REPORT ON STEAM-GENERATOR CONCEPT DEVELOPMENT

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1.0 INTRODUCTION

This report presents a summary of the conceptual design work on commercial steam generators by the General Electric Company for the ERDA Steam Generator Development Program. The purpose of this report is to make available to steam generator vendors some of the information that has been gathered about steam generator design and steam generator/commercial plant compatibility.

Three conceptual steam generator designs are included and discussed in some detail; the Hockey Stick, the J-Module and the Straight Tube with Expansion Bellows, all referenced to a 1500 MWe 4 loop commercial LMFBR design. The purpose of presenting these conceptual designs is to illustrate the development of each concept and the problems and advantages associated with them. In addition to these three conceptual designs, a summary of the advantages and disadvantages of several other steam generator concepts, as expressed by GE personnel, is included.

Single and double tube concept development is summarized and the effect of each upon steam generator reliability and plant availability is discussed. Double and single tubesheet concepts are discussed and possible ways of introducing leak detection systems for increased reliability are presented. A conceptual design of a Hockey Stick evaporator, for use in a 1200 MWe LMFBR, using double tubes and double tubesheets with a leak detection system is presented and discussed.

The concept of steam generator modularization is discussed and the advantages of large and small steam generator modules are presented. The conceptual designs presented in the report were based on the concept of a large module; this is not intended to limit the acceptability of a small module design.

This report presents conceptual designs for the evaporator unit only; two options are available concerning the superheater and reheater

(if either are used). These options are: 1) superheater/reheater identical to evaporator unit or 2) superheater/reheater different from the evaporator. In the case of option one above, design conditions of the superheater/reheater must be included with the evaporator design conditions.

The advantages and limitations of proposed "High" and "Low" Temperature Cycles are discussed. The feasibility of High Temperature Cycle design is demonstrated in the three commercial LMFBR steam generator designs for the 1500 MWe plant; the Low Temperature Cycle conditions are represented in the double tube double tubesheet Hockey Stick design for a 1200 MWe plant.

The information presented in this report is not intended to serve as a basis for design, but rather as a means of communicating some of the pertinent design issues and questions of a sodium heated steam generator for use in a commercial LMFBR.

2.0 STEAM GENERATOR WORK AT GE

Design work on the Clinch River Breeder Reactor and the GE Commercial Target Plant has required that some expertise in steam generators be developed and incorporated into the current projects. As a result, GE has developed some tools for the design and evaluation of steam generators and their performance. The Hockey Stick, the J-Module and the Straight Tube with Expansion Bellows have all been examined with these design tools. The design features are presented below. The advantages and disadvantages of the concepts are presented in tabular form in Section 2.3 along with other steam generator concepts that have received less development work in the ERDA sponsored study.

2.1 THERMOHYDRAULICS

A steam generator design and performance code called STMGEN has been developed that sizes and evaluates steam generators for given cycle

parameters. Tradeoff studies performed with the aid of STMGEN have revealed some important thermohydraulic information. The studies were performed for a specific cycle that corresponds to a representative 1200 MWe Commercial Target Plant (CTP) with relatively high temperature cycle conditions. The numbers and performance curves of the CTP cycle are useful because they serve to illustrate the thermohydraulic relationships that are common to most cycles.

The performance curves of Figures 2.1.1-4 show the changes in tube number, tube bundle diameter, I.D. heat transfer area and steam pressure drop as a function of tube outside diameter. Two active tube lengths are shown; 55 feet and 82 feet. The 55 foot tube length is equivalent in size to the Clinch River Breeder Reactor module with flow in the bend region of the hockey stick. The 82 foot tube length represents the length of the CTP tubes. Performance curves for both the evaporator and superheater units are shown.

A significant economic incentive is demonstrated in the performance curves for the maximum length tube. The 82 ft. active tube length reduces the number of tubes and bundle diameter significantly over the 55 ft. active tube length model. The tube length is then limited from one or more of the following: 1) manufacturers maximum length; 2) overall unit shipping length; and/or 3) steam generator building height costs. Presently, some tube manufacturers have commercially available tubes in 120 foot maximum lengths. Commercial shipping requirements are limited by railroad car sizes to 40-60 feet for single car shipment and 80-120 feet for double car shipment. The bandwidth of shipping length limits represents the maximum limits for different railroads. Since the building that houses the steam generators must accommodate unit installation and removal, the height of the structure is approximately twice the steam generator length.

A second economic incentive is demonstrated by the curves for small diameter tubes. The diameter of the tubes is decreased until a

Figure 2.1.1 Evaporator Performance Curves
4-Loop 1200 MWe Plant
Data from STMGEN Code

Figure 2.1.2 Evaporator Performance Curves
4-Loop 1200 MWe Plant
Data from STMGEN Code

Figure 2.1.3 Superheater Performance Curves
4-Loop 1200 MWe Plant
Data from STMGEN Code

Figure 2.1.4 Superheater Performance Curves
4-Loop 1200 MWe Plant
Data from STMGEN Code

limit in the steam pressure drop is reached or the geometry becomes restricting. For the CTP evaporator, the limiting steam pressure drop was not reached because the type of weld procedure defined the minimum tube size at 5/8". A reasonable balance in parameters might be an evaporator tube diameter of 5/8" OD and a superheater tube OD of 7/8". Decreases in tube diameter also decrease the tube bundle diameter which has the desirable effect of decreasing tubesheet diameter and thickness.

These correlations have served as guidelines in the design of specific steam generator concepts which result in more economic plant designs.

