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MASTER

HOCKEY–STICK STEAM GENERATOR FOR LMFBR

by

G. J. Hallinan

P. E. Svedlund

Energy Systems Group
Rockwell International
8900 De Soto Avenue
Canoga Park, California 91304

Abstract

This paper presents the criteria and evaluation leading to the selection of the Hockey Stick Steam Generator Concept and subsequent development of that concept for LMFBR application. The selection process and development of the Modular Steam Generator (MSG) is discussed, including the extensive test programs that culminated in the manufacture and test of a 35 MWt Steam Generator.

The design of the CRBRP Steam Generator is described, emphasizing the current status and a review of the critical structural areas. CRBRP steam generator development tests are evaluated, with a discussion of test objectives and rating of the usefulness of test results to the CRBRP prototype design. Manufacturing experience and status of the CRBRP prototype and plant units is covered.

The scaleup of the Hockey Stick concept to large commercial plant application is presented, with an evaluation of scaleup limitations, transient effects, and system design implications.

1.0 CONCEPT SELECTION

Rockwell International, Energy Systems Group, mounted an intensive effort in the mid 1960's to further improve design, reliability, ease of fabrication, and economics of sodium-heated steam generators for modern steam plant application. This effort was made against a background of numerous problems which had been encountered in a variety of sodium-heated steam generator designs. The causes of these problems were varied and included (1) insufficient flexibility to accommodate differential thermal expansion effects, (2) chloride stress corrosion, (3) materials/manufacturing difficulties, (4) flow instability, (5) sodium maldistribution, (6) caustic stress corrosion, and (7) erosion and tube vibration. The extensive steam generator engineering evaluation embraced a number of basic system and design features, such as steam cycle, once-through versus recirculation mode, materials, single versus double-walled tubes, cover gas versus solid system, separate versus combined evaporator/superheater sections, modularity, valving between units, tube-tubesheet joint design, leak detection technique, and other design aspects.

The steam generator designs considered included a variety of methods for accommodating differential thermal expansion between tubes and shell. Many of these concepts have been selected for development in LMFBR plants both here and abroad. Included in the survey were straight tube and shell, straight shell/flexible tube, flexible shell/straight tube, U-tube, bayonet tube, serpentine tube, and helical coil tube designs.

After a comprehensive evaluation of numerous design options, it was concluded that the hockey stick concept, employing 2-1/4 Cr - 1 Mo, best satisfies all concerns. The design, as shown in Figure 1, is of simple shell and tube configuration with water/steam mixtures flowing upward through the tubes. Sodium flows downward through the shell, parallel to the tubes along the entire length of the active heat transfer region. The offset leg at the top of the unit provides compliance which allows severe thermal transients to be accommodated while safe stress margins are maintained. The critical tube-to-tubesheet joint is of a butt-welded configuration which is fully inspectable for verification of integrity.

2.0 CONCEPT DEVELOPMENT

A number of development activities were identified as necessary to firm/select detailed design features and to verify ..ckey stick design characteristics. The specific purposes of these development activities are listed in Table 1. A number of the more significant development program tests are described in the following paragraphs.

A full-sized (length foreshortened) hydraulic model of the Modular Steam Generator (MSG) was tested at the Rocketdyne High Flow Test Facility. The results showed that pressure drops were as predicted, flow distribution was uniform across the bundle even down to flow rates of 1% of full flow, and tube vibration levels were low (less than 0.1 mm amplitude at span centers).

An extensive program was carried out to establish a tube-to-tubesheet weld procedure which would assure that high-quality, repeatable welds would be obtained at all times during production. Weld parameters investigated included weld speed, weld current, electrode location, electrode gap, angular mismatch, linear gap, shield gas parameters, cleaning, and chill configuration. As a result, a repeatable, high-integrity weld with large structural margins was developed and demonstrated.

The Atomic Energy Commission and Atomics International entered into an agreement in April 1970, covering the testing of the Modular Steam Generator (MSG) in the Sodium Components Test Installation (SCTI). AI provided the design and construction of the Section III, "N" stamped unit along with the test specification and post test examination, while the AEC provided installation in the SCTI, the test program, and removal.

The MSG operated for a total of 9303 hours in sodium, with 4015 hours of main-line steaming time. Thermal performance was slightly better than predicted, as indicated on Table 2. Heat transfer performance was mapped over both high and low pressure steam conditions. Operations were stable at all times, and integrity was maintained during a number of simulated transients. Test results enabled refinement of steam heat transfer correlations. Following the post test examination, the unit was found to be in excellent condition.

The MSG was subsequently modified for large-scale leak testing in the Large Leak Test Rig. The test results were used to validate the TRANSWRAP computer code, which was developed by AI and is used in the design of steam generator modules and systems. Post-test examinations showed that large leak effects are limited to local bowing of some tubes and small amounts of wastage (~0.25 mm) in the vicinity of the rupture.

