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CRBRP MODULAR STEAM GENERATOR TUBE-TO-TUBESHEET AND SHELL-CLOSURE WELDING

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The original Modular Steam Generator (MSG), which was designed, built, and tested by the Energy Systems Group (ESG) of Rockwell International, was a departure from conventional boilers or heat exchangers. The design was a "hockeystick" concept — the upper section of the generator is curved 90°. Factors affecting operating parameters were considered and incorporated in the original MSG design. The MSG was fully instrumented and functionally tested at the Energy Technology Engineering Center at Rockwell. The MSG steamed continuously for over 4,000 h, and at the conclusion of the 9,000-h test cycle, it was systematically dismantled and examined for wear to critical components. This paper explains the solutions to several manufacturing challenges presented by the unique design of the MSG.

The original MSG was manufactured to meet the requirements of the ASME Boiler and Pressure Vessel Code Section III, Class I, Subsections NA, NB, and all pertinent sections of the Code referenced by Section III. The manufacturing processes for production and quality assurance were conventional, and the hardware was easily produced using submerged arc welding for rotatable sections of the hardware and manual gas tungsten arc root, shielded metal arc fill passes for the elbow sections, and final closure welds of the nonrotatable sections of the generator. Tube-to-tubesheet welding was accomplished using a weld-cast into backup-tooling process and inspected using conventional gamma-ray techniques.

Based on the success of the MSG program, Rockwell was selected to manufacture steam generators for the Clinch River Breeder Reactor Program (CRBRP) to the following inspection criteria. Inspection procedures and equipment were developed that detected tube-to-tubesheet weld defects as small as 0.002 in. in diameter. Allowable defect level was decreased by specification to 0.022 in. total diameters. Linear indications of any type were unacceptable.

The challenges presented, particularly in the tube-to-tubesheet and closure welding phases of assembly, were met by advancing the state of the art of equipment and procedures for welding, preheating, postweld heat-treating, and inspection. The equipment developed for tube-to-tubesheet welding consisted of a Rockwell-designed inbore welding torch, a precision current source, and the adaptation of a delta pressure purge panel to control the balance of pressures between the inside diameter shielding gas and the outside diameter purge gas. Preheat and postweld heat-treat equipment consisted of a computer-controlled temperature monitor and clamp-on cartridge heating elements. Inspection techniques were developed and implemented that produced easily interpretable radiographs of the completed weld. The X-ray equipment was inserted in the bore of the tube and the film positioned on the OD of the weld. Over 1,500 welds were completed with a weld-related rejection rate of <1%.

The equipment developed for closure welding consisted of a gas metal arc welding unit equipped with an 8080A CPU-based computer (which controlled torch height and cross-seam position) and a newly developed dwell boost feature. The dwell boost feature allowed for a controlled increase in power levels during dwell periods of cross-seam oscillation. This feature was extremely important to closure welding (discussed below).

The equipment was used to deposit 6.8 miles of weld bead with a reject rate of 0.013%.

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A. TUBE-TO-TUBESHEET WELDING

The quality levels required for the steam tube-to-tubesheet welding were stringent. Weld porosity was considered rejectable if total diameters amounted to 0.022 in. A single pore of 0.011 in. diameter was rejected, and the weld was repaired or removed and rewelded. Weld profile was controlled within narrow limits. Concavity could not exceed 0.010 in., and maximum weld reinforcement could not exceed 0.010 in. for both inside and outside diameters. The narrow limits imposed for weld imperfections required a welding procedure that could reliably meet those limits and welding equipment that could repeat on a weld-to-weld basis within 4% of the total controllable and uncontrollable welding variables (i.e., welding current, voltage, travel speed, gas pressure and flow rate, tungsten configuration, tungsten clamping pressure, and other controllable variables could not exceed ±2% of the qualification level). To meet the 4% requirement, controllable variables (e.g., current, voltage, travel speed) were controlled to within 0.1% or better. This allowed for some drift in uncontrollable parameters (e.g., cleaning fitup, tooling tolerances) that are subject to operator judgment. To minimize the effect of uncontrollable parameters, two extreme measures were employed: (1) a clean room atmosphere was established during assembly and welding and (2) inspection points were inserted for each critical assembly step, including the setting of weld parameters. The continued enforcement of procedure verification resulted in the ability to attain the goal of uncontrollable parameter variations of within ±2%.

