate materials shown in Figure 2-a included T12/122/22, T23/24, T91/92, HR6W, Haynes 230, Inconel 617, and Alloy 800H.

The first material selected was alloy T92. As shown on the graph, T92 is above the requirements of temperature and stress needed to meet the performance requirements. It is identified in the Task 1A report and is also mentioned in a number of published documents as one of the materials having the required properties of a membrane wall in the upper section of an AUSC boiler. [2]

The other materials were reviewed to determine the next potiential candidate material to be used to build the prototype panels. Alloy T91 was considered, but was too close in properties and in all respects to the T92. In addition it was felt that using another CSEF did not give the boiler designer a choice since many of the parameters would be the same. If the fabrication of T92 panels was not successful, then using T91 would more than likely not be successful as well.

HR6W was considered as the second material to build the prototype membrane panels. HR6W is more economical than Alloy 617 or other high nickel alloys, it provides the designer plenty of margin in designs, and weld consumables are readily available.

It was ultimately decided to build prototype panels using T92 and HR6W tubing. Building panels from a CrMo based material and a nickel based material enabled a more comprehensive learning experience in comparison to building panels from two CrMo alloys such as T92 and VM12. Also, the design limits for CrMo based materials are quickly being reached and the next high-temperature material will likely be a nickel based alloy, thus it made sense to begin working with HR6W. It was also decided to evaluate the use of a ferritic stainless steel as edge bar material for the T92 panels in an effort to eliminate the need for a field post weld heat treatment (PWHT). Using ferritic stainless steel as the edge bar material would allow the membrane field welds to be a standard P7 to P7 weld and thus eliminate the field PWHT and the risk of **Stress Corrosion Cracking** (SCC) associated with non-heat treated Grade 91/92 weldments. The weldability and fabrication of the ferritic stainless steel was evaluated during both laboratory and shop panel welding. However, further design considerations such as compatibility of thermal expansion of the panel tubes versus the membrane material should be evaluated prior to the implementation of ferritic stainless steel edge bar material in a commercial unit.

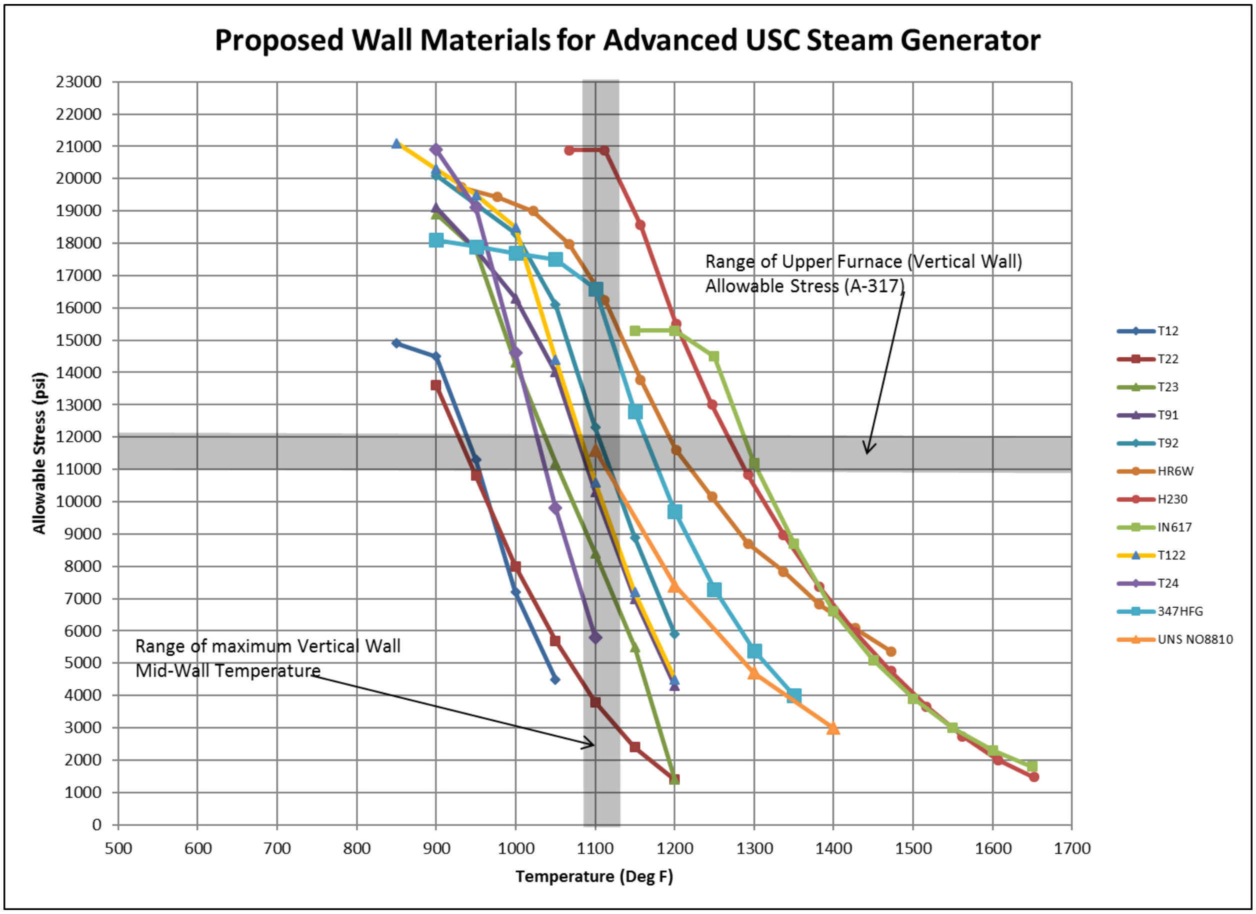

Figure 2-a Allowable Stresses for Potential Membrane Panel Materials for AUSC Steam Generator

2.3 Engineering Design Development

The prototype membrane panels were designed using the identified suitable materials, based on the AUSC main steam conditions of 1400 °F and 4000 psi. The design specified the tube thickness based on a maximum vertical wall mid-wall temperature of 1080-1130 °F and the required allowable stress of 11,000-12,050 psi. The design specified the membrane bar material and thickness and the weld configuration for the connection between the tube and membrane bar for the panels.

The design also included sections of the panels to simulate a bent tube boiler wall opening, a section of tube to simulate a shop/field repair, tube-to-tube connections to simulate the transition of materials as the wall approaches the top of the boiler, and a membrane bar splice. The tubing transition simulations for the T92 panel was fabricated using two T22 tubes, butt welded into the prototype panels. In full scale AUSC boiler design, the need for a transition from T22 to T92 material is anticipated.

The T92 panel design is shown in Figure 2-b and the HR6W panel design is shown in Figure 2-c.