3.0 CLINCH RIVER STEAM GENERATOR DESIGN

3.1 SYSTEM ARRANGEMENT AND REQUIREMENTS

The Clinch River Steam Generator System employs three separate steam generator cells, each of which is supplied by one of the three secondary sodium loops. Two evaporators (~117 MWt each) and one superheater (~91 MWt) are used per loop. A recirculation ratio of 2:1 is employed. The evaporators boil approximately 50% of the water supply, allowing departure from nucleate boiling (DNB) within the evaporator units. The 50% steam/water mixture is fed to a steam drum which, in turn, routes the saturated steam to the superheater unit, the saturated water being mixed with incoming subcooled feedwater and returned to the evaporator inlet by the recirculation pumps. The full power heat balance for the steam generator system is depicted in Figure 2.

To provide overpressure protection on the sodium side of the steam generators, rupture discs are employed on the superheater sodium inlet and evaporator sodium outlet piping. In addition, large drain lines are employed at the bottom of each unit to assist in draining the lower stagnant region in each steam generator. Overpressure protection on the water side is provided by power relief valves on the superheater steam outlet.

The steady-state full-rated power conditions are listed in Table 3. The steam generators are sized to obtain 100% rated power but, due to the expected conservatism in the thermal sizing calculations, it is anticipated that the units will be capable of operating substantially in excess of 100% rated conditions. For this reason, the structural design of the units is based upon 115% rated power conditions (see Table 4).

The design requirements include an extensive list of design thermal transients to be applied to the units (normal, upset, emergency, and faulted events are specified). Among the faulted events, the design basis leak, defined as a postulated guillotine rupture of a single steam tube followed almost immediately by the rupture of six adjacent steam tubes, is imposed. Additionally, the safe shutdown earthquake (SSE) event is classified as a faulted condition. Combination of the SSE with the guillotine rupture of a water/steam line is also a design requirement. The operating basis earthquake must be assumed to occur in conjunction with the worst upset transient at the worst time during that upset transient.

3.2 STEAM GENERATOR DESCRIPTION

The CRBR steam generators, depicted in Figure 1, are each approximately 20 m (65 ft) long, 1.2 to 1.4 m (4 to 4-1/2 ft) in diameter, and weigh 96 metric tons dry. The superheater and the evaporator units are identical with the single exception that water orifices for individual steam tubes are employed at the inlet end of the evaporators to provide additional hydraulic stability on the water side of the evaporator units. The superheater units do not contain these orifices.

The units are supported within the steam generator cells using an integral component support. A lower static restraint/seismic snubber component support is employed at the bottom tubesheet.

The steam generator internals consist of a full-length tubular shroud arrangement in the active region of the steam generators. The shroud serves to (1) position the tube spacers for the 757 15.9 mm (5/8-in.) diameter by 2.77 mm (0.107-in.) wall steam tubes, and (2) provide for thermal isolation of the flowing sodium from the 57 mm (2-1/4-in.) thick main shell by means of a stagnant sodium region between the outside of the shroud assembly and the interior wall of the main shell. Extensive thermal baffling (to isolate the thick shell sections from the severe sodium side transients) is employed throughout the unit, specifically in the hockey stick bend region and in the lower stagnant sodium region. Thick (approximately 38 mm) thermal shields are employed in the main sodium inlet, again to protect the thick 10.8 cm header from the effects of fast sodium side transients.

Shell side sodium enters the sodium inlet nozzle which is located beneath the hockey stick bend region. The inflowing sodium then circulates around the shroud, flows upwards in the annular region between the shroud and inlet header thermal liner, flows radially into the tube bundle through the shroud, downward along the 14 m (46 ft) active length of the units, exits through the lower shroud, and thence, through the sodium outlet nozzles. Both sodium outlet nozzles are employed on the superheater, whereas only a single sodium outlet nozzle is employed on each of the evaporators. In the lower stagnant sodium region, drain nozzles are provided to allow removing sodium from that region.

All pressure boundary material and steam tubes, along with most of the internals, are constructed of the low alloy ferritic steel 2-1/4 Cr - 1 Mo in the fully annealed condition. Plate, forgings, and tubing product forms are employed. The only other material of any consequence employed in the steam generator construction is Inconel 718, which is employed for (1) the tube spacers, (2) for selected internals bolting, and (3) for the studs which are used to bolt the removable steamheads to the tubesheets. The Inconel 718 is used in the solution-annealed then aged condition. All materials comply with the required ASME Section II Code provisions.

As previously noted, the prime internals member is the full-length shroud assembly which is used to carry the tube spacers. The shroud also provides for flow distribution of the inlet and outlet flowing sodium and forms the thermal liner for the main shell and main support ring.

The tube spacers are perforated plates which serve to position the 757 steam tubes on a 1.22-in. (31 mm) triangular pitch; 1522 flow holes are also drilled in the spacers to allow passage of the sodium on the shell side. The tube spacers are supported within the shroud by four locating pins located at 90^0 angles from each other. Structural support during design basis leak imposed loads is provided by segmented bolted rings located immediately, upstream and downstream of the spacers.

The main shroud is supported within the shell by a shroud support ring which bolts directly to the main shell support ring. The elbow shroud is positioned by and supported from the main shroud assembly. The elbow shroud carries vibration suppressors (which are slat-type assemblies) which serve to suppress any out-of-plane vibration.

