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FABRICATION AND INSPECTION DEVELOPMENT FOR CRBRP STEAM GENERATORS*

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ABSTRACT

One of the critical nonnuclear elements of the CRBRP is the steam generator that transfers the heat from the sodium system to the high-pressure steam system but must maintain integrity and separation of the two fluids. The construction material is 2 1/4 Cr-1 Mo alloy steel with high-purity (e.g. vacuum arc remelt) material being used for the tubing and tubesheets. For confidence in successful manufacturing of the several evaporator and superheater modules, key development activities are under way (1) for procurement of high-quality components, (2) to assure proper assembly (with emphasis on welding), and (3) to assure that adequate nondestructive testing methods are available to examine the units.

INTRODUCTION

One of the most critical of the nonnuclear elements of the CRBRP plant is the sodium-heated steam generator system, because of demands for high reliability of the sodium-to-steam/water boundary and the necessity to make the system capable of safely accommodating any failure of this boundary and the resulting sodium-water reactions that could occur. These demands are in addition to functional performance for extracting heat from the reactor to deliver high-temperature steam to the turbine at acceptable operating costs.

The design approaches for all the main elements of the steam generator system have been established and work is proceeding to final design, specification, and procurement of the equipment. Additionally, the necessary development and testing is being implemented under the CRBRP project and the ERDA-sponsored national steam generator development program, with General Electric the technical manager of this effort.

The construction material chosen for the superheater and evaporator units is 2 1/4 Cr-1 Mo alloy steel. The pressure boundaries are to be designed and manufactured as Class I according to procedures of the *ASME Boiler and Pressure Vessel Code,* Section III. Special care will be taken to design and fabricate the sodium/water boundary (tubes, tubesheets, and tube-to-tubesheet welds) to assure the desired success for in-service performance. The tubing and the tubesheet forgings will be prepared from high-purity material achieved by special fabrication processes such as vacuum arc remelting (VAR), in order to minimize flaws in the tubing and to improve the quality of the critical tube-to-tubesheet welds. The tube-to-tubesheet welds are the only welds in the tubing and are full-penetration butt welds between the tube ends and machined bosses on the tubesheets. Full-circumferential radiographic inspection will be made of every tube weld, with stringent limits on allowable porosity and other possible flaws. Extreme care is being employed in the design of the tube supports so that damaging tube vibration and wear of the tubes and the tube supports will be avoided.

To assure success in the correct manufacture of the components, key development activities have been initiated with expected results prior to undertaking fabrication of the plant units. Significant development items now under way are:

(a) Tubing and tubesheet qualification, especially the characteristics of VAR and electroslag remelted (ESR) reference alloy including weldability, NDT, and compliance of mechanical properties to minimum Code requirements.

(b) Welding development, tube-to-tubesheet joint (in-bore welding jigs and process).

(c) NDT inspection methods, development, and standards (e.g., x-ray anode, isotopic sources, ultrasonic back-up methods).

(d) Fabrication of Few Tube Test Model — (combine prototypical geometries and material, solve some handling and tube-spacing problems).

(e) Fabrication of a steam generator prototype, (full-size with all materials and processes identical to plant units will provide assembly, handling, and shipping experience).

(f) Development of "formed elbows" and "pulled nozzles" instead of miter joints and "paste-on" nozzles.

(g) Friction and Wear Tests in sodium to provide design basis for tube support hardware.

All of the above programs have either been initiated or are now under way. Critical areas of manufacturing and inspection procedures are reviewed in this report. Whenever appropriate recent results are described.

FABRICATION OF COMPONENTS

Tubing and Tubesheets

To ensure high integrity of the sodium/water boundary, the program places heavy emphasis upon metallurgical cleanliness of tubing and tubesheets that is to be attained through the use of VAR or ESR techniques. The primary objectives in specifying the melting practice were: (a) to reduce the size and quantity of inclusions in the tubesheet stubs, (b) to minimize or eliminate defective welds between the tubes and tubesheet stubs, and (c) to reduce residual impurities in the 2 1/4 Cr-1 Mo alloy that are likely to induce post-weld embrittlement. Standards prepared were: (a) Tubing: RDT M3-33T, using ASME SA-213 as the base and (b) Tubesheet Forgings: RDT M2-19T, using ASME SA-336 as the base.

In specifying chemical composition, phosphorus and sulfur were limited to 0.015%, carbon to 0.110%. The range for silicon content was set between 0.10 and 0.50% to accommodate expected variability in the ESR process. Low phosphorus and sulfur are required to obtain freedom from creep and temper embrittlement for the reference alloy during the lifetime of the steam generators (1). Weldments of 2 1/4 Cr-1 Mo have been reported to suffer embrittlement when exposed to the temperature range of 600–1100°F (320–590°C). In addition, a positive shift in nil ductility transition temperature has been reported with increasing phosphorus content. Empirical correlations proposed to arrive at "embrittlement factors" in weld deposits assign phosphorus as the most critical impurity:

$$\bar{x} = \frac{10P + 5Sb + 4\ Sn + As}{100} \quad .$$

Phosphorus, sulfur, and carbon are controlled primarily during the electric furnace arc melting stage of steel making using basic reducing slag (2). The upper carbon limit of 0.110% is desired to facilitate welding and restrict the available carbon likely to be dissolved into sodium via decarburization of 2 1/4 Cr-1 Mo at temperatures above 700°F (370°C). Several ton-sized heats of the reference material produced in this country by both ESR and VAR processes have met the desired chemical specifications. It is estimated that the two-stage melting (electro arc, then vacuum remelting or electroslag) results in 20–40% added costs over air melted ingots of this alloy.