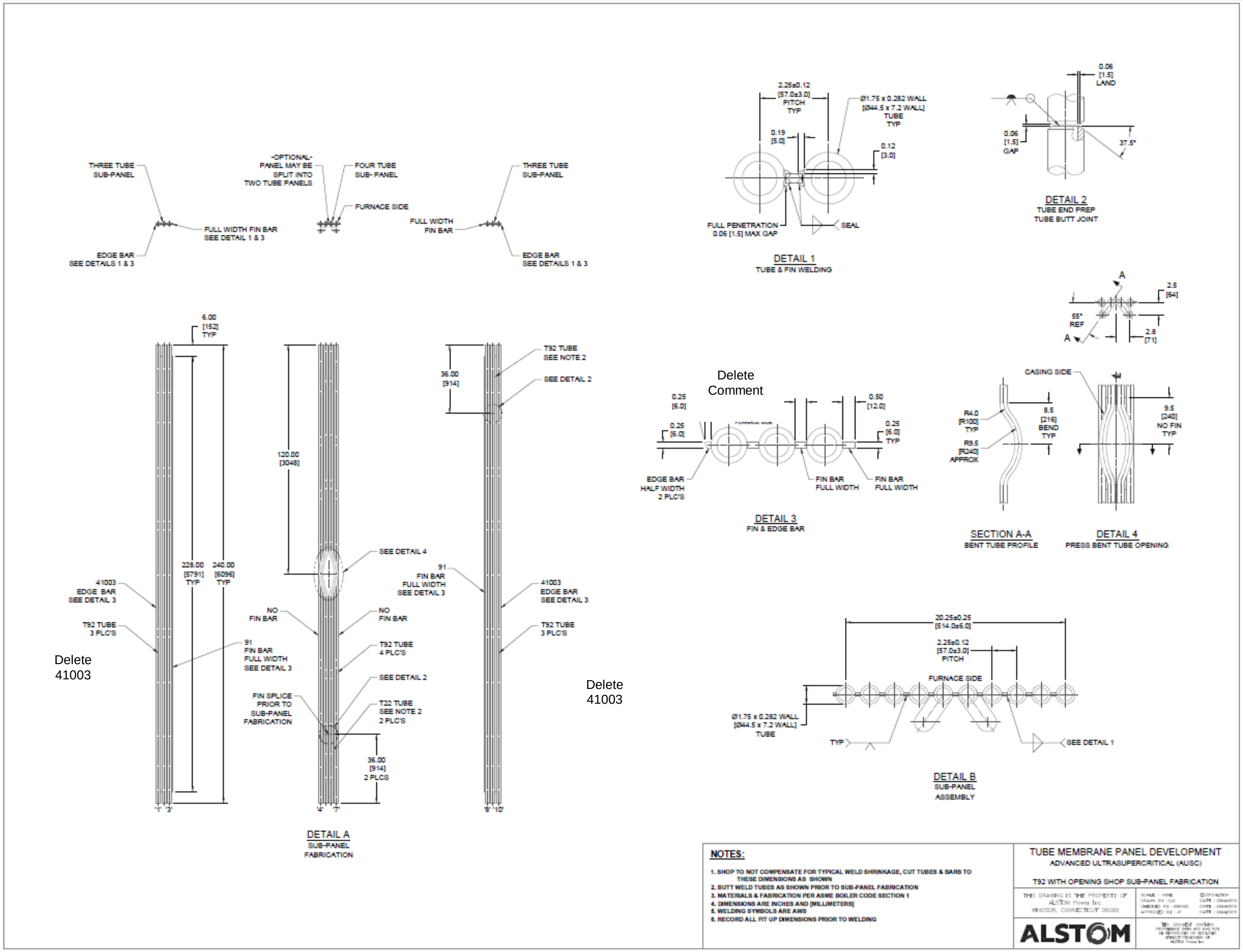

Figure 2-b Prototype T92 Panel Design

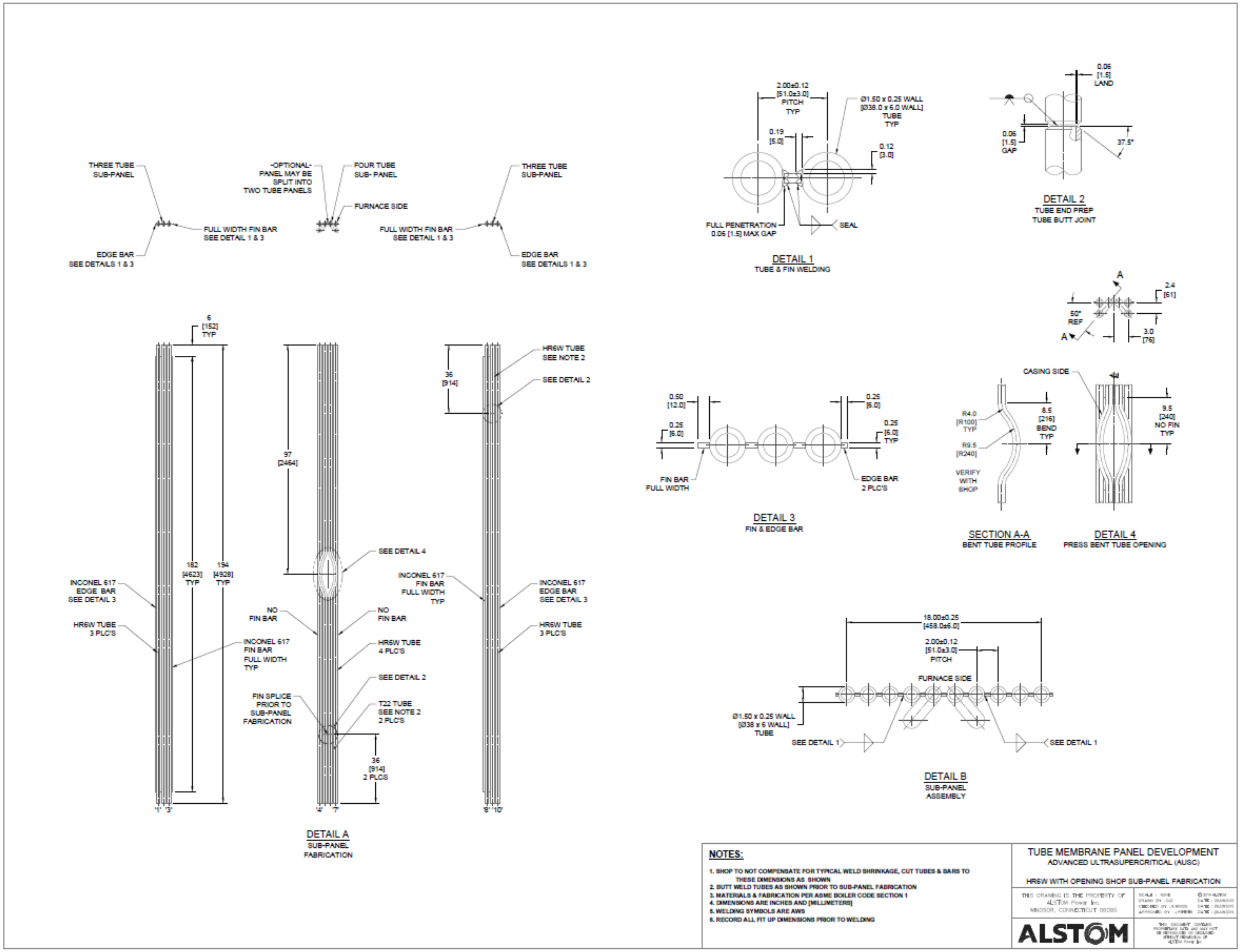

Figure 2-c Prototype HR6W Panel Design

2.4 Manufacturing Procedure Development

GE standard manufacturing procedures were adapted for the two (2) identified tubing materials based on technical data from the AUSC Materials Consortium, GE's own information and with input from the EPRI Technical Consultant.

The Panel Fabrication Specifications were adapted for each specific fin-welded wall panel material being used. These documents were used as manufacturing instructions to ensure that all aspects of panel fabrication are performed in strict accordance with the requirements of GE internal standards (as applicable) and ASME Code. These procedures and instructions are in full accordance with the requirements set forth in the DOE Statement of Project Objectives and include such items as: Material Types (grades) and Dimensions to be used, ASME Boiler and Pressure Vessel Code requirements, GE Internal and Supplementary Specifications and Standards References, Welding Qualification Procedures, Instructions for Sub-Panel Construction, Pre and Post Weld Heat Treatment Requirements, Tube Bend Radii, Membrane Weld Preparation Details and Requirements, Tube Splice Details, Tube and Panel Repair Requirements, Weld Termination Requirements and Shop Handling Recommendations. Internal procedures were used to adapt the existing fabrication specification for a fin-welded membrane panel to include panels fabricated from:

- Grade 91 and Grade T92 alloys (Code Case 2179)
- ASTM B167-11, UNS N06674 (CC 2684, HR6W – 47Ni-23Cr-23Fe-7W) and UNS N06617 (Alloy 617) Materials

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As the Panel Fabrication Specifications were being developed it was decided by the project team that small mock-up panels should be completed in GE's Chattanooga Laboratory. Lab mock-up panels were fabricated from T92 tubing and Grade 91 membrane material and from HR6W tubing and Alloy 625 membrane material. These mock-up panels would use less material to determine weld parameters, and could be completed in less time than in the manufacturing shop since these panels would be small and easily accept changes in welding. The decision to develop these mock-up panels in the lab is in line with this task and there was no schedule effect to the overall project. Having the welding and heat treatment parameters already set for the manufacturing shop allowed for the shop to treat the welding of the prototype panels as more of a normal production panel.

All the information from this subtask was used to develop the deliverables in latter tasks.

2.5 Manufacturing Drawing Development

Detailed design drawings of membrane panels were developed based on the engineering design. These drawings include a fully developed bent tube opening to mimic a tube membrane wall opening, a section of the panel designed to mimic the transition from water wall to membrane superheat panel, and details of the tube to membrane weld. The deliverables of this subtask were used for Task 3. Figure 4 shows the general mechanical design of the T92 panels; the HR6W panels are similar in design.

GE used its standard engineering details for panel fabrication. Expectations at the time were that standard shop detail drawings would be suitable for panel fabrication from the selected materials.