The pressure boundary components consist of the main shell welded to the lower side of the main support ring at the top and welded to the sodium outlet header at the bottom. The sodium inlet header is welded to the top side of the main support ring. The 10.8 cm (4.25-in.) thick elbow, formed in three 30^0 segments, is welded to the upper end of the inlet header and to the reducer section at the upper end. A similar type of reducer section is used at the lower end. The reduders form the transition from the shell to the tubesheets.

Bolt-on steamheads are employed at both the upper and lower tubesheets. The removable steamheads facilitate inservice inspection of the units and plugging of steam tubes, if required, during service. An interesting design feature of the steamheads is the incorporation of a so-called thermally matched tubesheet which abuts the main tubesheets. The purpose of these thermally matched tubesheets is to produce essentially equal radial relative expansion/contraction between the main tubesheet and the steamhead in order to reduce relative motion at the seal interface. This significantly lessens the chances of seal abrasion during service.

4.0 CRBRP TEST EXPERIENCE

A full diameter, foreshortened (approximately 25-ft (7.6 m) active length versus Clinch River Steam Generator 46-ft (14 m) active length) hydraulic test model was designed and fabricated to determine (1) sodium side flow distributions and (2) tube vibration characteristics prior to initiation of final design of the Clinch River Steam Generators. The results of this test confirmed AI-MSG test module results in that highly satisfactory sodium side flow distribution was obtained (essentially uniform flow being achieved approximately 4 ft - 1.2 m - downstream of the sodium inlet windows in the main shroud) and very low, safe, vibration levels for the steam tubes (the maximum deflection being on the order of approximately 6 mils (0.15 mm), whereas clearance between the tube spacers and steam tubes is on the order of 30 mils (0.75 mm).

Two "Few Tube Test Models (FFTM)" were constructed for performance verification testing as a superheater and evaporator by General Electric. These test models reflected the CRBRP steam generator configuration in most details. Shortly after being put into test in late 1978, excessive bypass flow (flow bypassing the tube bundle outside of the shoud) was observed. X-ray examination of the units indicated that the shrouds had raised off the shroud support flange, thus providing a path for the bypass flow. Additionally, tube deformations were observed in the elbow region which indicated jamming in the simulated vibration suppressors. Subsequent disassembly revealed a high susceptibility to debris contamination and galling of the 2-1/4 Cr - 1 Mo to 2-1/4 Cr - 1 Mo material couple. The previously observed jamming of the tubes in the vibration suppressors was verified and, in addition, tubes were found to be locked to several of the 2-1/4 Cr - 1 Mo tubespacers. No locking was found in the end Inconel 718 tubespacers. Those that appeared to be jammed came free as soon as the load was removed. As a result of these observations, Inconel 718 was adopted as the material choice for all tubespacers, all entrance lead-in angles which could collect debris were eliminated, and the tube-to-tubespacer hole clearances were increased in all tubespacers. The three suppressors were replaced by one tube support in the vertical position, and Inconel 718 was chosen as the material for the tube support bars.

Argonne National Laboratory conducted extensive testing of the thermal conditions associated with DNB which occurs in the Clinch River Steam Generator evaporator units. A single sodium-heated tube was employed, and the results have confirmed the acceptability of the tube wall thermal fluctuations associated with DNB relative to a 30-year tube fatigue life. This has allowed Clinch River to proceed with a 2:1 recirculation system allowing DNB in the evaporators.

In addition to small sodium/water reaction leak tests performed by the General Electric Company, large sodium/water reaction leak tests have been conducted using the modified AI-MSG test unit. The large leak testing was conducted at the Liquid Metal Engineering Center, operated by Atomics International, at Santa Susana, California. A total of 11 guillotine rupture sodium/water reaction tests have been conducted to date. Results have indicated that the TRANSWRAP II sodium/water reaction analysis code currently being employed for design basis leak analysis of the Clinch River Steam Generators produces conservative results.

Three significant special feature tests have been conducted in support of the Clinch River Steam Generator design. The first of these was a prototypic geometry/operating condition/loading condition tube-to-spacer wear test conducted in early 1976, which resulted in the selection of Inconel 718. This tube spacer wear test indicated that the use of 2-1/4 Cr - 1 Mo tube spacers for this application could result in galling and jamming of the steam tubes within the spacers in as little as four cycles under anticipated service conditions. The use of Inconel 718 with tapered tube holes, on the other hand, resulted in essentially zero wear for side loadings of up to 100 pounds (45 kg) and total travel of tube against spacer of greater than 2000 in. (51 m) (the maximum anticipated in a 30-year design lifetime of the Clinch River Steam Generators).

The second major feature test consisted of a bolting test to confirm the adequacy of the Inconel 718 bolting used to attach the removable steamheads to the tubesheets. In this test, full-sized Inconel 718 bolts were threaded into forged 2-1/4 Cr - 1 Mo test blocks and loads were applied simulating those anticipated in the Clinch River units. The Phase I test series employed prototypical loadings and indicated essentially zero creep of the bolted joint in approximately

200 hours operation. Phase II of the test utilized elevated temperature (approximately 1125^{o}F) to produce essentially the same creep strain as would be anticipated in 30-year operation at 950^{o}F. Less than 2% loss of preload was experienced, confirming the design of the bolted joint to maintain seal preload over the life of the Clinch River units.