2.2 CONCEPT DEVELOPMENT

As noted above, design effort has been directed primarily at three concepts; the Hockey Stick, the J-Module, and the Straight Tube with Expansion Bellows in the Shell. The Hockey Stick design is the reference steam generator concept for the Clinch River Breeder Reactor. Development of the Straight Tube with Expansion Bellows concept was initiated to investigate the potential of that configuration. Presented below are the latest data for these three concepts referenced to a 4-Loop, 1500 MWe Commercial Breeder Reactor. The cycle parameters of these designs correspond to a high temperature-type of cycle. This type of cycle is characterized by high temperature and pressure. Data on a low temperature cycle is presented in Section 5.1.

2.2.1 HOCKEY STICK

The Hockey Stick design is characterized by the 90° bend in the vessel and tubes near the top of the unit for relief of differential thermal expansion between the vessel and the tubes. Secondary sodium enters the unit immediately below the bend and flows in the annulus between the flow guides and the tube bundle upward around the bend to the windows where

it enters the tube bundle. The sodium flow is downward in the space between the tubes to the bottom of the unit where it exits the tube bundle and flows out the nozzle near the bottom of the unit. Steam or feedwater enters through the nozzle attached to the lower tubesheet and passes into the tubes through the tubesheet. The flow of water/steam is upward in the tubes to the upper tubesheet, where it leaves the unit.

2.2.1.1 DESIGN FEATURES

Three options regarding the 90° bend in the unit were apparent: 1) the region could be entirely inactive, 2) the region could be used as active heat transfer area by placing the sodium inlet nozzle above the bend, or 3) the region could be used as active heat transfer area with the sodium inlet nozzle placed below the bend. The design choice was to use the bend as active heat transfer area since a longer active tube length could be achieved without making the unit any longer. The sodium nozzle was placed below the 90° bend since the shipping width was too great when the nozzle was placed above the bend. (Drawings 261R154 and 852E404) This design choice leads to potential problem areas which have to be investigated. The problem of flow vibrations in the bend region may become significant, as well as the delivery of sodium flow to the tube bundle entry. Build up vibration suppressors were employed to arrest the vibrational problems and a flow guide with a 90° bend for sodium delivery was installed. Another problem with flow in the bend is the potential for causing temperature variations in the upper tubesheet as a result of the natural circulation of sodium.

In order to further reduce the shipping dimensions of the module, the steam inlet and outlet nozzles are bolted to the tubesheet. The unit is, therefore, shipped with flat plates bolted to the tubesheets which are removed at the site and replaced with the steam nozzles. The sodium nozzles are oriented in the same direction as the bend in the vessel to help reduce the shipping width.

The Hockey Stick design allows the tubes to be inserted into the tube bundle before the shroud and vessel are assembled. Furthermore, most of the longitudinal vessel welds are avoided during assembly because the vessel is designed to slide over the lower tubesheet as a cylinder. All vessel welds made during assembly are circumferential in nature with methods for weld inspection provided.

The orientation of the Hockey Stick tubesheets relative to each other impose some limits on the type of tube-to-tubesheet welds that can be used. The general procedure involves feeding the tube through all of the prepositioned tube supports of the long leg to the lower tubesheet. This primarily limits the upper tubesheet weld to an internal bore weld. Some work has been done on deflecting the tube slightly and slipping the tube through the tubesheet for a fillet weld. This is somewhat more involved but not impossible (the Low Temperature Double Tube concept presented later utilizes a fillet weld on the upper tubesheet). When the tube is deflected, the tube supports near the bend must be removed to allow for tube flexibility. The weld at the lower tubesheet is less restricted since the tube approaches the tubesheet along the final axis of the tube.

The vessel of the Hockey Stick is designed to withstand under faulted conditions the full postulated pressure (~ 1700 psi) of a sodium water reaction. All pressure relief systems, water sensors, and controls are located outside of the steam generator.

2.2.1.2 SUPPORT OF UNIT

The static support of the Hockey Stick is very simple due to the near-symmetrical geometry. The support ring, through which the unit will receive its main support, is located close to the bend in order to reduce the length of the vessel bend that is allowed to vibrate under dynamic loading conditions. Differential thermal expansion between the vessel and the supporting components can be accommodated with a

cylindrical mounting stand. The cylinder, upon which the support ring rests, is long enough to withstand the axial thermal gradient that it must experience between the support and the vessel.

2.2.1.3 SEISMIC RESPONSE

The behavior of the Hockey Stick (for the size being considered here) in a seismic event has not been studied. However, as was mentioned above, the location of the support ring brings the bend and horizontal parts of the steam generator closer to the support point, thus giving the upper portion of the vessel more rigidity. The unsupported portion of the lower part of the vessel consequently becomes longer. Should analysis show that the deflections of the lower end are unacceptable, snubbers can be easily added to the design. The behavior of the tube bundle within the vessel has not been studied. Support of the steam generator internals during seismic upset must also be considered.

2.2.1.4 ASSEMBLY PROCEDURE

The assembly procedure begins with the positioning of the tubesheets in a suitable jig. The inner half of the shroud is positioned. In this half shroud are placed the lower 21 tube support plates. These are carefully aligned with the lower tubesheet and bolted to the shroud.

The pieces of the shroud near the tubesheet are not installed at this point, since it is necessary to have access to the tube-to-tubesheet weld area. The vessel diameter transition ring that will eventually be welded to the upper tubesheet is positioned around the shroud half in the straight portion of the steam generator. This is necessary since the ring will not fit over the lower tubesheet. The same procedure is followed for the section of the vessel near the lower tubesheet.

At this point, tube insertion begins with the row of tubes that have the shortest bend radius. As each tube or row of the tubes is inserted, the tubes are welded to each tubesheet and the welds are inspected. At the same time the build-up tube supports in the bend region and the thermal baffles are gradually assembled. Should any tube experience binding during the insertion process, workers can readily locate the source and make the necessary adjustments; either by additional guiding of the tube or slight movement of the tube support plate, since only one half of the shroud surrounds the tubes. Upon completion of tube insertion, welding and inspection; the remainder of the shroud is moved into position. The second half is held in position by the bolted connection to the tube support plates; a simple weld along the two seams of the shroud prevents any sodium from leaving the shroud at the seams. One of the shroud support rings is welded to the shroud in the proper position.