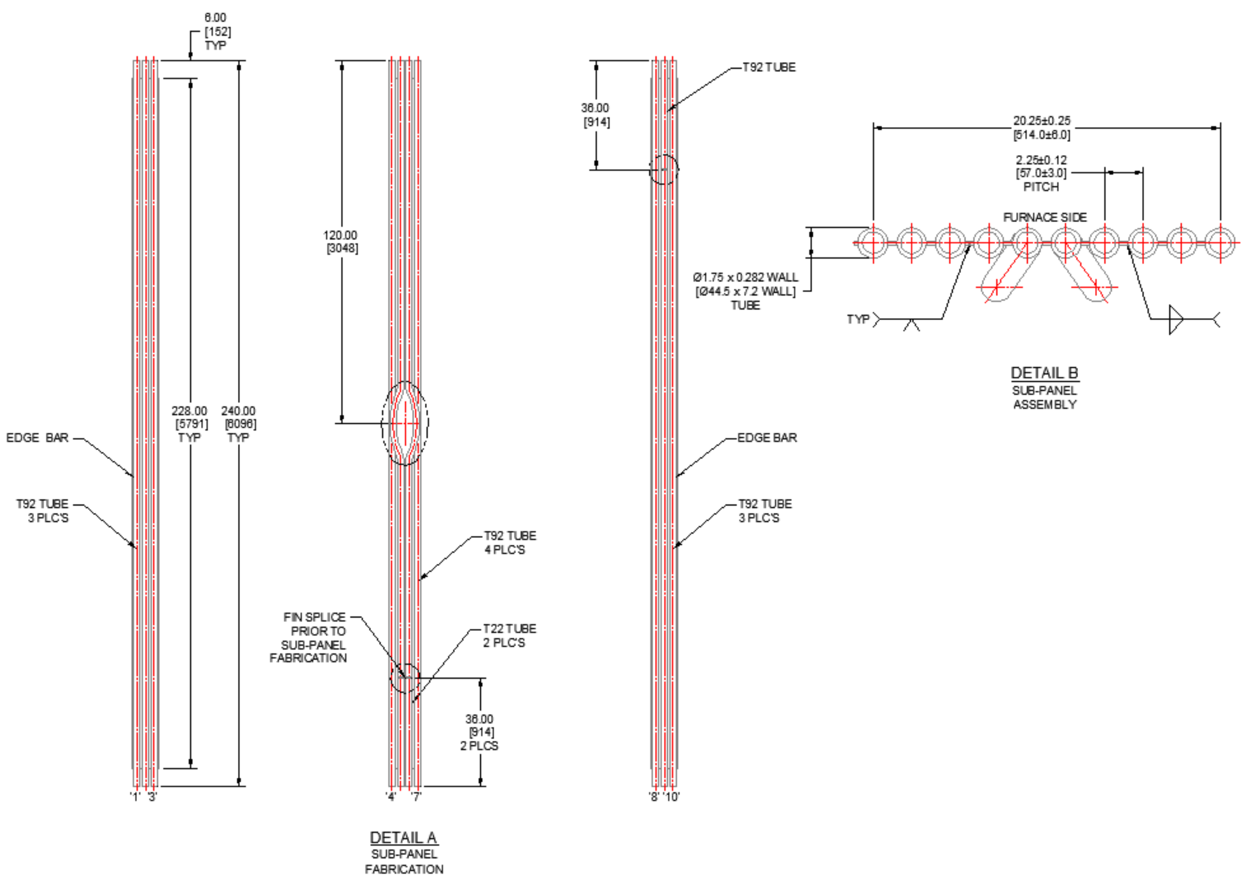

Figure 2-d General Mechanical Design of T92 and HR6W Panels

Use of standard detailing would provide evidence that these panels could be fabricated using the conventional shop equipment and handling procedures, thus retooling the shop would not be necessary for these panels. The standard six torch submerged arc welding (SAW) panel machine was planned to be used to fabricate the prototype panels in the Chattanooga Manufacturig shop using the the selected welding parameters and filler material.

2.6 Manufacturing Examination Test Plan Development

A non-destructive examination test plan was developed which was to be used by the Chattanooga Manufacturing Shop to measure and inspect the prototype type panels fabricated in Task 3 to determine if the design configurations are suitable for the successful fabrication and use of tube membrane panels in the AUSC steam cycle. The inspection and examination plans were to be implemented by the Chattanooga Manufacturing Shop following standard shop procedures and Code requirements. The Chattanooga Manufacturing shop typical non-destructive examinations include visual examination of all tube-to-membrane welds for items such as cracks, porosity, discontinuities, and undercut. Standard dimensional inspections include such items as straightness (sweep), flatness (bowing) and squareness.

GE Boiler R&D planned for additional inspections such as multiple tube-to-membrane weld samples cut from the panels for closer inspection and for weld parameter adjustment prior to prototype panel fabrication. Examples of these destructive examinations are shown in Section 3.2.3. The deliverable of this subtask is used for Task 3.

3 PROTOTYPE FABRICATION AND INSPECTION DEVELOPMENT

3.1 Prototype Material Procurement

The selected materials for the prototype tube membrane panels were procured based on the manufacturing drawings from Subtask 2.4 and according to shop practices and ASME Code requirements. GE followed internal processes for material procurement to ensure that all purchased materials used on the project meet or exceed specific ASTM and ASME Boiler and

Pressure Vessel Code requirements. The instructions included such information as ASTM standards requirements, ASME requirements and Code Cases, Required Material Chemistries, Material Heat Treatment Requirements, Material Mechanical Properties Requirements and NDE Test Requirements.

The tubing materials were located from stock in various locations for this project in an effort to maintain the project schedule and control project costs. Using the tubing from stock allowed for quicker delivery, did not require the project to purchase mill order runs, and allowed the project team the opportunity to perform welding on mock-up panels prior to prototype manufacturing.

The T92 tube is 1-3/4" diameter and the HR6W tube is 1-1/2" in diameter. Both of these diameters are common boiler tube sizes and thus have no influence on the success of the fabrication.

Purchase orders for the T92 material were written directly to the shop. A purchase order was required to replace the stock HR6W from another GE Boiler location, since this material was purchased and was needed for a future project.

3.2 Prototype Manufacturing – Grade 92 Panels

The R&D Tasks were performed in two phases:

Lab Panels: Laboratory sized test panels were welded at Chattanooga's Materials Technology Center (MTC) to establish welding parameters and to determine the appropriate welding consumables to use for the fabrication of a shop panel. The laboratory panels were evaluated for weldability and destructively tested to ensure that current panel fabrication specifications could be maintained.

Shop Panels: Prototype panels were fabricated using the PEMA six-torch moving tube continuous membrane welding equipment in the Chattanooga Manufacturing facility. In total, three panels were fabricated from SA-213, T92 tubing with Grade 91 membrane bars.

3.2.1 Laboratory Fabrication of Grade 92 Panels

Introduction

A number of three tube mock-uppanels were fabricated at MTC's laboratory using the Lincoln Powerwave® AC/DC 1000 submerged arc welding equipment. Fit-up of a T92 laboratory panel before welding is shown in Figure 3-a. Photos of the submerged arc welding process (SAW) on a T92 laboratory panel are shown in Figure 3-b.

Figure 3-a Lab Scale T92 Panel Ready for Welding

Figure 3-b Welding of T92 Panel with Sub Arc Process

A typical laboratory panel is shown in Figure 3-c. The tubing used was 1.75″ OD X 0.282″ MWT SA-213 Grade T92. Panels were fabricated using Grade 91 membrane bar material welded with an E9015-G (Gr.92 E9015-B9 mod.) and E90S-B9 (Gr.91) welding wire. In an effort to eliminate the need for a field PWHT, it was decided to evaluate the use of a ferritic stainless steel as edge bar material. Two fluxes were evaluated for weldability characteristics and slag removal properties. The combination welding wires and fluxes were tested to provide information on deposited weld metal chemistry and for instances in material selection where there could be more than one material that would provide acceptable service. Each laboratory panel was sectioned in two locations and visually inspected (10X magnification) to ensure that current panel fabrication specifications could be maintained.

Figure 3-c Example of three-tube laboratory scale panel fabricated at the MTC

Material Combinations

The T92 tubing was fabricated into laboratory scale panels using the manufacturer's recommended weldwire and flux combination. The chemical composition for the T92 tubing and Grade 91 membrane bar is shown in Table 3-a.

Table 3-a Chemical Composition of T92 laboratory panel base materials

Chemical Composition (Weight Percent)		
Element	Grade 92 Tubing	Grade 91 Membrane
Carbon	0.113	0.111
Manganese	0.54	0.43
Phosphorus	0.018	0.019
Sulfur	0.001	0.002
Silicon	0.19	0.22
Nickel	0.16	0.22
Chromium	9.18	8.99
Molybdenum	0.38	0.871
Vanadium	0.19	0.196
Columbium	0.062	0.073
Copper	0.13	0.05
Aluminum	0.012	0.008
Iron	Bal	Bal
Nitrogen	0.057	--
Tungsten	1.62	<0.01
Oxygen	0.001	<0.001

The weld metal from each combination was chemically analyzed to determine the chemical composition of the weld deposit. A chemical analysis table reporting the major elements of the weld deposit from each combination is compared in Table 3-b. This table can be used as an aid in the selection of materials and welding wire for membrane panel construction. The material combinations analyzed are shown in the table and a list of the consumables is noted below:

Consumables List:

- Thermanit MTS 616 - E9015-G (Gr.92 E9015-B9 mod.) – "Grade 92 wire"
- Thermanit MTS 3 - E90S-B9 (Gr.91) – "Grade 91 wire"
- Marathon 543 – SA FB 2 55 DC H5 - SAW Flux
- UV 305 – SA AR 1 76 AC H5 – SAW Flux

Table 3-b Weld Deposit Chemistry Results for the Grade 92 Laboratory Panels

Chemical Composition (Weight Percent)				
A – T92 to Gr.91 membrane bar welded with E9015-G (Gr.92 wire.) and Marathon 543 flux				
B – T92 to Gr.91 membrane bar welded with E9015-G (Gr.92 wire.) and UV 305 flux				
C – T91 to Gr. 91 membrane bar welded with E90S-B9 (Gr.91) and Marathon 543 flux				
D – T92 to 41003S membrane bar welded with E9015-G (Gr.92 wire.) and UV305 flux				
Element	A	B	C	D
Carbon	0.109	0.093	0.10	0.053
Manganese	0.55	0.73	0.79	0.80
Phosphorus	0.015	0.017	0.015	0.020
Sulfur	0.004	0.003	0.004	0.003
Silicon	0.21	0.41	0.41	0.62
Nickel	0.28	0.31	0.19	0.36
Chromium	9.12	8.76	8.09	9.98
Molybdenum	0.552	0.574	0.907	0.235
Vanadium	0.201	0.199	0.19	0.134
Columbium	0.068	0.068	0.063	0.037
Copper	0.08	0.07	0.03	0.08
Aluminum	0.017	0.023	0.026	0.023
Iron	bal	bal	bal	bal
Nitrogen	0.057	0.054	0.053	0.031
Tungsten	1.09	1.07	0.85	0.89
Oxygen	0.028	0.061	0.031	0.052

Flux Evaluation

Two fluxes were evaluated during the study. The Marathon 543 was tested following the manufacturers recommendation and its history of use with Grade 91 pipe. Bohler UV 305 was also tested based on its favorable use in high speed fillet welding and ease of slag removal. Laboratory panels were successfully welded using both of the fluxes noting acceptable bead appearance, slag removal, and weld deposit chemical composition. However, the UV 305 flux was selected for shop panel fabrication based on more favorable slag removal characteristics as compared to the Marathon 543 flux.