The third major test was a test conducted by General Electric Company under the auspices of the Department of Energy. The test, consisting of a single sodium-heated tube (an AI-MSG tube with magnetite film on the water side) produced data which showed that exfoliation of the magnetite film due to thermal fluctuations associated with DNB in the evaporator units did not occur. This confirms results obtained from the AI-MSG post-test examination.

5.0 CRBRP MANUFACTURING EXPERIENCE

5.1 TUBE-TO-TUBESHEET WELD

(to be added later)

5.2 SHELL WELDING

The experience with the heavy section metal fabrication of the hockey stick steam generator shell has been favorable and lends itself to discussion mostly in terms of welding. The shell material is fully annealed 2-1/4 Cr - 1 Mo and responds well to welding using conventional methods for heavy section fabrication. The welding processes used are submerged arc, semiautomatic and manual TIG welding, and semiautomatic out-of-position MIG welding.

On those portions of the shell which are straight and which could be welded using conventional heavy section fabrication techniques, there was very little difference between what is done conventionally on any other boiler and what was used on the Clinch River steam generator. The plates received from the steel mills were rolled into shape, weld prepped, welded together, stress relieved, and inspected. The other portions of the steam generator involving the hockey stick elbow and final closure were made out of subassemblies fabricated as just described; however, when installed on the steam generator itself, they were welded out of position (5 g) using a semiautomatic out-of-position MIG welding process.

Our experiences with all the welding processes indicate that somewhat higher than usual preheat is necessary in order to virtually guarantee an elimination of cracking. Nearly all welding to date was done with a preheat of 500 ± 50^{o}F, and no cracking has been experienced to date. Attempts to qualify the MIG welding process at lower preheat (350 ± 50^{o}F) have shown the process to be less tolerant and somewhat less likely to give good welds.

The fabrication flow time on the steam generator was reduced significantly by using high-temperature code cases which, while requiring two volumetric examinations of the completed weld, permitted radiography to be done prior to post-weld heat-treat and ultrasonic examination to be done after post-weld heat-treat. In actual practice, both examinations were performed prior to post-weld heat-treat and several welds were made in sequence with all heat-treated simultaneously, followed by a repeat of the UT examination. Since the welds were made with a high preheat, the risk involved in producing welds in a sequence which made the backside of the previous weld inaccessible was judged to be very low. No problems were experienced using this approach.

Some studies were done to examine weld shrinkage and determine its effects on the alignment of the final steam generator, and these proved to be successful in the sense that, for various thicknesses of weld using the same process, shrinkage rates could be reproduced. The shrinkage rate decreased nonlinearly until the welds got to about 2-1/2 in., after which they did not shrink appreciably.

The normal root-pass welding processes were not used on the out-of-position (5 g) welded sections of the steam generator shell. The backside of the welds was inaccessible to back gouging and rewelding as is the usual heavy section metal fabrication technique. In place of this, flexible backup tapes were used. These were held in place with removable fixturing which allowed the TIG welds to be made with a selected set of parameters which would accommodate a wide variety of fitups. The use of the backup tape permitted slightly higher currents to be used with very low risk of blowing through the weld and minimized the risk of incomplete penetration. As a result, with the exception of an occasional cold rod, the root-pass welds were defect free. The backup tape, while not controlling concavity, did an excellent job of controlling internal convexity on the backsides of the weld. None of the welds had to be ground for excess convexity, and the use of a set of parameters suitable to control concavity still resulted in acceptable welds in the other portions.

6.0 SCALEUP TO COMMERCIAL SIZE

Several studies have been undertaken to verify that the basic hockey stick steam generator concept adopted for CRBR is readily scalable to sizes suitable for large LMFBR plant application. These studies included sodium and water/steam flow distributions and corresponding thermal performance under all anticipated operating conditions, structural analyses of all critical areas, and assessments of creep-fatigue damage and cumulative strain under representative plant duty cycles. The evaluations showed that the hockey stick concept can be scaled up to 1000 MWt for 15.2 MPa/454°C (2200 psig/850°F) throttle steam conditions.

Table 5 compares parameters for the hockey stick design for large plant use (e.g., DOE-sponsored Conceptual Design Studies) with those for the smaller MSG and CRBR units.

The difference in size between the CDS evaporator and the CRBR unit are illustrated in Figure 3. The basic configuration, i.e., with the offset leg which allows differential thermal expansion between the shell and steam tubes, remains the same. The tube sizes, tube pattern, and tube-support characteristics are identical. Only the number of tubes, shell diameter, tubesheet, and nozzle sizes increase as the module size increases. Support for the larger module is located at the lower portion of the unit, with a horizontal stabilizer at the upper portion.

The modules are easily adaptable to either once-through or recirculation modes. This was demonstrated when the MSG, which was designed for once-through operation, was also tested under evaporator mode conditions when the latter approach was adopted for the CRBR.