A high degree of microcleanliness is desired to ensure freedom from inclusions and porosity at the tube-to-tubesheet welds and to yield clean cross sections at the "spigots," machined onto the tubesheets. Although the standard for the tubesheet forging specifies an ingot-to-forging reduction of 2 to 1 (to obtain randomly oriented grain size and a break down of the as-cast structure) the size of the CRBRP tubesheet forging is small enough to permit ratios up to 5 to 1, which have been recommended by the fabricators.

The desired full anneal is a heat treatment easily obtained for the massive forgings (tubesheets), but poses special problems in the case of 70-ft long tubing. Austenitizing to 1700°F (927°C) followed by direct cooling to 1300°F (704°C) and isothermally holding for at least 2 hr is recommended to obtain a high percentage (∿80%) of polygonal ferrite, with the remainder being tempered bainite (1). The microstructures obtained by this heat treatment have superior properties of creep rupture and creep-fatigue because of the stability of Mo_2C in ferrite. It has been shown that the annealed microstructure embrittles less than a normalized and tempered microstructure for this material when held at service temperature for long periods of time (3). Detailed studies show that either annealed or normalized and tempered [4 hr at 1350°C (740°F)] heat treatments are acceptable provided that a maximum tensile strength of 586 MPa (85 ksi) at room temperature is imposed in addition to a post-weld heat treatment at 1300°F (700°C) for 1 hr (1).

Heat treatment of tubing lengths of 70 ft (21.5 m) limit the number of tube producers, as long furnace heat zones are needed to obtain the "full anneal." The isothermal anneal specified can be obtained in atmosphere-controlled furnaces that are available. The specified heat treatments coupled with the use of VAR or ESR material should provide freedom from embrittlement at service conditions. (Dimensional tolerances and limits on size of wall defects (3%) can be achieved by either cold-drawing or cold-reducing processes of tube manufacturing provided the starting "tube hollows" are mechanically conditioned to narrow wall tolerances.) It is estimated that 20—30% of the final tube prices will be due to dimensional tolerances stricter than the ASME Standard. (Table I)

Shell and Mitered Elbow Joints

The shell for the steam generator will be fabricated from plate ordered in accordance with the requirements of SA-387, supplemented by certain additional requirements in order to subsequently upgrade the plate to RDT M5-22T. This approach was taken due to a reluctance

Table I. Comparison of ASME Code and RDT M3-33 Requirements For Steam Generator Tubing

	SA 213	RDT M3-33
Material	Electric furnace	VAR/ESR
Composition, %	0.15 C max	0.07–0.11 C, low residuals
Heat treatment	Anneal or normalize and temper	Anneal
Surface condition	Free from scale	Light treatment oxide, 63 μin.
Dimensions, in.		
Tolerance,		
outer diameter	±0.004	+0.005 –0
wall thickness	+0.020 –0	+0.010 –0
Check analysis	1 per heat	5% of tubes
Tensile properties		
Ultimate tensile strength, ksi	≥60	60–85
0.2% yield stress, ksi	≥30	≥30
Elongation, %	≥20	≥30
Hydrostatic test	In lieu of NDE, 1 or up to 24 fiber stress, ksi	In addition to NDE 4.5 ksi (22.5 ksi fiber stress)
Quality assurance	NA 3700 (1/1/75)	RDTF 2-4 NA 3700 (1/1/75)
Nondestructive evaluation		
Ultrasonic	20% or 0.004 in.	3% or 0.004 in. (optional 3% or 0.002 in.) statistical control
Liquid penetrant	Not specified	OD and ID (ID is optional provision), no indications
Eddy current	In lieu of ultrasonic	3% or 0.004 in. (optional provision)
Microcleanliness	Not specified	Required
Decarburization	Not specified	<5% of wall

in the steel industry to quote on 2 1/4 Cr-1 Mo steel plate directly to the requirements of RDT M5-22T. Originally, it was intended to fabricate the shell from cylinder forging sections welded together to form the shell. This approach was initially employed due to industry's reluctance to furnish plate. Changing market conditions in recent months, however, has indicated a greater willingness on the part of the material suppliers to furnish plate.

In addition to the plate material, various forgings are also employed in the fabrication of the shell. These forgings are (1) the reducer sections that attach each end of the shell to the tubesheets, (2) the tubesheets, (3) inspection ports (sweepolets), and (4) the support ring, a large drum forging that is the interface between the steam generator and the building support structure. These forgings, with the exception of the tubesheets, are fabricated in accordance with SA-182 for grade F22A alloy as supplemented by RDT M2-2T.

Design evolution has indicated the desirability of using (1) "pulled" sodium nozzles, and (2) formed elbows fabricated from plate material rather than the previously employed "paste-on" nozzles and mitered elbow sections fabricated from cylinder forgings. The "pulled" nozzles are preferred from both a structural standpoint and an inservice inspection (ISI) standpoint relative to the "paste-on" nozzles. The "paste-on" nozzle design suffers from the disadvantage of locating the header-to-nozzle weld in the most critically stressed region of the component. In addition, ISI of the crotch weld between the nozzle and header would require development of techniques to accomplish the necessary examination of these welds. For these reasons, a changeover has been made to the "pulled" nozzles and formed elbows. The "pulled" nozzles are fabricated from formed half cylinders of plate and the nozzle stub is literally pushed out of the plate to form the riser section to which the nozzle extension is attached. The two-shell half sections are then joined with a longitudinal seam weld to form the finished header. The formed elbows are formed with two half-shell sections that are subsequently welded together with longitudinal seam welds at the inside and outside radii, respectively.