Inspection and Testing

Each labortory panel received a visual inspection of each weld on the panel to ensure compliance with the following rejection criteria:

- Burn-Through
- Lack of Fusion
- Skips
- Undercut
- Cracks
- Porosity greater than 1/16" diameter

In no case were the panels found to exhibit any of the above and were considered acceptable based on the nondestructive visual inspection. Cross sections were removed from representative locations along the length of each panel and prepared for metallographic examination. The cross sections were visually inspected with the aid of the stereomicroscope (10X magnification) to confirm:

- Penetration into the tube wall was less than 50% of the tube wall in all cases.
- The sum of the effective throats was at least 1.15 times the membrane thickness.
- The weld zones were free from cracks.

There was no evidence of any hydrogen induced cold cracking; minor solidification cracking occurances were mitigated by adjusting the welding parameters. Representative samples from each of the laboratory panels were mounted and polished for metallography and hardness measurements. Laboratory panels demonstrated that there were no differences in weldability between Grade 91 and Grade 92 welding wire for fabrication. Both the UV305 and Marathon fluxes had good performance.

<u>Metallographic Examination and Hardness</u>

Specimens were prepared for metallography to investigate welding parameters used during fabrication. Figure 3-d shows an initial laboratory mock-up panel run where the wire position and angle was varied to influence weld penetration. The optimal wire angle and position for T92 panels was chosen from these initial runs. Optimal weld penetration is shown in Figure 3-e.

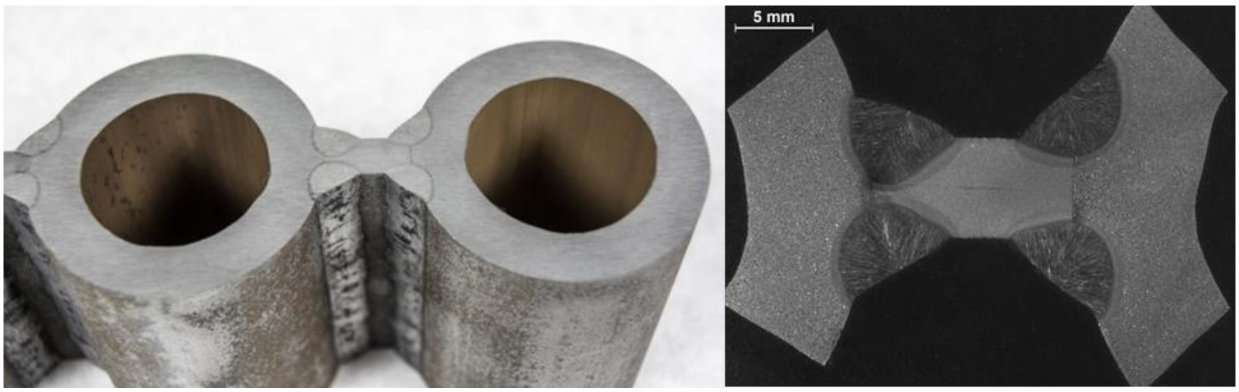

Figure 3-d Effect of Wire Angle and Position on Weld Penetration

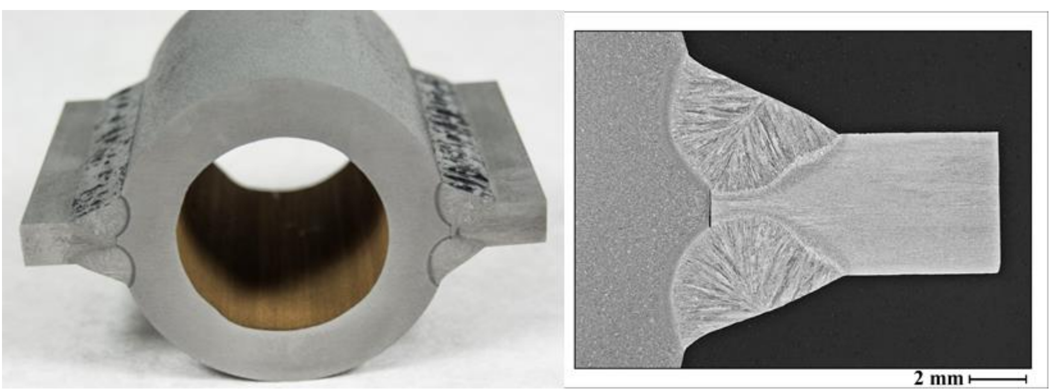

Figure 3-e Weld Penetration on Membrane Bar

Specimens were prepared for hardness measurements in several conditions to simulate the various scenarios possible during fabrication. The conditions evaluated are as follows:

- as-welded,
- PWHT for 30 minutes,

- PWHT for 60 minutes,
- normalized, and
- normalized and tempered for 30 minutes.

Hardness survey for each of the conditions is shown in Table 3-c The values shown in the table are the average of three 500 gf indents. In comparing the 30 minute PWHT to the 60 minute PWHT, it was decided that a 30 minute PWHT was likely adequate. However, it was decided that the shop prototype panels would receive a 60 minute PWHT for extra conservatism.

Table 3-c Vickers Hardness measurements for T92 mockup panels

T92-Grade 91 membrane bar					
	AW	PWHT-30	PWHT-60	Norm	N&T-30min
Tube BM	250	240	241	450	286
Tube CGHAZ	467	334	314	434	280
WM	440	314	300	427	275
Membrane CGHAZ	459	310	294	428	269
Membrane BM	237	230	233	446	281
T92-Ferritic Stainless Steel edge bar					
	AW	PWHT-30	PWHT-60	Norm	N&T-30min
Tube BM	254	241	240	455	278
Tube CGHAZ	472	322	308	435	275
WM	390	297	289	405	271
Edge bar CGHAZ	253	192	199	307	215
Edge bar BM	174	163	166	270	167

Hardness maps were made of the tube-to-membrane-bar welds for the T92-Grade 91 panels. The tube-to-membrane-bar was mapped for hardness in both the as welded condition and after post weld heat treatment for 60 minutes. Because of the coarse grain characteristics of the weld heat affected zone (HAZ) in Grades 91 and 92, samples were tested for hardness to assure that acceptable hardness was achieved after PWHT. As stated previously, a 30 minute PWHT was sufficient, but the shop prototype panels received a 60 minute PWHT for extra conservatism. Figure 3-f shows hardness maps of the T92-tube-to-Grade 91-membrane-bar welds in the as welded condition on the left and after PWHT for 60 minutes on the right.

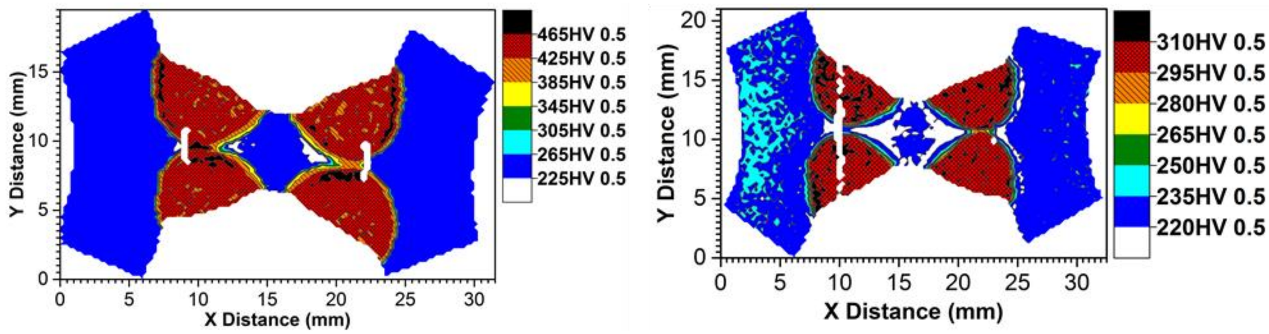

Figure 3-f As welded and PWHT hardness maps for T92-Grade 91 fin bar welds

Courtesy Electric Power Research Institute

A hardness map was made of the tube-to-edge-bar weld also. Figure 3-g shows the hardness map for the tube-to-edge-bar weld in the as welded condidtion.

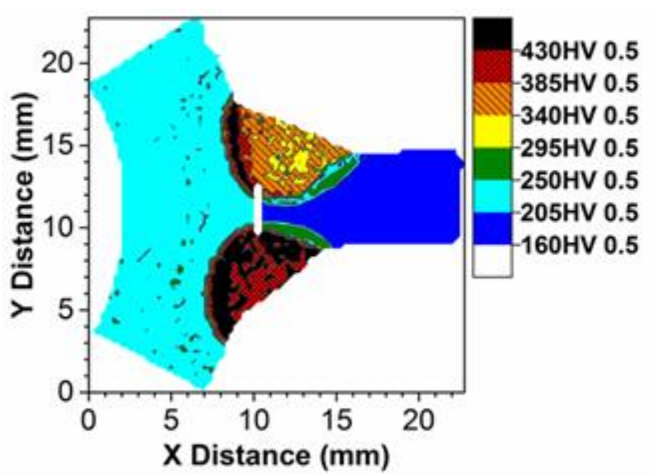

Figure 3-g As welded hardness map for T92-ferritic stainless edge bar welds

Courtesy Electric Power Research Institute

3.2.2 Shop Fabrication of Grade 92 Panels

Introduction

Three prototype test panels were fabricated using the PEMA six-torch moving tube continuous membrane welding equipment equipped with six Lincoln Powerwave® AC/DC 1000 power supplies in the Chattanooga Manufacturing facility. The panels were fabricated from 1.75″ OD X 0.282″ MWT SA-213 Grade T92 tubing using Grade 91 membrane bar material welded with an E9015-G (Gr.92 E9015-B9 mod.) wire and UV305 flux. The outer most edge bars were ferritic stainless steel material. The tubing was ~20' in length and the membrane/edge bars were ½" x ¼" x 10' (width x thickness x length) that were spliced to make 20' section to span the length of the tubing.