The fundamental thermal characteristics of the hockey stick are essentially independent of the steam generator size. The hydraulic characteristics are size-dependent mainly with regard to the entrance length required for full development of shell-side flow distribution. The tendency for shell-size flow maldistribution will increase as the tube bundle diameter increases, causing potential radial thermal gradients. These arc not of concern from a structural standpoint because of the individual tube-to-tube thermal expansion, and the effect of the "full bundle" tube supports is to produce uniform shell-size flow within a short distance of the entrance. Verification of adequate shell-side flow distribution is done by either model testing and/or analytical modeling.

The scaleup assessment in the structural area focused on identification of critical, potentially size-limiting features and the determination of structural margins in those regions. It was found that potentially critical design areas, e.g., tubes, shell, elbows, headers, and tubesheets, showed large design margins. However, one area required a design change: the bolted steamhead-to-tubesheet connection used in the CRBR design to provide full access to the tubesheet is not practicable because of the large bolt sizes. A welded steamhead-to-tubesheet connection is a more efficient design for commercial sizes. Access to the tube-sheet is provided by a manway.

7.0 CONCLUSIONS

The hockey stick concept provides a sound, reliable design providing good margins relative to allowable stresses and safe operating experience. Aside from EBR-II steam generator modules of 8 MWt size (which would appear to have severe size scaleup limitations), the hockey stick is the only test substantiated concept available in the United States. No other design concept can be tested before 1983. Based on the successful MSG test operations, good performance may be expected from the CRBR prototype tests and the CRBR plant modules. Over 30 module-years of hockey stick module experience will have accumulated by the time the next generation breeder reactors go critical.

5.1 Steam Tube Installation

The steam tubes are inserted individually into the shroud/shell sub-assembly. Sufficient clearance exists between the tube OD and the tubespacer hole that insertion is easily accomplished. Each tube is welded to bosses which protrude from the inboard faces of the tube-sheets. The weld is a square butt weld made with no addition of filler metal.

Each tube-to-tubesheet weld is made from the ID of the tube using a special design inbore weld head. An external manifold, equipped with heaters to preheat the weld joint, fits closely around the tube and tubesheet boss, but does not touch the weld area. A temporary plug is inserted in the tube some distance from the weld so that a blanket inert gas can be used during welding. The weld is made using an accurately controlled pulsating current. This, in conjunction with control of the blanket gas pressure between the inside and outside of the weld joint area, allows the weld shape to be controlled even through the molten metal is suspended in space while the weld is being made. The result of this process is a weld with a very low defect rate.

The individual tube-to-tubesheet weld is subjected to (1) a helium leak check, (2) a liquid penetrant inspection, (3) ultrasonic examination utilizing a transducer assembly which operates in water inside the tube, and (4) X-ray using a rod anode X-ray machine of Dutch design and manufacture. These machines represent the latest technology available, permitting resolution of defects, such as pores as small as 0.005 inch in diameter (and even smaller under optimum conditions). The X-ray source is a tungsten target which is positioned inside the tube at the centerline of the weld. The electron beam is accurately focused on the target by focusing coils or "lenses." The target/lens assembly is in the form of ... which is inserted ... hole in the tubesheet. The X-ray film, in a plastic pouch, is wrapped around the OD of the weld. Very tight limits are placed on the amount of porosity allowed in the weld. For example, no more than the equivalent of two 10-mil-diameter pores and one 5-mil pore is allowed anywhere in the weld if they are within 0.010 inch of each other. If isotope radiography were used, it is probable that none of these pores would even show on the film.

Postweld heat treatment of the tube-to-tubesheet welds is accomplished on each weld joint using a system of ID and OD heaters. Thermocouples are spot-welded to the tube and removed after PWHT.

The CRBRP steam generator contains 757 tubes (1,514 weld joints). During fabrication of the prototype unit, a defect rate of approximately 5% was incurred. All defects were repairable except three which necessitated plugging the tubes.