Flanges, Bolting, and Seals

The various flanges required for the steam generator (i.e., for the steamheads and steam line connections) are formed from drum forgings in accordance with SA-336 supplemented with the requirements of RDT M2-4T. The forgings are received in the rough-machine stage and final machined prior to assembly of the components.

Bolting for the steam generator consists of internal bolting for assembly of the steam generator internals, and the large steam head studs required for attachment of the steam heads to the tubesheets. The bolting required for the internals consists of (1) 2 1/4 Cr-1 Mo hex-head cap screws that are used to attach the tube spacer retaining rings to the inside of the shroud subassembly and (2) Inconel 718 bolting (to ASTM-637, Alloy 718, requirements) used to attach the shroud support ring to the steam generator support ring for positioning and support of the shroud subassembly within the steam generator shell. The large steam head studs and nuts are fabricated in accordance with ASTM-637-70, supplemented by the requirements of RDT M2-15.* Recently, *Code Case 1607* was approved by the *ASME Boiler and Pressure Vessel Code* allowing the use of Inconel 718 as a high-temperature bolting material. All of the Inconel 718 bolting used in the steam generator is fabricated from forged bar.

All seals are of the welded type, with the exception of the steam-head to tubesheet seal, which is accomplished with standard commercial Flexitallic gaskets. Preload on the Inconel 718 studs affects the seal. Calculations performed to date for both steady-state and transient operating conditions indicate acceptably low levels of joint rotational misalignment during operation so that the seal should remain leak-tight during operation.

ASSEMBLY OF COMPONENTS

Tube-To-Tubesheet Joint

The tube-to-tubesheet weld has been identified as the most critical item in the fabrication of the CRBRP steam generators. Many varieties of face-side welds have been employed in industry for conventional steam generators; some of these are shown in Fig. 1. The welds deposited from the face side are relatively easy to produce because accessibility is readily obtainable. However, the face-side weld has several serious disadvantages, i.e., the crevice between the tube and tubesheet may promote corrosion and premature failure if sodium-water reaction products accumulate there, inspectability is poor, and mechanical properties are impaired by the notch effect that is inherent with

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*ASME SB-637, which is now supplemented by RDT M2-18, was not in existence for Inconel 718 at the time the material RFQ was issued since *Code Case 1607* had not been approved at that time.

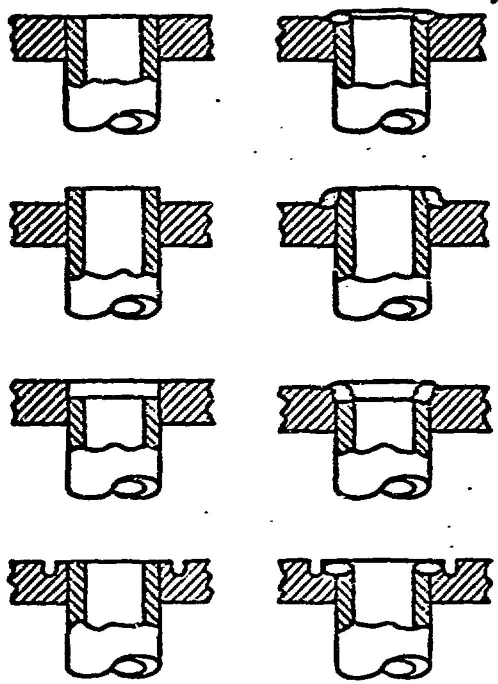


Fig. 1. Typical Tube-to-Tubesheet Joints for Heat Exchangers.

the joint. Since the bore-side weld design (Fig. 2) overcomes these limitations, it was selected as the reference design for the CRBR steam generator.

The bore-side weld design has been utilized in the United States (4) and Europe (5) for well over a decade, and the general experience has been excellent. For example, construction of the Atomics International Modular Steam Generator (AI-MSG) involved welding 158 2 1/4 Cr-1 Mo steel tubes, 1.6-cm diam × 0.28-cm wall (5/8-in. OD × 0.109-in. wall), at both the upper and lower tubesheets. This unit, fabricated in accordance with Section III, Class A, of the *ASME Boiler and Pressure Vessel Code* has accumulated over 4000 hr of satisfactory operation. In the United Kingdom, the Prototype Fast Reactor (PFR) evaporators involved the successful production of approximately 1000 such welds. Additionally, the bore-side design was used with outstanding success in the manufacture of the stainless steel intermediate heat exchangers for FFTF.

To produce reliable high-quality bore-side welds, several factors must be carefully considered. The base metal (forgings and tubes) must possess a minimum of inclusions or other defects; otherwise a leak path through the spigot may occur or a plane of weakness can result near the weld. As indicated earlier, a low inclusion-count material can be produced by VAR or ESR techniques, and this solution is being used for the CRBR application. In the case of the intermediate heat exchangers for FFTF, a weld overlay on the underside of the tubesheet was used to provide a high-integrity material.