The diameter transition ring and the vessel section near the lower tubesheet that were positioned around the shroud are now moved into their respective positions near the tubesheets. The welds are made and inspected. As the vessel pieces of the bend are slipped into position, the sodium inlet flow guide is also assembled. The long straight vessel section is welded to the support ring and inspected before being placed on the steam generator. As a unit, these two pieces are slipped into position and welded to the upper portion of the vessel. The weld is inspected through the hole in the vessel where the sodium inlet nozzle will eventually be placed.

The shroud support ring is bolted to the ring already attached to the shroud and then is welded to the vessel. The lower portion of the vessel is assembled jointly with the sodium outlet flow guide. The final weld in the vessel assembly is the weld located in the final diameter reduction. This weld is a rather uncommon geometry, yet it is anticipated that it can be coded.

The steam generator assembly is completed by welding the nozzles to the vessel. As each nozzle is installed the thermal liner is installed simultaneously. Clean up and flushing the unit prepare it for shipping. A pressurized inert gas is present in the unit for shipping and is contained by caps on the nozzles and flat bolted heads on the tubesheets.

2.2.2 J-MODULE

The J-Module steam generator concept is characterized by the J-type appearance. The 180° bend allows for relative expansion and contraction between the vessel and the tubes.

Sodium flow enters the unit in the long leg, flows downward in the space between the tubes, around the bend and up to the sodium outlet nozzle near the top of the short leg. Flow guides direct the sodium flow and control the leakage into the stagnant sodium region between the tube bundle and the vessel. Feedwater or steam enters through the nozzle and tubesheet on the short leg and flows in the tubes to the other end of the steam generator. (Drawings 261R164 and 852E494)

2.2.2.1 DESIGN FEATURES

The J-Module concept was originally designed to produce a steam generator of reduced height that could incorporate long tubes. This feature reduces the overall height of the steam generator building and hence reduces the building capital costs. There is a limit in building height below which the incentive for a shorter steam generator to reduce building costs does not exist. The reason being that the height of the building is then controlled by the height of the secondary sodium pumps. This limit implies that the steam generator can be on the order of 60 ft. in length before it begins to control the building height.

The J-Module is designed so that the sodium nozzles are perpendicular to the plane of the vessel. This is necessary since shipping limits greatly restrict the overall width of the unit. In the case of the J-Module for the 1500 MWe plant (Drawing #261R164), the bend radius is shorter than seems desirable because of the shipping restrictions.

It is intended that the J-Module of Drawing #261R164 will be suspended between two railroad cars for shipping, with the bend in the vertical plane since the vertical limits on a railroad are greater than the width limitations. The short leg of the J-Module will be located not on a flat car, but rather as close to the rails as seems safe. When this is done, the module meets the 18 ft. height limit of special railroads.

Since the flow of feedwater in an evaporator unit is first downward in the short leg, there exists a possibility of flow reversal at part load conditions due to boiling and vapor formation before the bend. In the 1500 MWe commercial plant design, if the vapor bubbles coalesce to form large slugs, it is possible for flow reversal to occur at a plant load of 40%. These figures are based on preliminary findings and should be substantiated or refuted by further analysis since the problem of flow reversal in the evaporator can have particular consequence during the plant cycle. The unit was designed so that boiling would begin at the bottom of the long leg at full plant power. Present work on the low temperature cycle indicates that the length to nucleate boiling is about 13 ft. It is doubtful that this is enough length to accommodate the entire bend and sodium outlet nozzle length requirements. In other words, even with the short leg as short as possible, boiling at full power might occur at some point in the bend, rather than at the bottom of the long leg.

The J-Module steam generator design has maximum versatility with respect to the types of tube-to-tubesheet welds that can be used. Due to the fact

that the tubesheets are oriented parallel to each other in space, the tubes can be attached to either tubesheet in any fashion without having to deform the tube. This feature makes the steam generator concept readily adaptable to both the double tube and the double tubesheet concepts while maintaining a relatively uncomplicated tube-to-tubesheet weld procedure.

The bend region of the tubes must be protected against flow induced vibrations. Build-up vibration suppressors are designed to limit the allowable vibration in the bend while allowing for expansion and contraction of the tubes relative to the vessel. The bend introduces another problem, whose impact is unknown. Due to the bend, the tubes are all of different length; the tubes of shortest bend radius are shortest in length and so forth. It is anticipated that the variation in tube length could cause a more severe radial temperature gradient in the tube bundle than might otherwise be experienced. All thermohydraulic relationships were derived using the temperatures of nodes located on the center tube.

The design of the J-Module in Drawing 261R164 allows the tubes to be inserted before the vessel is installed, eliminating the need to insert tubes blindly into the bundle.

The J-Module vessel is designed to withstand in a faulted condition the postulated pressure of a large sodium water reaction (~ 1700 psi). All related systems for sodium water reaction control are located outside of the steam generator.

2.2.2.2 SUPPORT OF UNIT

The support of the J-Module may be very complicated. In the quasi-static case, heat-up of the unit may require that the short leg be prestressed in position or allowed to move. Should rigid support of the short leg

result in excessive stresses in the bend, sliding contact supports might be used or a ring support that is maintained at the respective vessel temperatures. Detailed work on these and other support methods for the J-Module has not been performed at GE.

2.2.2.3 SEISMIC RESPONSE

Preliminary studies of a J-Module unit supported solely on the long leg indicate that restraint of some type is necessary on the short leg in the event of seismic excitation. The tube bundle support for seismic events has also been identified as a potential problem area.