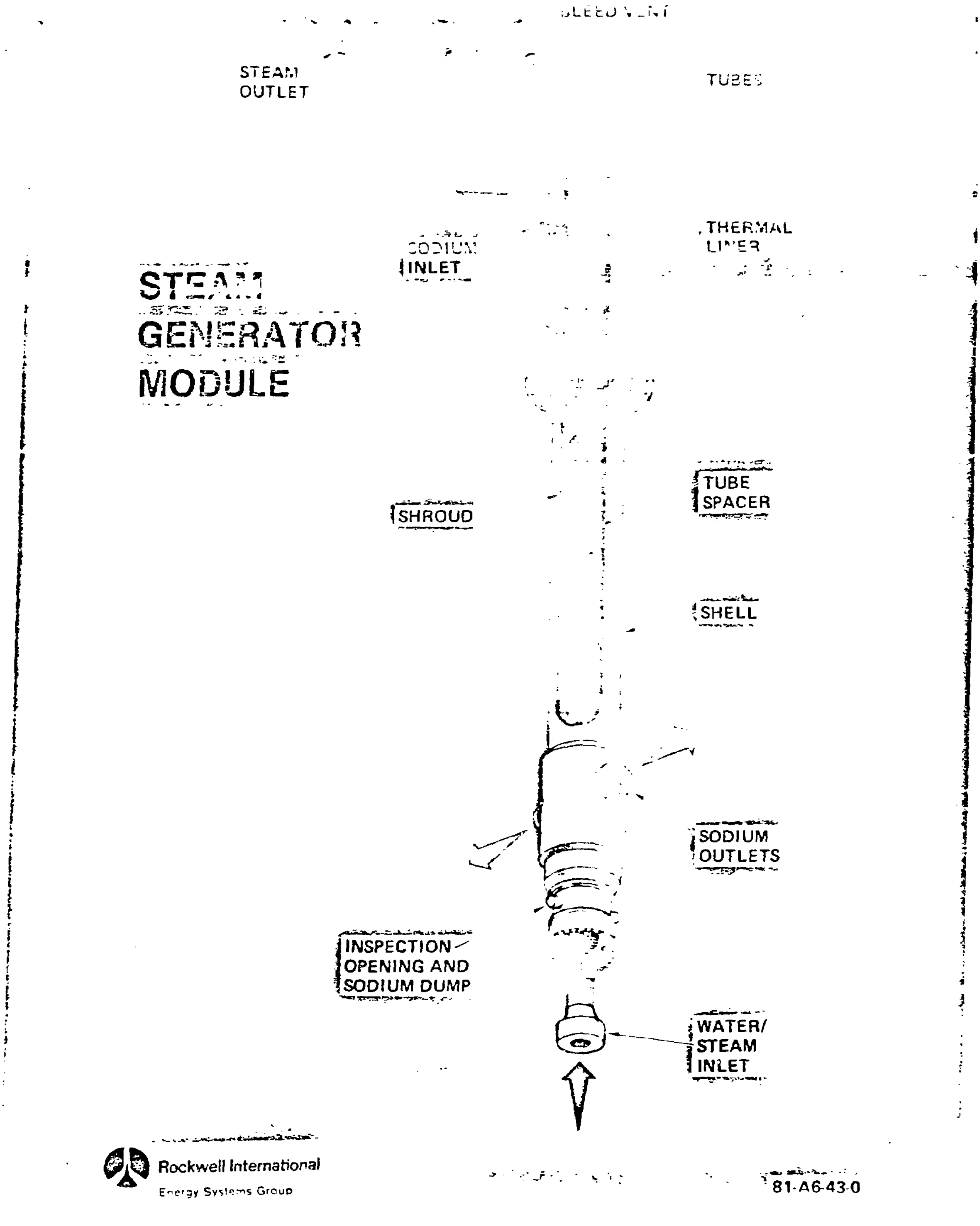

Figure 1. Hockey Stick Steam Generator

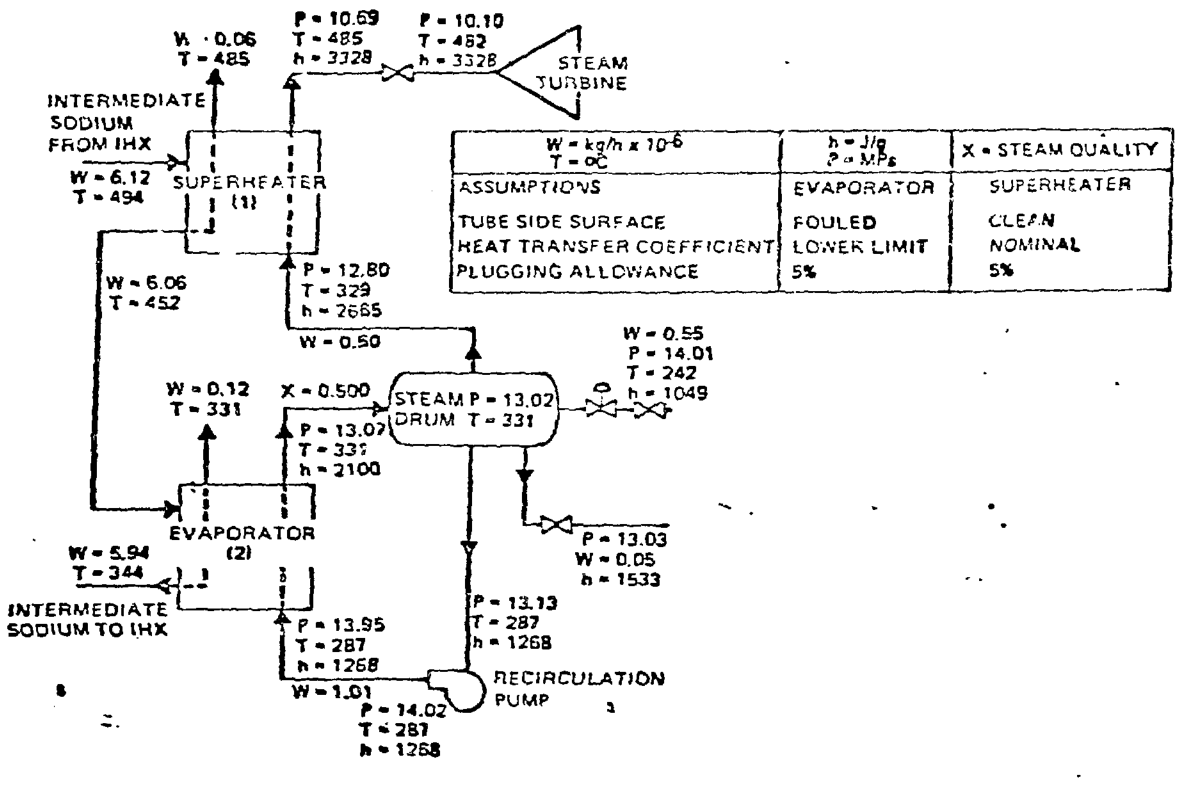

Figure 2. Clinch River Breeder Reactor — Steam Generator Thermal-Hydraulic Design Conditions (Metric Units)