Bore-side welds are also more difficult and expensive to produce than conventional face-side welds. There is limited access, and visibility during welding is essentially nonexistent. Some additional areas of difficulty in application of this technique lie in the proper

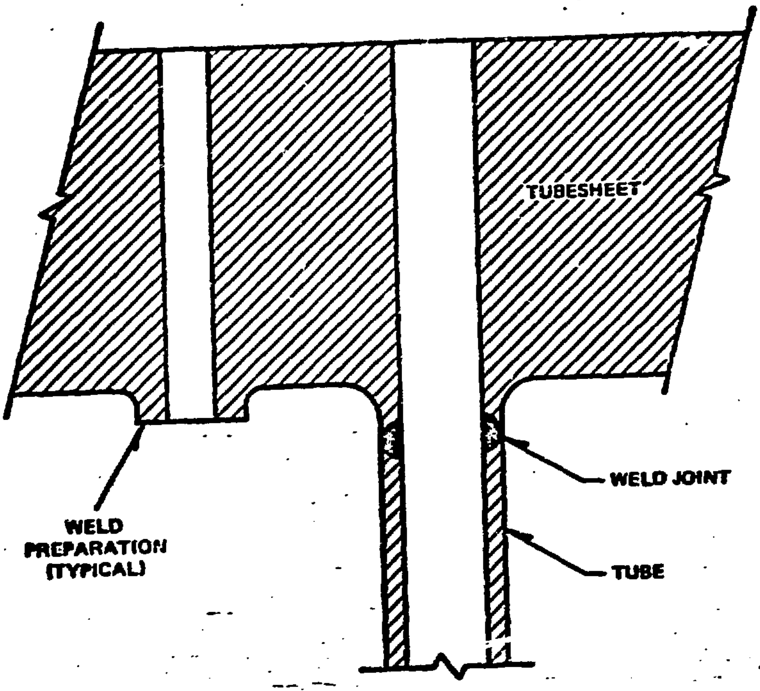


Fig. 2. Reference Tube-to-Tubesheet Weld Joint.

alignment of the tungsten electrode with respect to the joint, proper cooling of the tungsten electrode and electrode holder, control of the inert-gas environment and pressure both inside and outside the tubes, and control of the weld bead profile (i.e., penetration and drop-through).

The small-diameter, heavy-wall tubes in the CRBR steam generators present particularly challenging problems for welding equipment and procedures. Much of the earlier work with the bore-side design has involved larger diameter ~2.5 cm (1 in.) tubes. The 1.6-cm OD × 0.028-cm (5/8-in. OD × 0.109-in.)-wall tubes of the CRBR plant do not permit room for filler wire feeding, water cooling of the electrode, or automatic voltage control of the electrode-to-work distance. Thus, these welds will have to be made autogenously (without filler wire additions) without the benefits of water cooling and automatic voltage control. A thorough program for welding procedure development and qualification will be required of the steam generator fabricators to assure the utmost in reliability.

Shell-To-Tubesheet Weld

The joint between the 33-cm (11 1/2-in.)-thick 2 1/4 Cr-1 Mo steel tubesheet and the shell sections (which are approximately 7.7-cm (3-in.)-thick in the tubesheet regions) must have high integrity. To provide this, the tubesheet forging is machined with a 7.7-cm (3-in.)-thick ring on its inner surface for welding to the shell section. This butt-weld joint geometry is very advantageous from the standpoints of improved weldability, reduced stresses, and increased inspectability.

The welding process and detailed welding procedure will be specified by the steam generator fabricator. However, the joint lends itself to fabrication by conventional welding processes such as submerged-arc or shielded-metal arc.

Attaching Nozzl nd Flanges to the Units

The nozzle-to-shell joints (particularly at the sodium inlet region) are of particular concern because of the high-stress concentrations at these locations. As discussed earlier, an initial design utilized a "paste-on" concept involving welds in high-stressed regions; but simplified inelastic analyses predicted a strain accumulation in excess of Code strain limits, and there were problems with inspection. The current forged "set-in" nozzle concept automatically increases the strain limit at the high stress region by a factor of 2 by relocating the weld joint. Multiple sodium inlet nozzles are also under consideration. As in the tube-to-tubesheet and shell-to-tubesheet joints, the welding processes and detailed welding procedures will be developed and specified by the steam generator fabricator.

Sequence of Assembly, Tubes and Tube Spacers

The assembly sequence currently planned for the steam generator is indicated in Fig. 3. Briefly, the assembly consists of fabricating the shroud subassembly, including the installation of tube spacers within the shroud and then subsequently loading the shroud into the straight section of the steam generator shell. The tubesheets are then positioned at either end using special tooling to hold the physical alignment of the tubesheets in the appropriate position relative to the shell. Tubes are then pushed into the assembly (in rows) and positioned within the vibration suppressor support subassemblies (a slat type of vibration suppressor allowing in-plane thermal expansion, but suppressing out-of-plane vibration modes) in the hockey-stick region.

Fig. 3. CRBRP Steam Generator Module Assembly Sequence.