Sub-Panel Fabrication

A schematic of the sub-panel configuration is shown in Figure 3-h. The "two tube" sub-panels were fabricated first, followed by the "edge bar three tube" sub-panels (three tubes with four membrane bars requiring all six torches). The panels were preheated to 200°F using flame burners located below the moving tubes approximately 3' prior to the welding torches. In order to achieve the desired preheat temperature the tubes and membrane bars were tack welded on the leading edge and rolled back and forth across the burners. The panels were welded from one side (front side) then turned over and placed back into the machine to weld the second side (back side). After the two 'two-tube' sub-panels (4-5 and 6-7) were completed they were joined by dropping in a membrane bar to make a four tube sub-panel. The four tube sub-panel was then joined to the edge bar three sub-panels completing a ten tube panel. Care was taken while flipping and transporting the panels as to not introduce shock that could cause cracking. To simulate a tube repair/replacement, two 3' sections of T92 tubing were removed and replaced with T23 tubing. This tube butt weld was completed prior to sub-panel welding. The completed 10 tube panel and an image of the sub-panels prior to joining are shown in Figure 3-i.

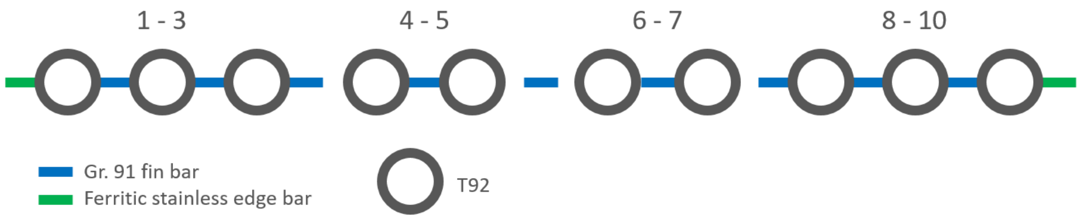

Figure 3-h Configuration and sequence of the sub-panel construction

Figure 3-i Completed sub-panels prior to final assembly (left) and completed 10-tube panel (right)

<u>Postweld Heat Treatment</u>

Prior to any PWHT, the temperature of the panel was dropped below 200°F to ensure the completion of the martensitic transformation. Panels were given a post weld heat treatment at 1350-1425ºF for a 1 hour hold followed by a still air cool. In an effort to minimize cracking potential during fabrication, sub-panels and completed panels required PWHT within 12 hours after welding. This would minimize the potential of hydrogen cracking and stress corrosion cracking associated with condensation at reduced temperature at night.

3.2.3 Inspection and Testing of Grade 92 Panels

Completed prototype panels were subjected to visual examination and approximately 25% of the welds were inspected using Magnetic Particle Testing (MT). Solidification cracks were observed at the weld centerline at several locations on the first completed 10 tube panel. A review of the welding parameters and consumables revealed that a suspect SAW flux had been loaded into the heated flux hoppers and used for welding a portion of the first 10 tube panel, which subsequently resulted in solidification cracks. The newly opened bag of flux flux (UV 305) was loaded into the flux feed system and an additional six tube panel was constructed to replace the first panel that was welded using the suspect flux. This highlights the fact that these panels require extra care, training, and attention to detail in the shop. In total, two (2) 10 tube panels and one (1) 6 tube panel were fabricated.

As expected, and is considered normal when manufacturing membrane panels, minor repairs were necessary due to stops-starts and occasional defects. Panels were repaired using standard Grade 91 welding procedures and the gas tungsten arc welding process. Minor MT indications were apparent on the second 10 tube panel at the weld centerline. A photograph of a typical MT indication is shown in Figure 3-j. There were no cracks evident on the surface of the weld deposit; however, the indication suggested sub-surface solidification cracks could be present. Sections were removed from the area for metallography and the presence of solidification cracking was confirmed just below the surface.

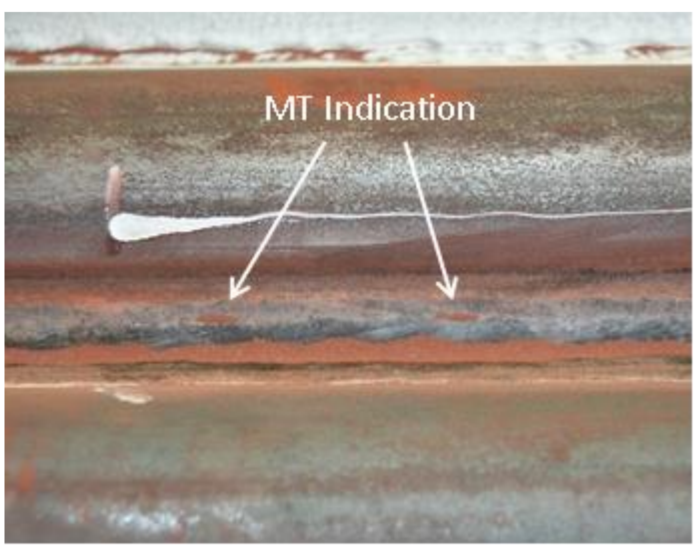

Figure 3-j NDE inspection showing an MT indication suggestive of intermittent centerline solidification cracking

A micrograph of the solidification cracking is shown in Figure 3-k.

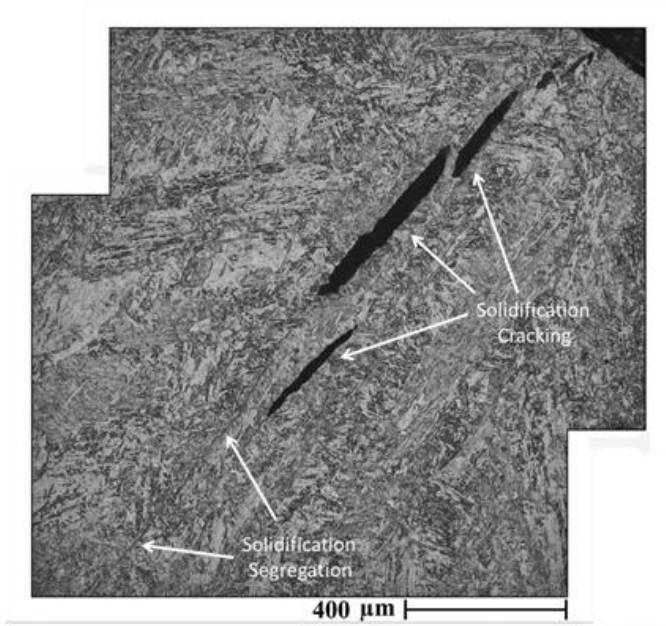

Figure 3-k Micrograph of solidification cracking and compositional segregation in the second 10-tube shop panel

Prior to fabrication of the third and final prototype panel, the welding parameters were adjusted to create a more convex weld shape and mitigate solidification cracking. Visual and MT inspections of the final panel did not reveal any indications or apparent cracks. Shrinkage measurements revealed that the Grade 92 panels closely resemble the shrinkage values for T23/T24 materials in current commercial units.

Panel openings were fabricated by hot pressing two tubes using a hydraulic press and die system. The membrane between the tubes was cut using plasma arc. The two tubes and adjacent areas were preheated to ~1250°F prior to bending. The tubes were sequentially bent (one and then the other) using an 8.5” die. After bending the panels were visually inspected and panels were given a final post bend heat treatment for 30 minutes. An image of the panel openings is shown in Figure 3-l.

Figure 3-l Photograph of the press openings in T92 sub-panels

A simulated "Dutchman" repair was done on one of the completed T92 panels. This portion of the work was done in the GE Boiler Services Rocky Mountain Service Center in Denver, Colorado. A three tube section roughly twelve inches in length was cut out from the panel to create the area to be repaired. Another three tube section that was twelve inches in length was cut from a different T92 panel to use as the repair element.

Standard shop procedures were used for the welding and PWHT. Photos of the repair are shown in Figure 3-m. This demonstrated the ability to make repairs in a shop environment. Heat treatment would be required for repairs made in the field, but that is current practice when making field repairs on T23 panels in commercial units.

Figure 3-m Shop Repair of T92 Panel Before Fill Out and After PWHT

Metallographic Examination and Hardness

Several specimens were removed from the final prototype panel (6-tube panel) for metallographic examinations. Macrographs from Tube 3 to Tube 4 (T3-T4) were taken at two locations along the length of the weld and are shown in Figure 3-n. Two locations were examined along the same weldment; Tube3-Tube4 Section A (left) and Tube3-Tube4 Section B (right) It can be seen in the micrographs that the weld contour was convex for three of the four welds while the top left weld exhibited a flat contour. During welding, all six SAW torches were set to identical settings. However, it is believed that the wire feed speed on one of the SAW machines was slightly slower than the others which resulted in the top left bead having a flat contour. This is significant because sub-surface solidification cracking was only present along this weld.