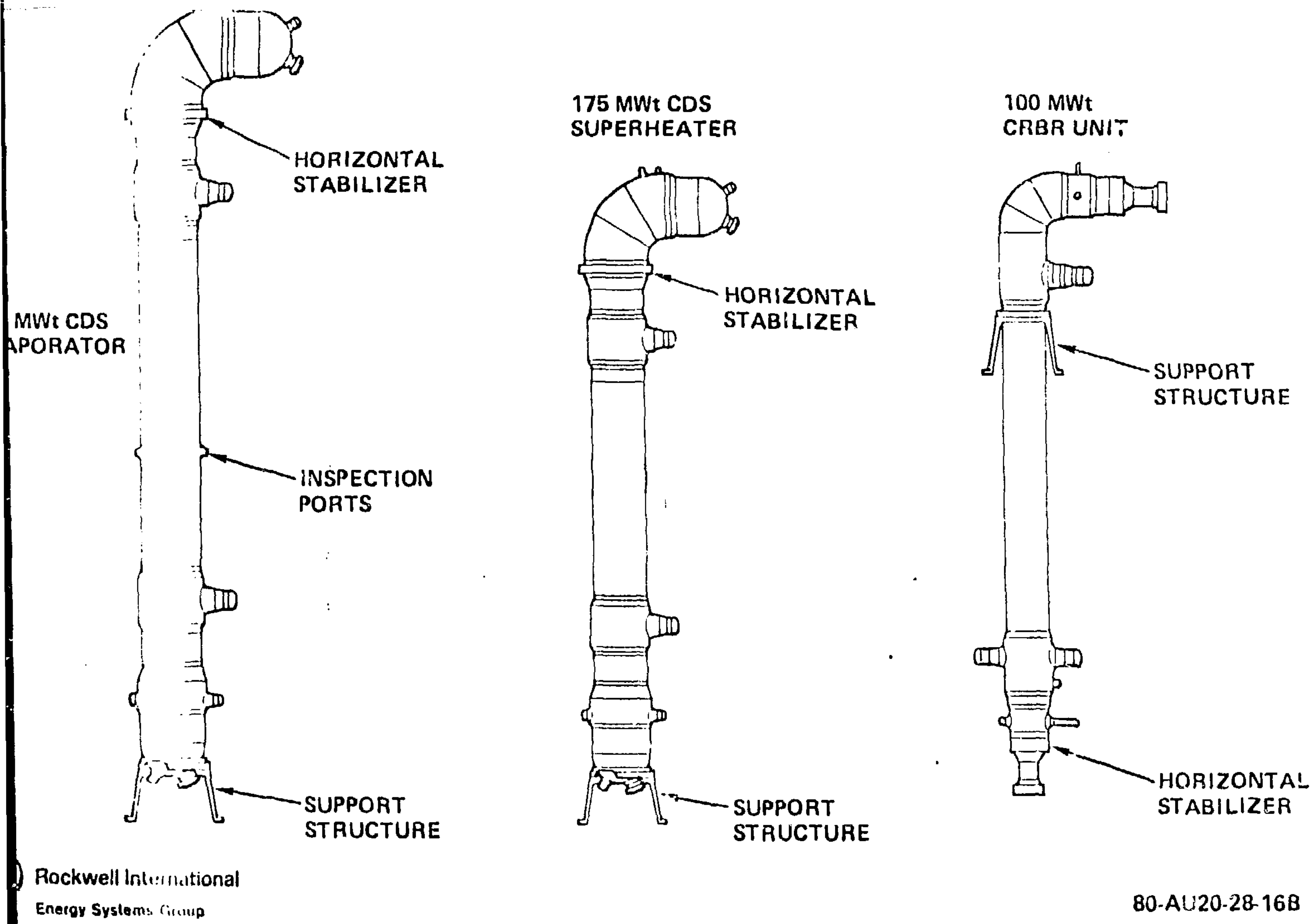

Figure 8. Comparison of CRBR and CDS Hockey Stick Designs

TABLE 1

HOCKEY STICK DEVELOPMENT REQUIREMENTS

- Establish material properties
- Optimize tube supports
- Verify vibration, hydraulic characteristics
- Verify tube-tubesheet weld reliability
- Verify shell fault capability
- Establish tube wear effects
- Qualify and demonstrate manufacturing/inspection procedures
- Demonstrate small leak detectability
- Verify component performance
- Verify operational integrity
- Verify large leak integrity
- Verify long-term effects