2.2.2.3 ASSEMBLY PROCEDURE

The inner half of the shroud and the two tubesheets are placed in a jig. Around the shroud are the two ring pieces of the vessel that are welded to the tubesheets. These rings are placed back from the tubesheet to allow access to the tube-to-tubesheet weld area. The 19 tube support plates that are in the straight portions of the vessel are bolted to the half shroud that is already in position. Alignment between the tube supports and tubesheets is necessary. Thermal baffle plates can be one of two types; either a build-up type or a slide-on type. Build-up baffles are assembled row by row with the tubes, whereas the slide-on type have oversized holes for the tubes and are anchored temporarily at the first tube support plate at the top of each leg. Tubes are inserted from the bottom, row by row, beginning with the innermost row and proceeding outward. Each tube is welded and inspected before the next row is begun. The tube insertion process is readily exposed to the workers and any binding of the tubes can be dealt with directly.

The second half of the shroud is placed around the bundle and bolted to the tube support plates. The seam in the shroud is welded to eliminate a sodium flow path out of the tube bundle. One of the two shroud support rings is welded to the bundle in the appropriate place on each leg.

The first parts of the vessel to be positioned and welded are the two rings that fit immediately below the tubesheets. The vessel assembly proceeds by placing the clamshell halves of the bend together on the tube bundle beginning at the bottom and proceeding up each leg. Welds are inspected as they are made. Shroud centering bolts and blocks are also installed as the process works toward the top. The sodium inlet and outlet flow guides are assembled around the shroud after the narrower diameter vessel pieces are in place. The final weld is the vessel closure weld near the tubesheets. The nozzles are installed and the unit is prepared for shipping. This includes the cleaning and pressurization of the unit with an inert gas. The nozzles are capped and flat heads are bolted to the tubesheets in the place of the steam nozzles.

2.2.3 STRAIGHT TUBE WITH EXPANSION BELLOWS IN THE SHELL

The straight tube design employs the use of a bellows expansion joint in the vessel for relief of the differential thermal expansion between the tubes and the vessel. Sodium enters the top of the unit and flows toward the exit at the bottom in the space between the tubes. Steam or feedwater enters the tubes through the lower tubesheet and flows upward to the upper tubesheet where it leaves the unit.

2.2.3.1 DESIGN FEATURES

The major feature of this configuration is the use of the bellows in the shell. For several reasons this application of a bellows is difficult. They include the large diameter requirements, the high temperature application, and the high pressures that might be encountered in a sodium water reaction. (Drawings 261R155 and 188F580)

Placement of the expansion bellows near the lower end of the unit is intended to reduce the magnitude of several load cycles. For example, the change in pressure at the bottom of the unit is a smaller portion of

the existing pressure than at the top of the unit. Indeed, the original pressure is larger, but the fluctuations seem smaller when referenced to the higher initial pressure. A second important reason for placement of the bellows near the bottom is the lower temperatures encountered at that end as compared to the steam outlet end.

It was considered to be too stringent a requirement to submit the bellows to the full sodium water reaction pressure; therefore, a method for reducing that pressure was designed. It consists of a sliding, piston ring sealed surface in the vessel that provides a large pressure drop in a flow due to the area restriction. This seal is further aided in bellows overpressure protection by a rupture disk located immediately below the bellows. The disk is designed to burst at 185 psi (maximum sodium pressure is 150 psi and bellows test pressure is 210 psi). The area of the rupture disk and associated piping is greater than the area of the piston ring seal, therefore, after the disk breaks the pressure will always be well below 185 psi.

The bellows is protected from sodium decarburization by a recirculating cover gas. The gas enters the vessel immediately below the bellows, inside the cover gas shield. Cover gas flow is upward past the bellows to the slip joint between the vessel wall and the cover gas shield. The gas flow is adjusted so that the flow rate out of the slip joint is greater than the diffusion rate of sodium vapor into the gap. The gas pressure maintains the free surface of sodium below the top of the shield cylinder. The cover gas system must include a sodium removal system that could perhaps be as simple as a condenser. This gas system could be used for occasional bellows leak testing purposes.

The bellows is designed so that it can be removed from the vessel, in the event of a leak, with minimum effort. The vessel must be drained of sodium. The bellows chamber is cut above and below the bellows, which then slides off the bottom of the unit. A section of the water piping is cut out to allow final removal. This allows a new bellows

to be installed and replaced without an in-place, awkward, uninspectable axial weld in the bellows. The bellows chamber is welded back together in the places where it was cut.

The expansion bellows is protected by multiple layers of steel and sodium from temperature transients. The bellows is protected from an axial temperature gradient by the upward flow of the exit sodium. If one end of the bellows were hotter than the other, extreme strain and creep problems would result when the hotter convolutions absorbed all of the relative motion between vessel ends.

The bellows is designed for a maximum operating excursion (full compression to full extension) of 1.9 inches. The bellows in a faulted condition can experience excursions greater than this at a sacrifice of operating lifetime.

The bellows material was originally specified as stainless steel 316H in order to achieve higher strength and to eliminate the post weld heat treatment requirements of the $2\frac{1}{4}$ Cr - 1 Mo vessel material. This requires a transition weld between the $2\frac{1}{4}$ Cr - 1 Mo and stainless steel parts, which can be accomplished. These welds are located in the bellows chamber, away from the bellows where access is not a problem and inspection can be easily performed. A problem with the differences in coefficients of thermal expansion between the chromium and stainless steels was discovered that could have considerable impact on the bimetallic weld area. It has been suggested that one of the Incoloy metals has a more compatible coefficient of thermal expansion than does stainless steel but that the Incoloy metal retains the strength and welding properties of stainless steel. This has not been fully investigated at this point and no firm recommendations are available.

The straight tube steam generator approaches the limits of length, both from the shipping restrictions and the capital cost of the building to house it. It requires, however, very little floor space in the building.