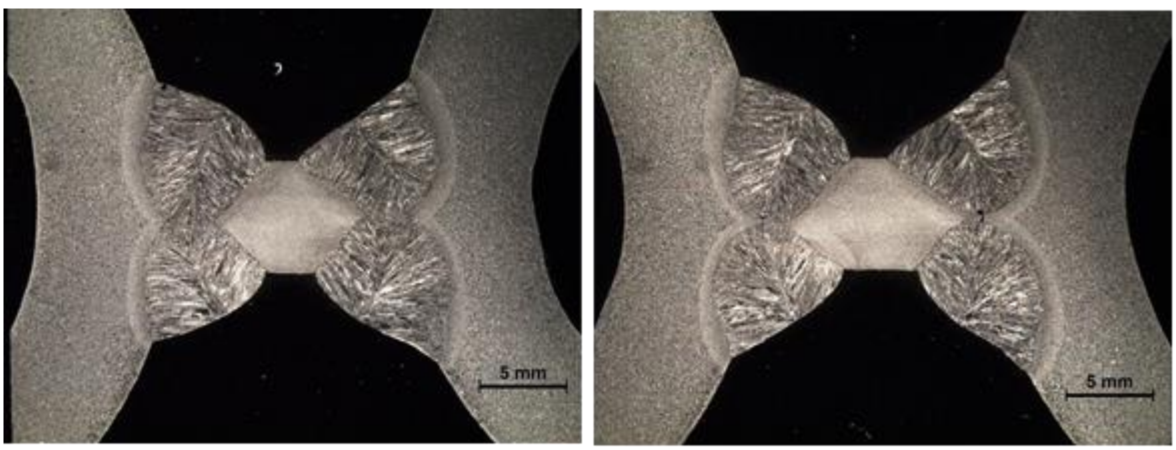

Figure 3-n Macrographs from the final T92 6-tube prototype sub-panel at T3-T4 weld.

Micrographs of the weld deposit, base metal, and heat affected zone (HAZ) of the T3-T4 weld are shown in Figure 3-o. The microstructure revealed an as-expected tempered martensitic structure. Region A1 shows sub-surface solidification cracking of the flat/concave weld. Region A2 shows the bulk weld deposit. Region A3 shows the Grade 91 membrane bar CG HAZ. Region A4 shows the T92 tube CG HAZ. Region A5 shows the T92 tube base metal.

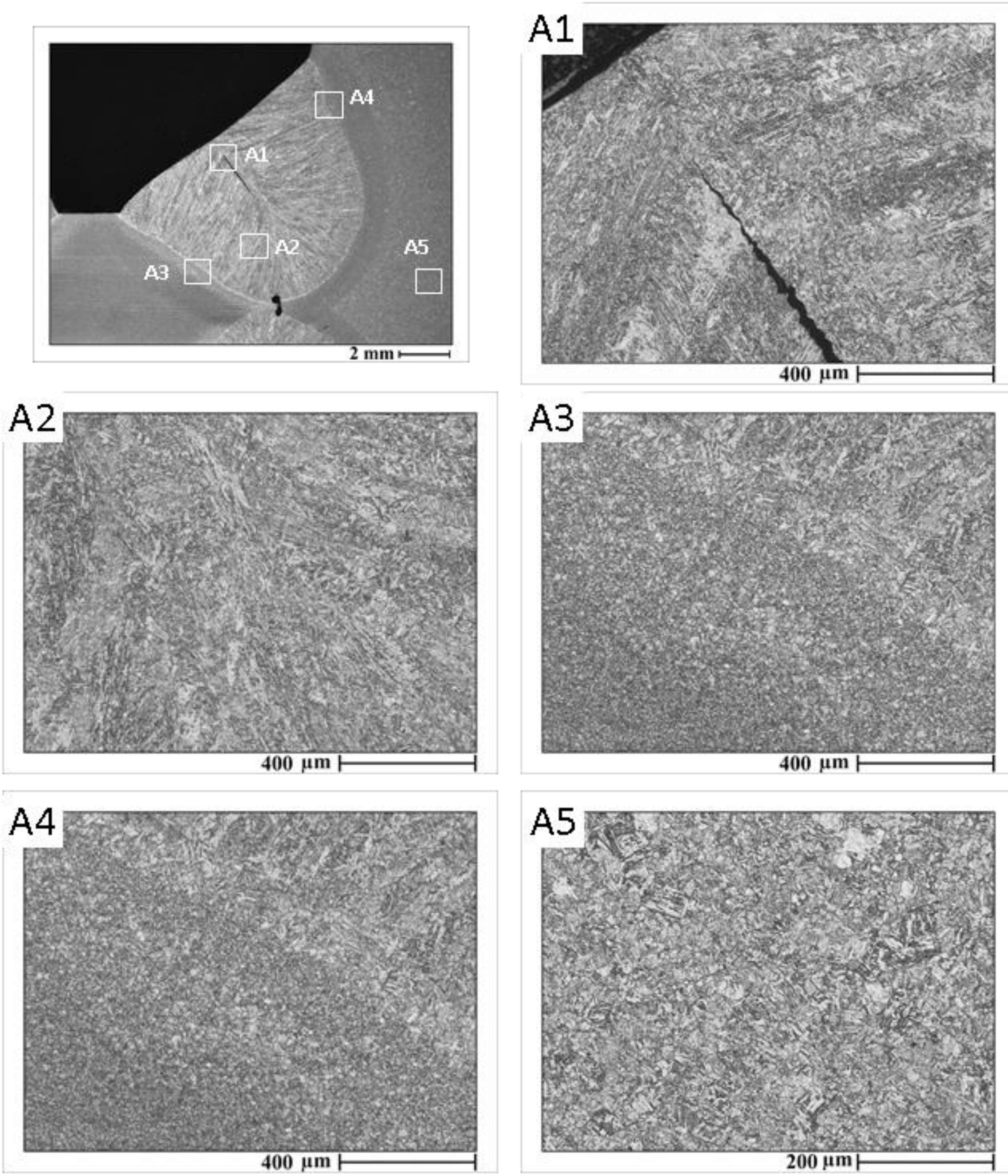

Figure 3-o Micrographs from the Tube3-Tube4 weld on the final T92 prototype panel

Hardness measurements for each region of the weldment are given in Table 3-d for the 6-tube shop panel for the weld between Tube 1 and Tube 2. It can be seen that the values fall within the normal Grade 91/92 hardness ranges.

Table 3-d Hardness measurement of T92 shop panel

Test Location	**HV Hardness**		
	Testing performed using a 500g test load		
	Average	**Range**	
		Min.	**Max.**
T92 BM (Tube)	234	232	236
T92 FG HAZ (Tube)	233	232	235
T92 CG HAZ (Tube)	304	302	307
Weld Deposit	301	294	306
P91 CG HAZ (Bar)	291	289	293
P91 FG HAZ (Bar)	266	253	280
P91 BM (Bar)	234	230	237

3.3 Prototype Manufacturing – HR6W Panels

Similar to the T92 panels, the Tasks were performed in two phases:

Lab Panels: Laboratory sized test panels were welded at the MTC to establish welding parameters and to determine the appropriate welding consumables to use for the fabrication of a shop panel. The laboratory panels were evaluated for weldability and destructively tested to ensure that current panel fabrication specifications could be maintained. Laboratory sized test panels were fabricated from UNS N06674 Code Case 2684 HR6W tubing and UNS N06625 Alloy 625 membrane bar.

Shop Panels: Prototype panels were fabricated using the PEMA six-torch moving tube continuous membrane welding equipment in the Chattanooga Manufacturing facility. Two panels were fabricated from UNS N06674 Code Case 2684 HR6W tubing and UNS N06617 Alloy 617 membrane bar.

3.3.1 Laboratory Fabrication of HR6W Panels

Introduction

In total, five sub-panels were made using three-foot long sections of tubing and two membrane bars. They were welded in the MTC laboratory using the Lincoln Powerwave® AC/DC 1000 submerged arc welding equipment. A typical laboratory panel is shown in Figure 3-p. The tubing used was 1.50″ OD X 0.250″ MWT UNS N06674 HR6W tubing. Laboratory panels were fabricated using UNS N06625 Alloy 625 membrane bar material welded with an Inconel 617 filler metal and IncoFlux NT100 SAW flux. Shop prototype panels were welded using Alloy 617 membrane bar and lab test sized panels were welded using Alloy 625 membrane bar due to material availability and sourcing. Due to the limited number of consumables available for the material combination, no other wire/flux combinations were tested.

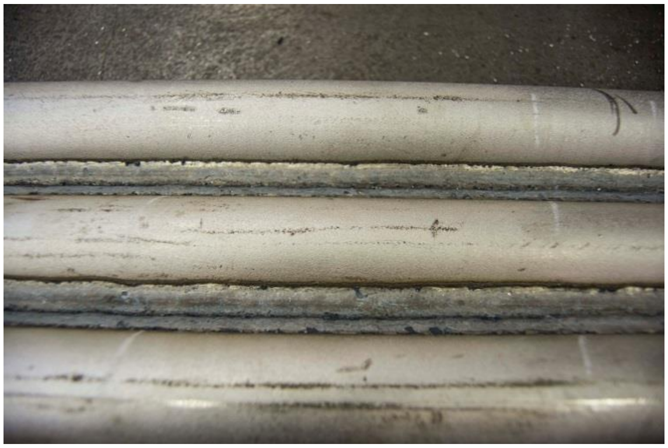

Figure 3-p Example of three-tube laboratory scale HR6W panels fabricated at the MTC

Each laboratory panel was sectioned at two locations and visually inspected (10X magnification) to ensure that current panel fabrication specifications could be maintained. A chemical analysis, reporting the major elements of the weld deposit, HR6W tubing and Alloy 625 membrane bar are compared in Table 3-e.