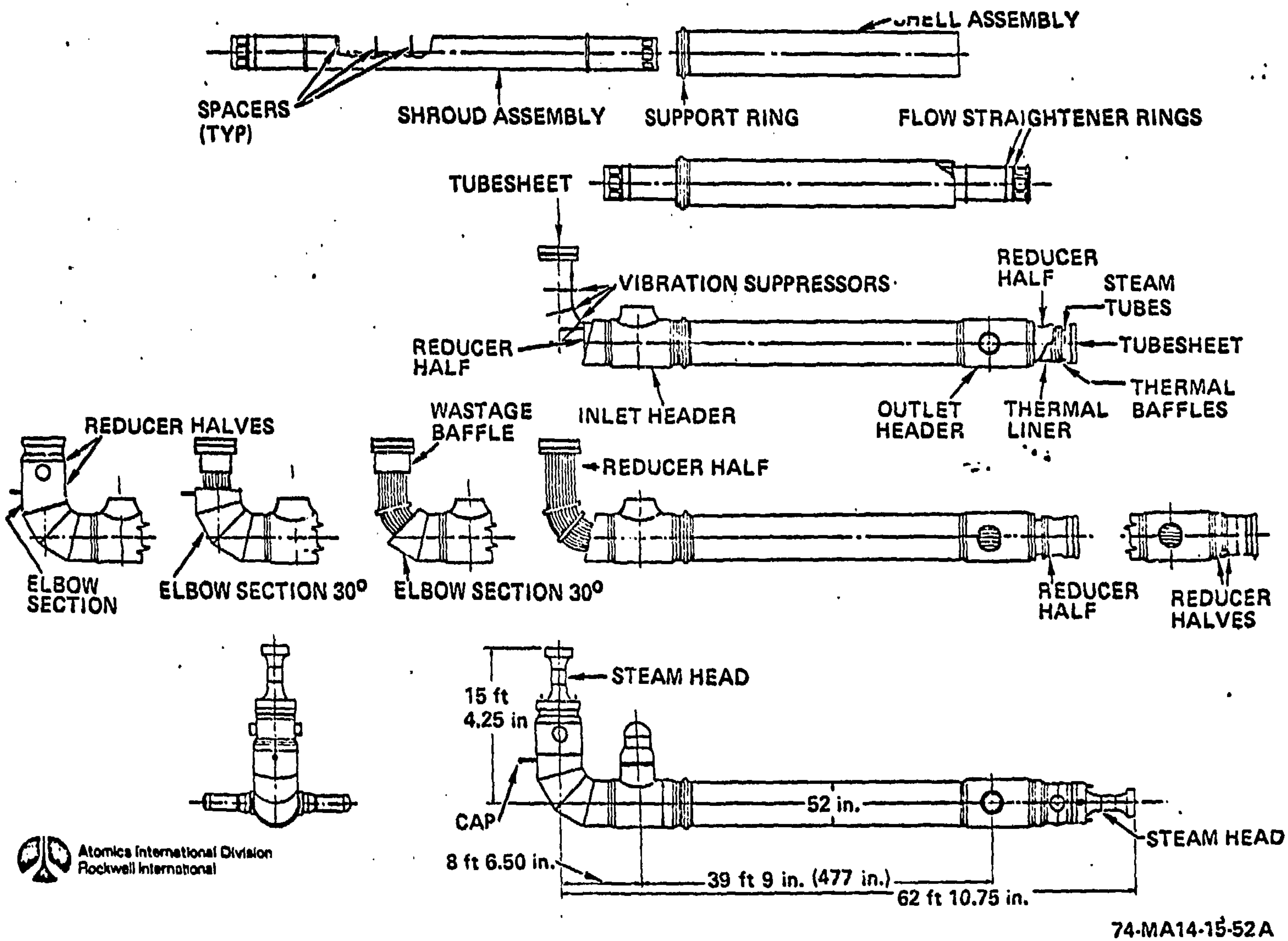


Fig 3

In the assembly sequence, perhaps the most critical assembly step is positioning of the tube spacers within the shroud subassembly. It is necessary during fabrication of the shroud subassembly to ensure that all spacers are appropriately aligned with respect to each other to allow ease of loading of tubes and to ensure that binding of the tubes from one tube support to another does not occur. This is accomplished by using guide tubes positioned at strategic tube hole locations in the spacers as the buildup of the assembly proceeds.

Figure 4 shows the completed shroud assembly used in the fabrication of the hydraulic test model (HTM) that was recently completed at Atomics International. The end-tube spacers are readily visible, and the cap screws that are used to position and retain the split rings that hold the tube supports in place are in evidence. Figure 5 illustrates the loading method employed during fabrication of the HTM.

The tube that is exiting the lower tubesheet is a special thin-walled stainless steel tube with a "bullet-nosed" end fitting. This tool facilitates threading of the steam tube through the tube spacers. Experience with the HTM indicated that proper alignment of the tube spacers within the shroud greatly facilitates loading of the tubes.

Following layup of the tube bundle, the remainder of the fabrication sequence is relatively straightforward. The elbow sections are loaded in place over the tubesheet using special fixturing to hold the tubesheet while this is accomplished. Assembly of the units then continues with final closeout welds being accomplished at the reducer sections. The nozzle fittings at either end of the unit are used for inspection of these closeout welds prior to final capping of the inspection port (sweepolet) nozzles.