A major restriction of the straight tube concept thus far appears in the plugging of tubes. The plugging operation is accomplished very simply but the tube then runs at the sodium temperature; i.e. hotter than the other tubes. This case, and the case of a cold running tube (corroded inlet orifice or unbalanced flow) can cause high tube stresses in the affected tube. The plugged tube case might be solved by cutting the tube, however, the problems associated with a severed tube should be carefully studied.

The straight tube configuration is limited in the variety of tube-to-tube-sheet weld configurations that are available. Tubes are either inserted through one tubesheet to the other, limiting the type of weld used in the first tubesheet to a fillet weld, or flowered in the middle as explained in Section 2.2.3.4. The second tubesheet enjoys a less restricted weld configuration. This feature quickly becomes complicated when double tubesheets are considered.

2.2.3.2 SUPPORT OF UNIT

The main support of the straight tube design is very simply accomplished with the support ring in the vessel. Loads that originate in the piping can, in all cases except one, be resisted directly by the vessel. Those loads applied by the steam or feedwater inlet pipe are resisted primarily by the tube bundle or the vessel joint. Generally, in the case of the evaporator, the feedwater pipe will experience few transients or changes in temperature that would result in loads on the tubes. In spite of this, loads that would yield the inlet pipe generally do not stress the tubes excessively. A cyclic fatigue problem does exist and, addition of this problem at the tube-to-tubesheet welds, is in need of serious consideration.

2.2.3.3 SEISMIC RESPONSE

The area of greatest concern in a seismic upset is undoubtedly the lower tubesheet. Snubbers can be added to this portion of the vessel without affecting the operation of the bellows significantly.

2.2.3.4 ASSEMBLY PROCEDURE

The assembly procedure using the double tube evaporator shown in Drawing 261R155 is outlined below. The two tubesheets are placed in a jig, one half of the shroud is positioned and the rings that are welded to the tubesheets are positioned around the shroud away from the tubesheet weld areas. Tube support plates are bolted into position in the half shroud and thermal baffles for the tubesheets are temporarily fastened to the nearest tube support plates.

Tube insertion begins from the side upon which the shroud has already been placed. Tubes are inserted row by row through the lower tubesheet, welded in position and inspected. Upon completion of tube installation, welding and inspection, the thermal baffles are positioned in their location near the tubesheets and the second half of the shroud is installed. Bolts hold the shroud to the tube supports plates and then the shroud seam is welded to prevent sodium leakage from the tube bundle.

The rings that were positioned around the tube bundle are moved into position by each tubesheet; each is welded and then inspected. The ring for the shroud support is welded to the shroud. Centering blocks can also be attached at the same time. The vessel sections are slipped over the lower tubesheet to their positions; each joint is welded and inspected. In the areas where flow guides are shown, these are assembled about one step ahead of the vessel. The final vessel section is installed and the piston ring seal forms the lower joint. The upper weld is inspected through the hole for the sodium outlet nozzle.

The bellows chamber construction begins by forming the transition weld (from the $2\frac{1}{4}$ Cr - 1 Mo vessel to the stainless or Incoloy material of the bellows) on the short stubs in the vessel wall. The chamber is assembled until the bellows slips on as the last piece. A weld top and bottom is made. It is expected that the welds will be allowed to be

ultrasonically tested from the outside, rather than radiographed, because of a proposed Code Case that is in development. Assembly is completed by installing the nozzles, anchoring the bellows joint for shipping and cleaning the unit.

An alternate assembly procedure to the one presented above allows both tube-to-tubesheet welds to be Internal Bore Welds. The variation in the procedure is explained below.

Rather than prepositioning both tubesheets, only one tubesheet is positioned in the jig. One half of the shroud and the tube support plates are also placed in position, with the exception of the tube supports near the end where the tubesheet has not been placed. These tube supports can either be a build-up type or a 2 plate slide-up assembly.

Tubes are inserted into the bundle and welded to the one tubesheet, row by row. At the other end, tube support plates are far enough removed to allow "flowering" of the tubes; i.e., the ends are peeled outward. The second tubesheet is placed in position and the tubes are brought in from the flowered position row by row and welded.

The disadvantage of this method is that any tube-to-tubesheet weld that is unacceptable and unrepairable in position must be plugged; tubes cannot be removed from the bundle. The first method of assembly avoids this problem.

2.3 OTHER STEAM GENERATOR CONCEPTS

In this section are listed the advantages and disadvantages of several steam generator configurations including the three concepts presented in Section 2.2.

FIGURE 2.3.1 HELICAL COIL

2.3.1 HELICAL COIL (Figure 2.3.1)

2.3.1.1 ADVANTAGES

- a. The active tube length can be as long as desired
- b. Long tubes reduce number of tubes
- c. Fewer tubes reduce tubesheet diameter and number of tube-to-tubesheet welds
- d. Vessel design is compact
- e. Secondary sodium building can be more compact and less costly
- f. Can be extrapolated to large sizes
- g. Can be designed with a removable tube bundle

2.3.1.2 DISADVANTAGES

- a. Tube inspection for wastage after one leaking tube is discovered is difficult -- each tube has many neighbors
- b. Support of helical coiled tubes is difficult
- c. Difficult to fabricate
- d. Availability may be poor due to tube inspection difficulties
- e. Greater potential for tube vibration and wear problems
- f. Method of assembly can restrict tube-to-tubesheet weld type
- g. Long tubes may require butt welds in coiled region (for tubes longer than 120 ft.)
- h. Coiling of tubes leads to greater uncertainty in tube integrity
- i. More difficult to use the double tube - double tubesheet concept

2.3.2 BAYONET TUBE (Figure 2.3.2)

2.3.2.1 ADVANTAGES

- a. Bayonet tubes or tube bundle can be removable
- b. Tube supports have a simple design