Table 3-e Chemical Composition of HR6W laboratory panel

Chemical Composition (Weight Percent)				
Element	HR6W Tubing	Weld Deposit	625 Membrane*	617 Filler Wire*
Carbon	0.074	0.056	0.010	0.083
Manganese	0.93	0.30	0.09	0.02
Phosphorus	0.010	0.007	0.005	0.003
Sulfur	0.007	0.008	0.001	0.001
Silicon	0.25	0.20	0.15	0.04
Nickel	44.46	54.77	62.8	55.20
Chromium	21.94	23.18	22.72	22.60
Molybdenum	0.10	7.621	8.77	9.00
Vanadium	0.058	0.022	--	--
Niobium	0.15	1.32	3.38	--
Titanium	0.093	0.23	0.19	0.30
Cobalt	0.309	4.799	0.05	11.30
Copper	0.06	0.06	--	0.000
Aluminum	0.037	0.437	0.12	1.20
Boron	0.001	0.0012	--	--
Tungsten	9.37	1.41	--	--
Iron	22.08	5.50	1.50	0.20
*per CMTR				

Inspection and Testing

Each labortory panel received a visual inspection of each weld on the panel to ensure compliance with the following rejection criteria:

- Burn-Through
- Lack of Fusion
- Skips
- Undercut
- Cracks
- Porosity greater than 1/16” diameter

In no case were the panels found to exhibit any of the above and were considered acceptable based on the nondestructive visual inspection. Cross sections were removed from representative locations along the length of each panel and prepared for metallographic examination. The cross sections were visually inspected with the aid of the stereomicroscope

(10X magnification). There was no evidence of any cracking occurances while welding the labortory panels and the welding parameters were adjusted for bead shape and penetration. As expected, the depth of penetration into the tube and membrane bar was significantly reduced when compared to CrMo panel welds using SAW. Representive samples from select labortory panels were mounted and polished for metallography and hardness measurements.

Metallographic Examination and Hardness

As-welded specimens were prepared for metallography and hardness measurements. A macrograph of a three tube laboratory panel cross-section is shown in Figure 3-q.

Figure 3-q Macrograph of three tube HR6W laboratory panel

A Hardness survey for each region of the selected weldment on a 3-tube lab panel is shown in Table 3-f. No anomalies were noted with the hardness and metallographic examination and therefore the welding parameters were considered acceptable for shop fabrication of the prototype panels.

Table 3-f Vickers Hardness measurements for HR6W laboratory panel, as-welded condition

Test Location	HV Hardness		
	Testing performed using a 500g test load		
	Average	Range	
		Min.	Max.
HR6W BM (Tube)	184	170	195
HR6W HAZ (Tube)	195	190	200
Weld Deposit	219	217	223
Alloy 625 HAZ (Bar)	243	240	246
Alloy 625 BM (Bar)	250	247	252

3.3.2 Shop Fabrication of HR6W Panels

Introduction

Two 10-tube prototype test panels were fabricated using the PEMA six-torch moving tube continuous membrane welding equipment equipped with six Lincoln Powerwave® AC/DC 1000 power supplies in the Chattanooga Manufacturing facility. The panels were fabricated from 1.50″ OD X 0.250″ MWT UNS N06674 HR6W tubing and the membrane bar was UNS N06617 Alloy 617 material. Shop panels were welded with an Inconel 617 filler metal and IncoFlux NT100 SAW flux. The tubing was ~197” (5 meters) in length and the membrane/edge bars were ½” x ¼” x 100” (width x thickness x length); they were spliced to make 200” membrane bars.

Sub-Panel Fabrication

A schematic of the sub-panel configuration is shown in Figure 3-r. The “two-tube” sub-panels were fabricated first, followed by the “edge bar three-tube” panels (three tubes with four membrane bars requiring all six torches). The welding parameters were established during the laboratory weld trials and no preheat was needed for this alloy.

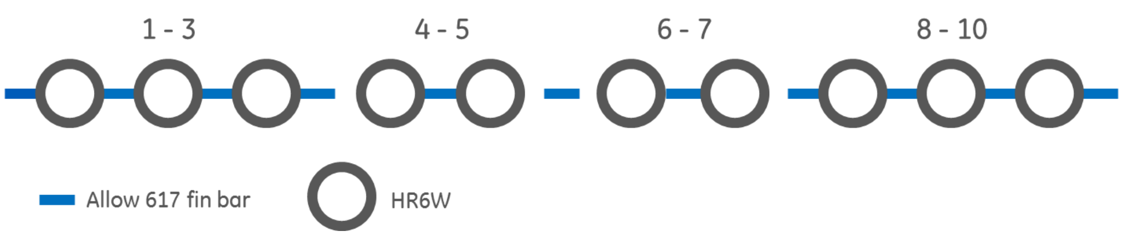

Figure 3-r Configuration and sequence of the HR6W sub-panel construction

It was quickly determined that welding with multiple power sources at once affected the weldability. The initial welding parameters were set using a single SAW torch. When multiple torches were used during shop welding, the total heat input into the tubes increased; therefore, the welding parameters (voltage and amperage) were reduced to account for the added heat input.

All panels were welded from one side (front side) then turned over and placed back into the machine to weld the second side (back side). After the 2-tube sub-panels were completed they were joined by dropping in a membrane bar to make a 4-tube sub-panel. The 4-tube sub-panel was then joined to the edge bar 3-tube sub-panels, thereby completing a 10-tube panel. The completed 10-tube panels are shown in Figure 3-s.

Figure 3-s Completed HR6W 10-tube shop sub-panels

3.3.3 Inspection and Testing of HR6W Panels

Completed prototype panels were subjected to visual examination and repairs were completed using the gas metal arc welding process (GMAW). The majority of repairs were stops/starts that were related to wire feed issues that required all welding to stop and the replacement of a contact tip. The wire was 1/16” diameter and a corresponding 1/16” contact tip was used; however, it was determined that the manufacturer-specific contact tips were slightly undersized.

By switching to a different brand tip, the wire feed issues were mitigated. No solidification cracks were observed during the visual inspection.

Shrinkage measurements revealed the center tube on the edge bar three sub-panels (T2 & T9) shrank ~7/10 of an inch during welding. The 2-tube sub-panels (T4 through T7) did not exhibit any shrinkage in length. The shrinkage is believed to be associated with the sub-panel welding sequence having lower heat input for tubes T4 through T7. The 4-tube sub-panel was made by first welding two pairs of tubes with one membrane bar (Tube 4-Tube 5 and Tube 6-Tube 7), then T5 and T6 were joined by dropping in a membrane bar to make the 4-tube sub-panel. This configuration resulted in a lower heat input in comparison to welding the edge bar 3-tube sub-panels which utilized all six SAW torches.

Panel openings were accomplished by cold pressing two tubes using a hydraulic press and die system. The membrane bar between the tubes was cut using plasma arc. After bending the panels were visually inspected and were given a final post bend solution anneal at 2100°F for 15 minutes followed by cooling in still air. An image of the press openings is shown in Figure 3-t.

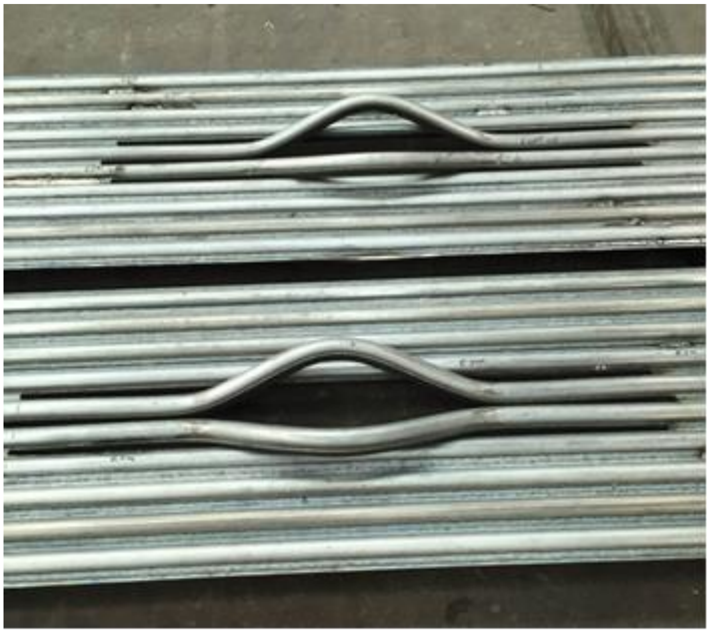

Figure 3-t Press openings in the HR6W panels

Metallographic Examination and Hardness

Several specimens were removed from a completed HR6W panel for metallographic examination. Macrographs from Tube 4 to Tube 5 (T4-T5) and Tube 6 to Tube 7 (T6-T7) are shown in Figure 3-u. Due to the low thermal conductivity and the viscous molten weld puddle associated with welding nickel alloys, the penetration into the membrane bar was limited. It was suggested that the membrane bar be beveled to increase penetration if additional penetration is needed.