The tube-to-tubesheet welding was performed in the 5-G position from the inside of the tube bore. The position of welding and the inability to see the progressing weld demanded a method to ensure that the desired weld bead profile could be reliably attained. Welding in the 5-G position, we would expect a droop of the weld root at the 6:00 position and a droop of the weld face at the 12:00 position, which would exceed the 0.010-in. concavity limit. The use of a delta-pressure purge control plus the gas tungsten pulsed arc welding process permitted the close control of weld bead profile; the delta pressure purge control maintained a preset differential pressure between the inbore gas purge and the OD gas purge. The differential pressure aided in producing the desired weld profile. The pulsed arc GTAW process equipment provided sufficient time at the low portion of the current pulse for the weld to solidify in short intervals. Exact reproducibility of pulse time intervals, travel speed, and low/high current levels produced the effect of controlled overlapping spot welds. The combination of the differential pressure control and the pulsed arc process provided the control necessary to reliably produce a weld profile well within the specified limits.

In addition to the rigid in-process control previously mentioned, two (each) process control specimens were welded at the start of each shift on tube-to-tubesheet welding.

In the actual welding sequence, welding at each end of the tube was staggered to ensure that gas leak rate and pressure were not affected by both ends of the tubes being sealed simultaneously. The resultant weld quality was excellent: rejection rate of <1% of total weld length, thus proving the techniques used.

Postweld heat-treating of tube-to-tubesheet welds was accomplished using a PWHT console designed and built by Rockwell.

B. OUT-OF-POSITION GAS METAL ARC WELDING

The hockeystick design of the MSG for the CRBR produced a major challenge for economically completing the closure welds of the modular steam generator hardware. The major design challenge was the inability to rotate weld joints past a fixed point. Conventional processes, such as submerged arc welding, could not be used on 14 major weld joints of the generator. GTAW welding was judged unsatisfactory due to the low deposition rate of the process.

GMAW welding had the most desirable process characteristics, although there was doubt as to its ability to produce a high-quality weld at a reasonable deposition rate. An industry-wide search for GMAW technology disclosed that its use was restricted to the flat 1G position and usually to the spray arc mode of operation. Therefore, a weld development program (including welding process and equipment) was clearly needed.

The weld development program was conducted as follows. We began with initial equipment selection, process gas and wire selection, bead on plate test welds, and 2-in.-thick groove welds in the 3G and 4G positions. This stage showed that quality GMA welds could be produced if the parameters were closely controlled.

It became obvious that successful welding on steam generator components would require better than ordinary equipment and process control. The main objective was to remove as much of the operator's influence on process application as possible. The removal of operator influence included height control (contact tube-to-work distance) and torch position (seam tracking).

Two welded plate samples were made and subjected to NDE and destructive testing. The quality of the weld deposit was excellent.

Prototype equipment was assembled and installed on an 80-in.-diameter track. Two 56-in.-diameter test parts, 10 in. wide x 4-1/2 in. thick, had been machined to the joint configuration shown in Fig. 1. The mechanical portions of the equipment for the GTAW root pass consisted of drive system, arc weld head, wire feeder, and oscillator. The electrical equipment included controls for the drive, oscillator, wire feeder, and arc head. All of the electrical controls were integrated through a 450-A current source equipped with a special sequence control panel. The sequence control panel provided start and stop delay functions for the oscillator, wire feeder, arc, and travel.

Preliminary tests showed that the travel speed of the equipment as it translated around the track varied by up to 7%. The situation was corrected by using a closed-loop servo system. The initial weld pass (root) was irregular with lack of penetration, holes, and lumpy bead appearance (Fig. 2).

The equipment was rearranged and assembled for the GMAW mode of operation as shown in Fig. 3. The minor weld spatter was shown (by high-speed motion pictures of the welding arc) to result from the periodic short circuiting that was occurring particularly during the dwell periods of oscillation. The current source was completely checked out and recalibrated. The maximum pulse rate obtainable was 20 pulses/s. This was verified by the Standards and Calibration lab.