FIGURE 2.3.2 BAYONET TUBE

- c. Thermal expansion problem completely eliminated
- d. Only one tubesheet in contact with sodium
- e. Concept could use protector tubes to reduce tube wastage
- f. No bends in tubes
- g. Low tube wear potential
- h. Tubes fully inspectable for wastage
- i. One tube-to-tubesheet weld per tube
- j. Vessel is straight -- no complicated bends
- k. Good availability potential due to thick tube walls, low tube stresses and one tubesheet weld per tube

2.3.2.2 DISADVANTAGES

- a. Tubes cannot be drained
- b. Upper plenum region is complex
- c. Regenerative heat losses in bayonets
- d. Heavy unit
- e. Heat transfer area requirements are greater than other designs
- f. Tubesheets will be large, possibly causing thermal transient problems that could limit the size of the design
- g. Tubes are large in diameter and hence have thicker walls which reduce heat transfer
- h. Low heat transfer requires more tubes

2.3.3 U-TUBE WITH STRAIGHT SHELL (Figure 2.3.3)

2.3.3.1 ADVANTAGES

- a. Long tube length in shorter shell -- efficient mechanical configuration
- b. Compact unit
- c. Vessel is straight -- no bends
- d. Inexpensive fabrication
- e. Efficient use of tube surface
- f. Can use double tubes and double tubesheets

FIGURE 2.3.3 U-TUBE WITH
STRAIGHT SHELL

2.3.3.2 DISADVANTAGES

- a. Flow instability in downcomer particularly at low load
- b. Tubes are not drainable
- c. Transient protection is difficult
- d. Difficult wastage inspection in bend area
- e. Temperature difference in water plenums
- f. Elaborate tubesheet thermal transient protection required
- g. Tubesheet is large
- h. Double tubesheet option is difficult

2.3.4 SERPENTINE TUBE (Figure 2.3.4)

2.3.4.1 ADVANTAGES

- a. Longer and larger tubes than most other designs
- b. Has potential compactness
- c. Minimizes number of tube-to-tubesheet welds by using fewer but longer tubes
- d. Straight vessel design
- e. Water and sodium are drainable

2.3.4.2 DISADVANTAGES

- a. Severe bending of each tube is required -- high tube stresses, decreased tube integrity
- b. Vessel diameter is large
- c. Difficult to inspect tubes for wastage
- d. Difficult tube support method required
- e. Tube-to-tubesheet welds are limited to a few types
- f. Unit is difficult to model
- g. Tubesheets will be large
- h. Tubesheets require thermal transient protection

FIGURE 2.3.4 SERPENTINE TUBE

- i. Potential for high fabrication costs
- j. Potential for tube vibration problems
- k. Possibility of non-uniform heat transfer and flow instability problems
- l. Long tubes may require butt welds (longer than 120 ft.)
- m. Difficult to use double tubes

2.3.5 STRAIGHT TUBE WITH SINE WAVE BEND (Figure 2.3.5)

2.3.5.1 ADVANTAGES

- a. Received attention in European countries
- b. Unit is compact, although tall
- c. Inexpensive
- d. Straight vessel design
- e. Water and sodium are drainable
- f. Simple concept
- g. Accommodates differential expansion between tubes (for individual hot or cold tubes)

2.3.5.2 DISADVANTAGES

- a. High tube stresses in bend region
- b. Most tube supports must be built up
- c. High potential for tube wear problems in supports
- d. High stresses in tube-to-tubesheet welds
- e. Type of tube-to-tubesheet weld is restricted
- f. Assembly of unit is hindered by bend in tubes
- g. Tube vibration problem in bend region if flow is allowed
- h. Tube inspection is difficult
- i. May not accommodate double tube concept

FIGURE 2.3.5 STRAIGHT TUBE
WITH SINE WAVE BEND

2.3.6 HOCKEY STICK (Figure 2.3.6)

2.3.6.1 ADVANTAGES

- a. Received considerable development -- reference design for Clinch River Breeder Reactor
- b. AI has built and tested a Hockey Stick steam generator
- c. Few restrictions on type of tube-to-tubesheet welds
- d. Can be adapted to use double tubes and double tubesheets
- e. Straight forward fabrication and inspection
- f. Bend in vessel reduces building height
- g. Efficient use of vessel cross-section
- h. Simple vessel support
- i. Few problems in seismic upset

2.3.6.2 DISADVANTAGES

- a. Bend in vessel requires extra design effort
- b. Tube integrity compromised by bending
- c. Borders on shipping limits
- d. Sodium flow in bend around outside of shroud may cause regenerative heat transfer losses
- e. Potential for tube vibration problems in bend
- f. Inservice tube inspection hampered by bend

2.3.7 J-MODULE (Figure 2.3.7)

2.3.7.1 ADVANTAGES

- a. Overall unit height is reasonable
- b. Relative tubesheet orientation allows all types of tube-to-tubesheet welds
- c. Easily adapted to double tubes and double tubesheets

FIGURE 2.3.6 HOCKEY STICK

FIGURE 2.3.7 J-MODULE

- d. Can have long active tube length without reaching the vessel height limitations
- e. Accommodates relative thermal expansion between individual tubes
- f. Efficient use of vessel cross-section

2.3.7.2 DISADVANTAGES

- a. Bend in vessel complicates fabrication
- b. Tube support in bend is complicated
- c. Potential for flow induced tube vibration in bend
- d. Possibility of flow instabilities at low load
- e. May not be adaptable to Low Temperature Cycle Evaporator without boiling in upcomer (tube length to the beginning of boiling is short).
- f. Support of unit may be difficult if the short leg must be allowed to move horizontally as temperature changes
- g. Seismic Response of unit is complicated due to the unsymmetrical shape
- h. Width of unit is limited by shipping requirements
- i. Shipping of unit is awkward due to shape
- j. Tube wear potential
- k. Requires more floor space than some of the other designs