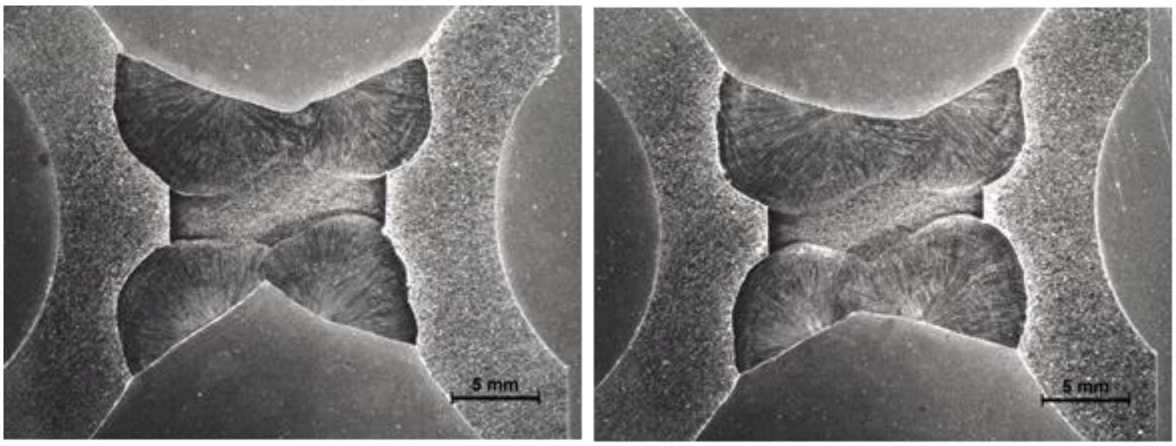

Figure 3-u Macrographs from a HR6W panel at T4-T5 weld (left) and T6-T7 (right)

Micrographs of the weld deposit, base metal, and HAZ of the T6-T7 weld are shown in Figure 3-v. Region A1 shows the weld metal. Region A2 shows the tube fusion zone. Region A3 shows the membrane bar fusion zone. Region A4 shows the tube base metal. The microstructure did not reveal any anomalies or discontinuities.

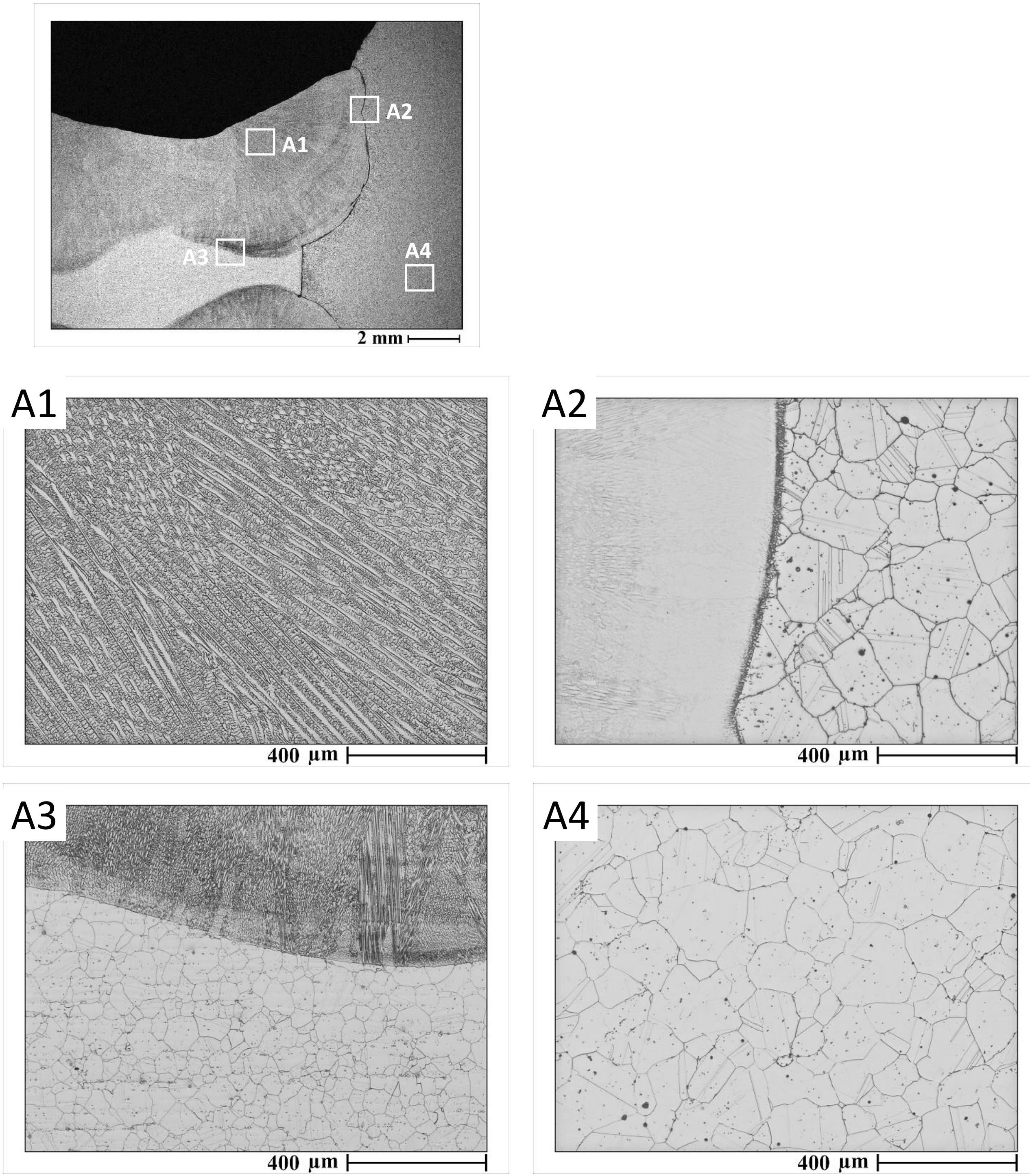

Figure 3-v Micrographs from the T6-T7 weld on the HR6W prototype panel

Hardness measurements for each region of the weldment for the Tube 4 and Tube 5 weldment in the solution annealed condition are given in Table 3-g.The table shows that the values fall within the normal range for HR6W and Alloy 617 materials.

Table 3-g Hardness measurement of HR6W shop panel

Test Location	HV Hardness		
	Testing performed using a 500g test load		
	Average	Range	
		Min.	Max.
HR6W BM (Tube)	211	211	211
HR6W near fusion line	202	197	206
Weld Deposit	212	203	218
617 near fusion line	240	235	247
617 BM (Bar)	216	218	214

4 Conclusions

It has been demonstrated that maintaining the overall quality of a 9-Cr membrane panel during fabrication is feasible with the proper attention to the thermal requirements of Grade 92/91 for preheating and PWHT. The risk of hydrogen induced cold cracking can be reduced by control of the flux throughout the system and through the use of preheat, extended preheat, interstage postweld heat treatments, and the careful handling in the as-welded condition. Without the proper attention necessary during the fabrication of Grade 92/91 components, the overall quality and therefore serviceability of the welded panel could be jeopardized. Solidification cracking is a risk that requires tight control of the welding process in order to reduce this risk The panel fabrication sequences should be planned well enough that excessive gaps in the weld joint and other contributors to a concave weld bead are eliminated. Based on the results, convex welds appear to be necessary.

In addition to the concerns associated with cold cracking and solidification cracking, stress corrosion cracking must also be considered. Each fabricated panel will need to be stored in an area where it will remain completely dry until an interstage or final postweld heat treatment is performed. It is likely that the only way to maintain complete dryness of the entire component is to have a holding oven the for the sub panels until final assembly and immediate postweld heat treatment. A photograph of the completed Grade 92/91 prototype panel is shown in Figure 4-a.

Figure 4-a Completed 26-tube Grade 92 membrane panel

Shrinkage, bowing, cupping, ovality and other dimensional distortions after welding were within normal ranges for membrane panels when fabricating using the T92 material. These prototype panels were roughly one-fourth the size of commercial scale membrane panels, so there is potential for more dimensional distortion when fabricating the 10’ wide by 40’ long membrane panels typical of commercial applications.

Laboratory trials were conducted with both Grade 91 and Grade 92 welding wire for fabrication of the T92 panels, and there were no differences in weldability between these two welding wire materials. Two fluxes were chosen for T92 panel fabrication, and both the UV305 and Marathon fluxes had good performance.

The next step required for AUSC membrane panel development is fabrication of larger panels, field erection of larger panels, and steam-cooled operation of larger panels for an extended period of at least one year. This will provide some operating experience with AUSC membrane panels to better validate the fabrication and field erection procedures by subjecting the panels to the one sided heating, mechanical stresses, and thermal cycling at steam temperatures in the range of 700-900 °F.

The successful fabrication of a nickel based HR6W membrane panel further progresses the AUSC technical readiness level. It was demonstrated that conventional fabrication/joining techniques can produce satisfactory results given the proper attention to details. Because there were no preheat and no PWHT requirement for HR6W, production time for the HR6W panels was faster than the T92 panels. High quality welds that are crack free can be attained with the proper welding parameters and consumables.

Key details to note are the importance of travel speed and overall heat input to the nickel based panel while utilizing multiple welding torches. Another factor to consider is the depth of penetration into the membrane bar. It is assumed that proper heat conduction can be achieved with marginal weld penetration and thus the current convention requiring near complete joint penetration should be reviewed. The HR6W prototype panels are shown in Figure 4-b.

Figure 4-b HR6W prototype panels after the post-bend heat treatment

Shrinkage, bowing, cupping, ovality and other dimensional distortions after welding were within normal ranges for membrane panels when fabricating using the HR6W material. These prototype panels were roughly one-fourth the size of commercial scale membrane panels, so there is potential for more dimensional distortion when fabricating the 10' wide by 40' long membrane panels typical of commercial applications.

Internal processes were used to adapt internal procedures for the existing fabrication specification for a fin-welded membrane panel to include panels fabricated from:

- Grade 91 and Grade T92 alloys (Code Case 2179)
- ASTM B167-11, UNS N06674 (CC 2684, HR6W – 47Ni-23Cr-23Fe-7W) and UNS N06617 (Alloy 617) Materials

References

1. DOE/NETL Topical Report, "Boiler Materials for Ultra Supercritical Coal Power Plants" February 2003

2. "Run Hotter but Take Care," Power Engineering International June 2014 No. 6, pp 35-39