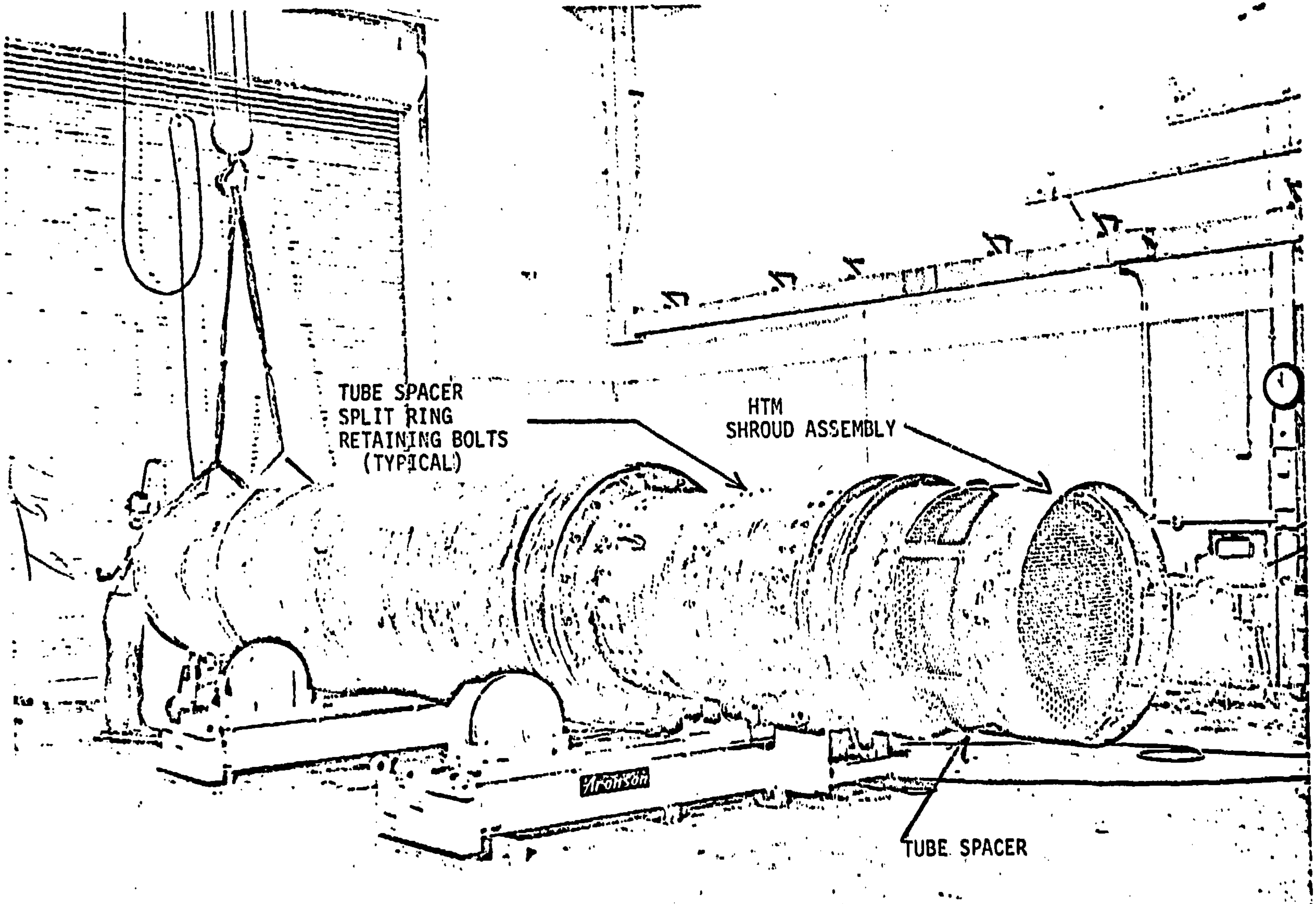
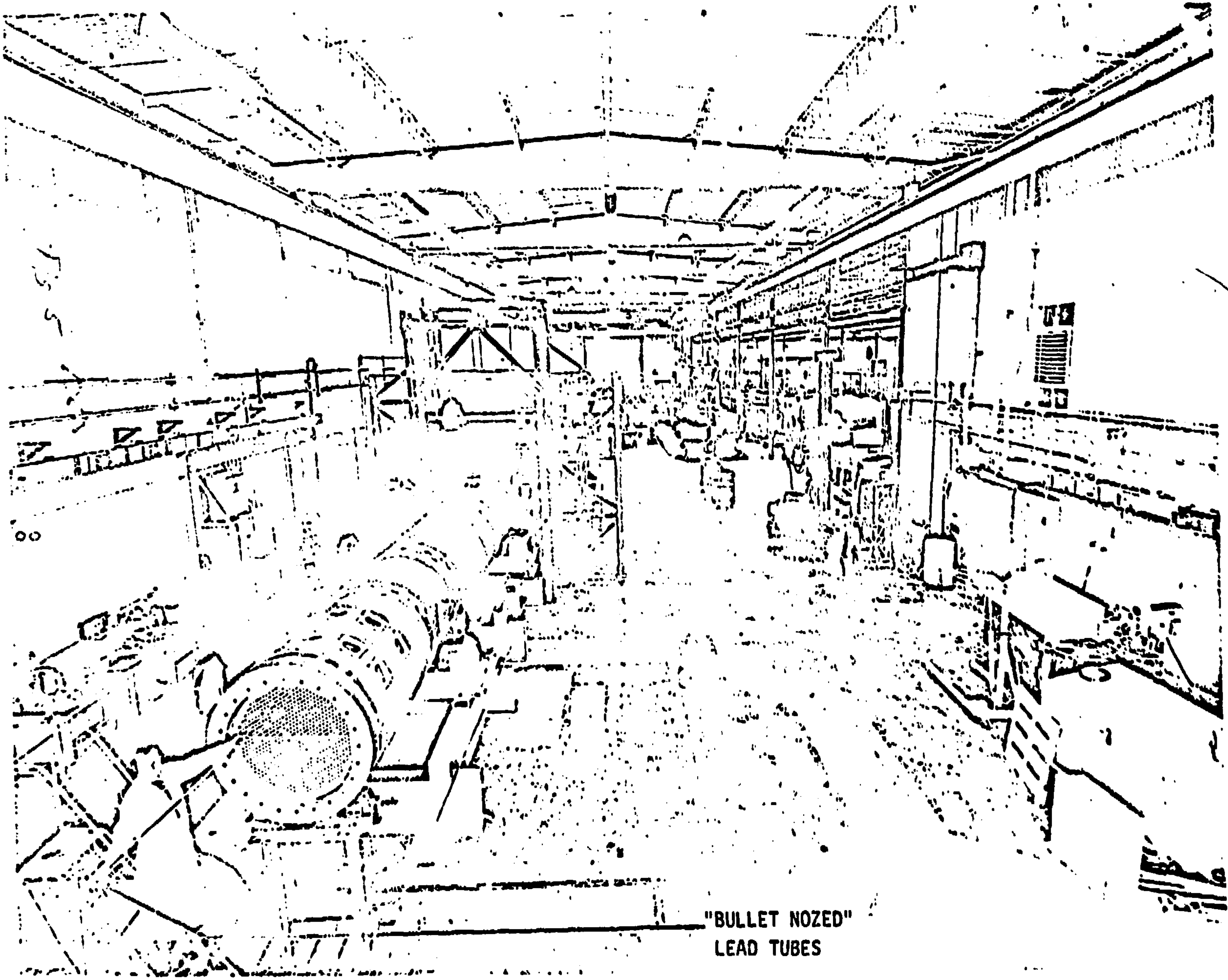