one column

TABLE 2

HIGHLIGHTS OF SCTI TEST OF AI MODULAR STEAM GENERATOR

• First Steam Produced	July 9, 1971
• Performance	
. Design Power	28.4 Mwt
. Maximum Power at 100% Flow	32.1 Mwt (for 2400 psig Steam)
	33.8 Mwt (for 1450 psig Steam)
. Maximum Steam Conditions	2430 psig/930^{o}F
• Test Results	
. Total (Main Line) Steaming Time	4015 hr
. Total Sodium Operating Time	9305 hr
. Vibration	Levels Low, Safe
. Startup/Shutdown	37 Cycles, Stable
. Heat Transfer Performance	Parametric Data Obtained from 1450 to 2450 psig
. Endurance	
. Combined Evaporator/Superheater Mode	500 hr
. Evaporator Mode	500 hr
. Low Flow Stability	Stable, All Conditions of Interest
. Leak Detection	Detectability of 10^{-6} lb/sec H_2O Demonstration
. Transients	Integrity Maintained

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TABLE 3

CRBR STEAM GENERATOR THERMAL HYDRAULIC DESIGN CONDITIONS

	Rated Full Load
Duty Per Loop	325 MWt
Sodium Flow per Loop, Maximum	13.5×10^6 lb/h (6.1×10^6 kg/h)
Steam Flow Rate, Superheater	1.11×10^6 lb/h (0.5×10^6 kg/h)
Water/Steam Flow Rate, Evaporator	1.11×10^6 lb/h (0.5×10^6 kg/h)
Superheater Outlet Steam Temperature	905°F (485°C)
Superheater Outlet Steam Pressure	1550 psia (10.68 MPa)
Friction Pressure Loss, Steam Drum to Superheater Inlet	35 psia (0.24 MPa)
Friction Pressure Loss, Evaporator to Steam Drum	6.3 psi (0.04 MPa)
Friction Pressure Loss, Stream Drum to Pump Inlet	6.7 psi (0.05 MPa)
Friction Pressure Loss, Pump Outlet to Evaporator Inlet	10.1 psi (0.07 MPa)
Superheater Sodium Inlet Pressure	208 psia (1.43 MPa)
Superheater Sodium Inlet Temperature, Maximum	936°F (502°C)
Feedwater Temperature	468°F (242°C)
Na Friction Pressure Drop, Maximum	
Superheater	62 psi (0.42 MPa)
Evaporator	16 psi (0.11 MPa)
Recirculation Ratio	2:1
Continuous Drain Rate from Steam Drum (Saturated Conditions)	0.11×10^6 lb/h (0.5×10^6 kg/h)

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TABLE 4

CRBR STEAM GENERATOR STRUCTURAL DESIGN REQUIREMENTS*

Design Pressures		
Sodium to Air Boundary	340 psia	(2.34 MPa)
Sodium to Steam/Water Boundary	15 psia	(0.10 MPa)
Evaporator Water Inlet	2415 psia	(16.65 MPa)
Evaporator Water/Steam Outlet	2215 psia	(15.27 MPa)
Superheater Steam Inlet	2215 psia	(15.27 MPa)
Superheater Steam Outlet	1915 psia	(13.20 MPa)
Design Temperatures		
Superheater Sodium Inlet	$965^{o}F$	($518^{o}C$)
Superheater Sodium Outlet	$885^{o}F$	($474^{o}C$)
Evaporator Sodium Inlet	$885^{o}F$	($474^{o}C$)
Evaporator Sodium Outlet	$775^{o}F$	($413^{o}C$)
Evaporator Water Inlet	$650^{o}F$	($343^{o}C$)
Evaporator Water/Steam Outlet	$650^{o}F$	($343^{o}C$)
Superheater Steam Inlet	$650^{o}F$	($343^{o}C$)
Superheater Steam Outlet	$940^{o}F$	($504^{o}C$)

*General Electric Equipment Specification 22A3453, Section 3.5.3.1

TABLE 5

HOCKEY STICK STEAM GENERATOR EVOLUTION

	MSG	CRBR	CDS	O-T*
Decade	1960s	1970s	1980s	1980s
Thermal Power, MWt	30	117 Evaporator 91 Superheater	470 Evaporator 175 Superheater	646
Tube, OD, mm (in.)	15.88 (0.625)	15.88 (0.625)	15.88 (0.625)	15.88 (0.625
Tube Wall, mm (in.)	2.77 (0.109)	2.77 (0.109)	2.77 (0.109)	2.77 (0.109)
Active Tube Length, m (ft)	17.68 (58)	14.02 (46)	17.98 (59) Evap. 12.80 (42) Suph.	23.47 (77)
Number of Tubes	158	757	2300 Evaporator 1200 Superheater	4400
Shell Diameter, m (ft)	0.46 (1.5)	1.37 (4.5)	2.01 (6.6) Evap. 1.77 (5.8) Suph.	(8.3)
Steam Pressure, MPa (psig)	16.75 (2430)	10.51 (1535)	15.69 (2275)	15.69 (2275)
Steam Temperature, °C (°F)	499 (930)	485 (905)	457 (855)	457 (855)

*Once-through 1000 MWe, four-loop plant, one steam generator module per loop.