2.3.8 STRAIGHT TUBE WITH EXPANSION BELLOWS (Figure 2.3.8)

2.3.8.1 ADVANTAGES

- a. Tubes are straight
- b. Efficient use of vessel cross-section
- c. Assembly is straightforward
- d. Support of unit is relatively simple
- e. Requires little floor space
- f. Could be adapted to the double tube and double tubesheet concepts
- g. Bellows can be removable
- h. Bellows can have a leak detection system
- i. Bellows can be a two-ply testable type

FIGURE 2.3.8 STRAIGHT TUBE WITH
EXPANSION BELLOWS

2.3.8.2 DISADVANTAGES

- a. Special bellows design required - high temperature, high pressure and large diameter application
- b. Seismic response of lower tubesheet could be a problem
- c. Support of lower tubesheet and the loads from some pipes are borne directly by the tubes
- d. Potential for tube wear problems
- e. Vessel seal problems at slip joint
- f. Bellows overpressure protection required either in rupture disk or backing rings
- g. May have to test bellows for coding purposes
- h. Bellows is extremely rigid in torsion; sources of torsional loads in the piping must be eliminated
- i. Bellows may require additional systems i.e., cover gas recirculation system, pressure relief piping and reaction products separator, etc.
- j. Unit is long which increases secondary sodium building costs
- k. Bellows technology needs development
- l. Tubes that are running at a different average temperature than the rest experience high stresses

3.0 TUBE AND TUBESHEET DEVELOPMENT

Application of the foregoing steam generator concepts to the LMFBR program requires a reliable boundary between the sodium and the water. In an attempt to decrease the probability of a sodium water reaction in a steam generator during the operating life of a plant, many types of tube and tubesheet configurations have been investigated. Some of these concepts will be presented in this section.

3.1 SINGLE TUBE

The use of single tubes in a steam generator relies on the capability of the manufacturer to detect and avoid small flaws in the tubes and tube-to-tubesheet welds. There is a definite economic advantage in the use of single tubes if the reliability of the double tube concepts is not significantly greater than the single tube reliability.

3.1.1 WELDS SUITABLE FOR SINGLE TUBE APPLICATION

The single tube has the widest variety of welds available. The limitation on the types of welds that are employable in a certain single tube steam generator generally originate from limits in the geometry of the steam generator concept, not the weld itself.

Suitable welds include the internal bore weld, the fillet weld above the tubesheet and the fillet weld below the tubesheet.

3.1.2 RELIABILITY

The use of a single tubes relies on the inspection procedure. This process can become as tedious as one can imagine and still some flaws have a chance of passing through the inspection process undetected. The success of the single wall tube depends on the frequency that leaks develop and the downtime to repair the leak. If either or both become excessive,

the single wall will not remain competitive against the double wall, assuming that the double walled tube is more reliable. To date a wide range of numbers have been used as expected failure rates. The failure rate equation used in the Clinch River design effort was developed at Westinghouse (WARD-4210T2-1) and is:

$$F.R. = 5 \times 10^{-9} N + 10^{-9} A, \text{ tube failures/hr}$$

where; N = number of heat transfer tubes per plant

A = O.D. heat transfer area in plant, ft²

This equation was developed for the water reactor industry and therefore its applicability to sodium systems is a matter of great debate. A steam generator reliability study for sodium systems is presently being performed under ERDA contract at GE. Results will be available by mid-July, 1975.

Assuming that the above equation is approximately correct (within an order of magnitude), two leaks per year can be expected in a 1000 MWe plant. The major question is; can downtime be kept within reason? The major concerns of a large LMFBR once a leak develops are: first, can small leaks be detected early enough to allow a shutdown before a major sodium-water reaction occurs?; and second, once a small leak is detected can it be located when the plant is shutdown? Design efforts should answer these questions as well as others about single tube reliability that might be raised.

3.2 DOUBLE TUBE

The tendency to use double tubes in place of a single tube is based on the idea of requiring multiple minor failures to occur before a major failure can occur. Hence, two barriers are provided in the place of one. Some variations on the concept are presented in the following paragraphs.

3.2.1 CONFIGURATION OF DOUBLE TUBES

Several ways of using double tubes have been proposed; these are presented in brief form.

3.2.1.1 TWO TUBES DESIGNED FOR FULL STEAM PRESSURE

In this case, the two tubes are each sized as if the other were not present. Several options are available. They include: 1) assembling the tubes such that there is no initial gap without inert gas, 2) allowing a certain size gap to exist between the tubes and introducing an inert gas, 3) placing grooves on either the outside of the inner tube or on the inside of the outer tube and placing some inert gas in the grooves, or 4) bonding the two tubes together. Each of these options will be discussed below.

Allowing no initial gap with no inert gas between the tubes will result in either the presence or absence of a gap at operating conditions. The inner tube may expand with pressure and temperature sufficiently so as to close any space left by the thermal expansion of the outer tube. In this case, a failure in the inner or outer tube will not allow a sodium water reaction. The reaction will only occur when both tubes fail. Heat transfer through the two tubes will be limited by the contact resistance to heat transfer and the added metal thickness.

Should the outer tube expand more than the inner tube, the tendency to form a vacuum will exist, thereby reducing the heat transfer significantly.

The presence of a gap between the tubes filled with gas provides double barriers between sodium and water, and leak detection capability if the gas is circulated and monitored. Preliminary studies show that a gap of 0.0001" requires about 5% more heat transfer area in order to maintain the same thermal power as a tube with no gap.