Fig. 4. Completed Shroud Assembly for Recently Completed Hydraulic Test Model.

Fig. 5. Loading of Heat Exchanger Tubes into Hydraulic Test Model.



NONDESTRUCTIVE EXAMINATION METHODS

The successful performance of nondestructive examination depends upon proper selection of techniques and equipment as well as upon sound operator training. In addition to the technical specifications, the examination methods must be attuned to existing commercial codes, RDT Standards, and other requirements that may be imposed by regulatory agencies.

The bulk of the examination requirements (6) will rely heavily on existing state of the art, but because of the unique service performance requirements for the Clinch River Reactor, there are some special requirements for components or situations that require engineering development (7).

Steam Generator Tubing

Tubing in the steam generator provides the water/sodium boundary and as such its integrity will significantly affect the performance of the units. Experiments conducted at GE and in France indicate that microscopic leaks in tube walls, if present, are likely to enlarge and cause sodium/water reactions (8). The likelihood of such events must be eliminated or minimized by the Nondestructive Test Program specified to be performed by the tubing fabricator. The specifications invoked are based on a combination of need for in-service performance and existing tube fabrication experience.

The present requirements for inspection of steam generator tubing are stated in RDT M3-33 and summarized below.

Test Method	Acceptance Limits
Helium leak	less than 10^{-9} std cm^3/sec
Hydrostatic	to 22,500 psi fiber stress (SA 450)
Ultrasonic	no indication greater than 0.002 in. or 3% of wall, whichever is greater
Dye penetrant	free of indications

It is anticipated that standard commercial ultrasonic techniques for tubing with minor upgrading will be adequate. The upgrading includes (1) a multiple notch standard for establishing statistical confidence and (2) slightly decreased flaw sizes. The ultrasonic inspection procedure will use a 12-notch standard; 6 of the notches [0.05. 0.077, and 0.125 mm (0.002, 0.003, and 0.005 in.) in depth, all 6.5 mm (0.250 in.) long] are oriented in a longitudinal direction with respect to the tube axis, the remaining 6 notches lie in the transverse direction. It is intended to establish statistical methods of acceptance, for a 0.99 confidence interval with 0.95 probability for the response of a given inspection unit (9). Thus, the probability of accepting discontinuities equivalent to the 3% wall notches is below 0.05. Tests have shown that notches with a depth 1% of wall thickness in 2 1/4 Cr-1 Mo tubing of the reference size can be detected.

Dye penetrant examinations are required as a backup to the ultrasonic examinations that are sensitive to flaw orientation. The outer surface of all tubing will be examined by standard liquid penetrant techniques, and selected samples of tubing will be split for penetrant examination of the inner surface. Hydrostatic tests have been specified for the assembled units as a code requirement, thus it is judged prudent to ascertain tubing strength prior to testing the unit so as to avoid repair work. Helium leak testing assures the absence of through-wall microscopic leaks of 10^{-6} std cm^3/sec size, which have been found to propagate or enlarge in sodium/steam test rigs.

Tubesheets

The main reasons for inspecting tubesheets are to: (1) determine flaws and microstructural cleanliness of the bulk material, (2) assure absence of inclusions at the tube-to-tubesheet joints, and (3) certify soundness of the ligaments separating coolant channels. Present requirements (RDT M2-19T) require ultrasonic and liquid penetrant inspection. Although there is no present specification governing the ligaments or tube stubs, these will be inspected by fluorescent magnetic particle inspection and ultrasonic methods. The anticipated requirements are summarized below:

Method	Acceptance Criteria
Ultrasonic inspection of forging	No indications larger than 0.25-in. flat bottom hole equivalent (forging only); added to: ASME NB 2546.3; also 1/32-diam-hole drilled on side of specimen used for reference.
Liquid penetrant	Added to: ASME, Section III, Class I, NB 2546.3 (no indications that bleed more than 0.02 in.).
Ultrasonic inspection of ligaments separating coolant channels	No indications larger than 15% of distance between S.G. tubes, equivalent.
Ultrasonic inspection of tubesheet stubs	No indications greater than 3% of tubing wall thickness.
Magnetic particle inspection	No linear discontinuities (weld prep and adjacent area only) per RDT M2-19T.