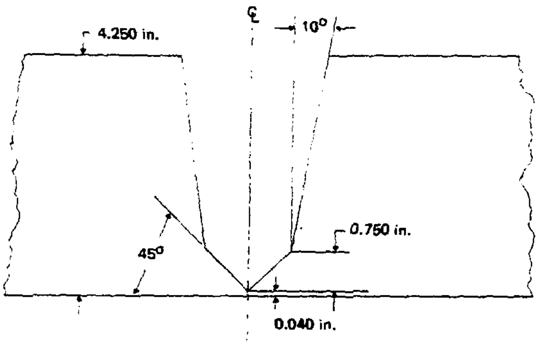

Figure 1. Production Joint Design

Figure 2. Root Pass Showing Erratic Weld Deposit

Figure 3. Prototype Welding Head

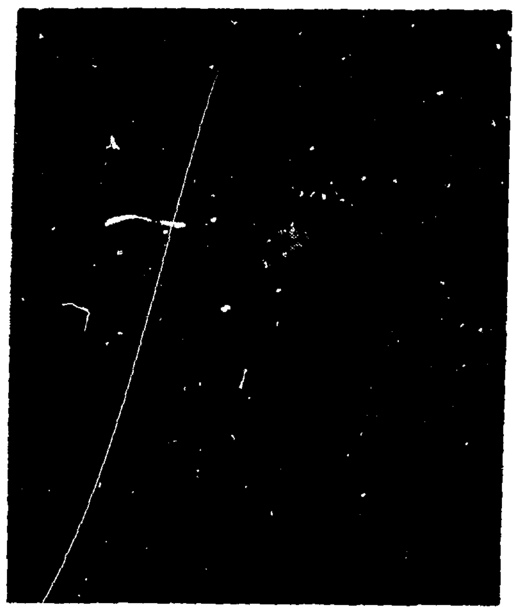

Figure 4. Production Welding Head

The mode of transfer remained in the short circuiting range (i.e., 110 A, 21 V) for the remainder of the ∿45 weld passes eventually completed. The deposition rate was measured, using the wire feed rate, to be ∿3 lb/h. To improve this rate and eliminate the spatter buildup in the gas shielding cup, a more versatile power supply was sought by bid. One manufacturer agreed to comply with the specification and also to provide certain improvements (e.g., high pulse, synchronized pulsation, constant voltage on demand wire, constant current). Preliminary results from sample welds made using a prototype GMAW unit were dramatic: arc stability was exceptional, weld freeze lines were uniformly spaced, and the weld was virtually spatter free. Additionally, a deposition rate of 5 lb/h was easy to obtain in the 3G vertical up position. However, further testing was needed.

The final equipment used is shown in Fig. 4. Procedure qualification was conducted, tested, and accepted in accordance with specification requirements.

The initial production closure welds, welds 1 and 10, were completed in July 1980. Weld 10 (upper tubesheet-to-reducer) was flawless. Weld 1 (lower tubesheet-to-reducer) had three minor defects which were repaired. The final closure welds, welds 37 and 91, were completed in June 1981. Single minor defects were discovered and repaired in both. A final quality level of <0.013% of deposited weld bead was considered well within acceptable manufacturing standards (Fig. 5).

C. CONCLUSION

The initial challenges for inbore tube-to-tubesheet welding and closure welding of the steam generator caused by extremely rigid quality requirements and the unique design of the generator were successfully met by the development of equipment and welding techniques which assured that production rates and quality levels could be consistently met. The solutions to the challenge of out-of-position welding with the GMAW process was innovative and resulted in the issuance of a U.S. patent for process and equipment. Welding modular steam generators of the "hockeystick" design can be accomplished with relative ease and confidence based on the results of the prototype generator.

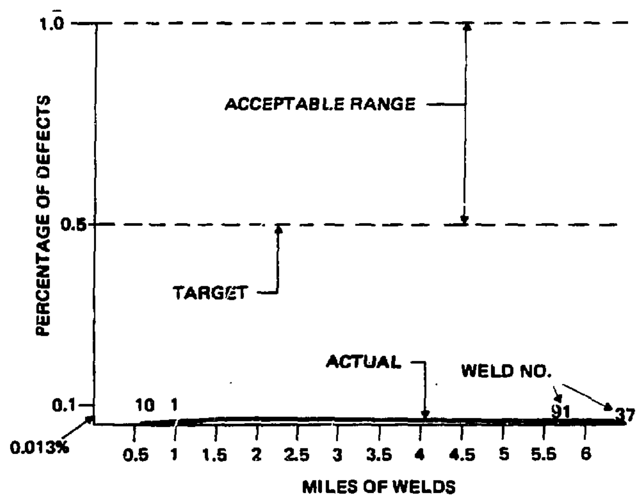

Figure 5. Welding Quality Obtained During Production Welding of Steam Generator