State-of-the-art techniques are likely to be adequate with the possible exception of the high-sensitivity inspection techniques for inclusions for which engineering development may be necessary.

Tube-to-Tubesheet Welds

The tube-to-tubesheet welds are by far the most critical areas in the steam generator modules.

The most prevalent flaw that may exist in a tube-to-tubesheet weld is porosity. Should pores be present, information about their number, location, and size will be required to assess their potential impact on component performance. For example, single isolated pores may be harmless but a string of such pores across the weld cross section will not be acceptable because these may result in a leak path. Such occurrences must be reliably detected. All welds will be examined with a volumetric (radiographic) method that can detect pores down to 0.38 mm (0.015 in.) in diameter. It is envisioned that when the new small-rod-anode x-ray microfocus machine is available and its operation demonstrated, the acceptable porosity size will decrease.

In addition to the radiographic method, helium-leak checking has been specified and ultrasonic examination is also being planned. Unlike most of the other examination requirements of the steam generator modules, significant development effort was required for the tube-to-tubesheet joint since state-of-the-art techniques were inadequate. The radiographic studies incorporated comparison of capabilities and limitations between a laboratory-model, small-rod-anode x-ray unit [80 kvp with a focal spot of approximately 0.25 mm (0.010 in.) and radio isotopic sources (ytterbium and thulium with sizes of approximately 0.63 mm (0.025 in.)]. The image quality of the radiographs was quantitatively compared using both plaque- and wire-type penetrameters. Penetrameter sensitivities of 2, 3, and 4% were obtained with the x-ray unit, the thulium, and the ytterbium, respectively. Exposure times of 1 min or less were possible with the x ray and ytterbium;

the thulium required exposures more than an order of magnitude longer. It is anticipated that the wire-type penetrameter will be used as an image quality indicator to minimize interpretation difficulties. Figure 6 is a sketch of the small rod anode of the x-ray unit in position for radiography.

Bore-side ultrasonic probes and techniques using multicrystal elements are being developed for inspection of the welded joints as a complementary procedure. The ultrasonic examination will improve the confidence for detection of crack-like flaws. Preliminary studies indicate a capability for detecting flaws in the welds as small as approximately 0.15 mm (0.006 in.) deep. This value may be affected by the surface condition of the welded joint. Figure 7 is a photograph of a prototype bore-side ultrasonic probe used to direct the sound into the weld joint for flaw detection.

Feasibility studies have demonstrated the potential for bore-side eddy-current techniques (with magnetic saturation) to be applied for examination of the ferromagnetic alloy tubing and welds. Although the current emphasis with eddy currents is for in-service examination of the tubing, ultimate consideration will be given for application to both manufacturing and in-service examination of tube-to-tubesheet welds. The current requirements for quality of the tube-to-tubesheet welds are shown below:

Method	Acceptance Criteria
Helium leak test	no leaks larger than 10^{-9} std cm^3/sec
Radiography	no pores or inclusions larger than 0.015 in. and no cracks or aligned porosity
Ultrasonic	no indications greater than 10% of wall thickness

Fig. 6. Sketch of Small Diameter Rod Anode of the X-Ray Unit in Position for Radiography. (Print to be supplied later.)

Fig. 7. Prototype Ultrasonic Bore-Side Probe for Tube-to-Tube Weld Inspection. (Print to be supplied later.)

Tubesheet-to-Shell Welds

The criteria to be met for tubesheet-to-Shell welds includes full thickness weld penetration and freedom from cracks, excessive inclusions, and pores. The tubesheet to shell weld will be inspected by radiographic techniques and by ultrasonic methods tailored to the geometry. Magnetic particle inspection will be used to Code requirements (Section III NB 5130). Both radiographic and ultrasonic tests are needed for these joints to meet the double volumetric examination requirements of the *ASME Boiler and Pressure Vessel Code*. It is anticipated that near state-of-the-art techniques will probably be adequate for these examinations. The following is a summary of the NDT requirements for the tubesheet to shell welds.

Method	Acceptance Criteria
Magnetic particle of weld prep area	NB 5130 Section III
Ultrasonic inspection	NB 5330 Section III
Radiographic inspection	NB 5320 Section III

CONCLUSIONS

A development program is under way to assure that high-reliability steam generators are available for service in the CRBRP. Extreme care is being taken to obtain the necessary quality of 2 1/4 Cr-1 Mo alloy steel in all components including high-purity material for the tubing and tubesheets. The assembly details for the steam generators are being confirmed on smaller test models with welding development where necessary. Nondestructive testing procedures will build upon state-of-the-art techniques with the principal improvements being in quality requirements for the tubing and tubesheets and in development of advanced examination techniques for the tube-to-tubesheet welded joints. These, and other steps in quality assurance, lend confidence and high expectation that the steam generators will be successfully fabricated and operated in the CRBRP.

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Figure Captions

1. Typical Tube-to-Tubeshcet Joints for Heat Exchangers.
2. Reference Tube-to-Tubesheet Weld Joint.
3. CRBRP Steam Generator Module Assembly Sequence.
4. Completed Shroud Assembly for Recently Completed Hydraulic Test Model.
5. Loading of Heat Exchanger Tubes into Hydraulic Test Model.
6. Sketch of Small Diameter Rod Anode of the X-Ray Unit in Position for Radiogrpahy.
7. Prototype Ultrasonic Bore-Side Probe for Tube-to-Tube Weld Inspection.