A design involving grooves between the tubes, either in the inner or outer tube, combines the advantages of the no-gap and initial-gap tubes. The grooves can provide a leak detection system while inner to outer tube contact in the remainder of the tube interface maintains the higher heat transfer characteristics of the no-gap tube. Studies of the grooved tube concept indicate that grooves on the inside of the outer tube cause high peak stresses should the outer tube experience full steam pressure. On the other hand, if the grooves are placed on the outside of the inner tube the peak stresses are lower than the previous case. The Hockey Stick Evaporator of Drawing Number 261R166 uses grooves on the outside of the inner tube allowing leak detection.

Metallurgically bonding the two tubes together eliminates the option of leak detection. A nickel bond, however, is expected to preserve the double tube advantage.

3.2.1.2 DOUBLE TUBE LINER

To reduce the overall thickness of the tube walls in a double tube concept, a single tube with a thin inside liner is proposed. The outside tube is designed for full steam pressure and the liner is made as thin as is feasible. The liner is allowed to yield with the steam pressure until it contacts the outer tube. This concept provides a double barrier between the steam and sodium.

3.2.1.3 ALTERNATIVES FOR GAP BETWEEN DOUBLE TUBES

Three methods of handling the gap between double tubes are low helium pressure, high helium pressure and a stagnant helium volume. The use of recirculating helium in the gap at either high or low pressure provides a means of leak detection. Considering the low helium pressure case, should a leak occur in the outer tube, helium enters the sodium

system. An inner tube leak allows steam to enter the helium system. Questions have been raised regarding steam jet impingement on the outer tube and the possibilities of moisture filled helium entering the sodium and causing a reaction.

The second alternative, high helium pressure in the gap, causes helium to leak into either system depending on the failed tube. For example, an inner tube failure would allow helium to enter the steam system since the helium pressure is greater than the steam pressure. A leak in an outer tube would allow pure helium, even if an inner tube leak existed, to enter the sodium. In studying this concept, it has been found that the increased helium pressure slightly reduces the gap heat transfer coefficient.

A third alternative has been proposed that combines the high and low pressure helium concepts. The alternative suggests that the helium pressure remain low until a leak is discovered, where moisture is present in the helium, at which time the helium pressure would be increased in that module and allowed to leak into either system. It is proposed that the unit operate in this fashion until a long scheduled outage is reached at which time the leak(s) can be repaired.

Use of stagnant helium layer in the gap depends on the reduced probability of a double failure for sodium-water reaction protection.

3.2.2 DOUBLE TUBE RELIABILITY

The reliability of double tubes has been tested in EBR-II. The concept of double tubes can effect the reliability of a steam generator in one of several ways depending on the tube concept employed.

First, unit availability may not be improved, not because of sodium water reactions, but because of frequent leak discoveries that require

shutdown for repair. On the other hand, leaks may not occur and the unit availability may be good, but what then is the second tube for? It seems that a single wall concept could provide the same availability.

Second, the availability of a plant might be improved by designing a steam generator that is capable of operating with leaks until an outage of sufficient duration allows the tube repairs to be accomplished.

Thirdly, the availability of a unit might be improved by maintaining a stagnant helium volume in the gap and relying on the smaller probabilities of a double failure to protect the unit from a sodium water reaction.

3.3 DOUBLE TUBESHEETS

In the design of double tube steam generators with leak detection systems, double tubesheets are sometimes needed to provide plenums for the leak detection gas (see Drawing 261R166). The Europeans feel that since the tube-to-tubesheet weld is a weak point, that the more welds between the sodium and the water, the greater the protection against a reaction. Continuing this line of reasoning, it is, therefore, feasible to use double tubesheets with a single tube welded to both tubesheets. Although this provides two or more welds between the two systems, differential thermal expansion problems between the tubes and the vessel in the tubesheet regions becomes critical as well as the relative radial thermal expansion between the two tubesheets.

3.3.1 WELDING TECHNIQUES FOR DOUBLE TUBESHEETS

The use of double tubesheets generally introduces the need for a fillet weld in the construction at some point. It becomes difficult to use the internal bore weld in all locations. This is one of the restrictions in using double tubesheets.

3.3.2 LEAK DETECTION SYSTEMS

The use of double tubesheets makes the leak detection system rather straightforward. When the inner tube is welded to the upper tubesheet and the outer tube to the lower tubesheet, the space between the tubesheets becomes the plenum for the gap or grooves between the tubes.

3.4 SINGLE TUBESHEETS

Single tubesheets are generally used with the single tube concepts. The possibility exists, however, of using double tubes with and without leak detection.

3.4.1 WELDING TECHNIQUES FOR SINGLE TUBESHEETS

Single tube, single tubesheet designs may use any type of weld geometry. The only limits that are imposed are generally due to the geometry restrictions of the particular steam generator concept. Internal bore welds and fillet welds can be used. If double tube, single tubesheet designs are used, the types of welds are generally restricted to fillet welds.

Where double tubes and single tubesheets are used, certain potential problems have surfaced. Generally, the gap between the tubes must contain a trapped gas. The tubes are welded together at each end, thus allowing no flow in or out of the gap. Should the inner tube develop a small pinhole-type leak, and steam diffuse into the gap, certain plant transients may possibly cause steam pressures in the gap that will yield the outer tube or buckle the inner tube before sufficient steam can flow back through the small pinhole into the steam system.

3.4.2 LEAK DETECTION SYSTEMS

Leak detection systems for single tubesheet steam generators have been studied. These systems generally require additional work on the tubesheet. A leak detection system for double tube single tubesheet steam generators is shown in Figure 3.4.2.1. A helium system monitors the gap (or groove, as the case may be) for the presence of sodium or steam. When a leak is detected, it is a simple matter to locate the row of tubes containing the leak, hence, streamlining the repair process.

The single tube single tubesheet with leak detection system, shown in Figure 3.4.2.2, is a modification of the double tube leak detection system discussed above. The leak detection ports may either be vented to the atmosphere (similar to EBR-II) or contain a helium gas system. In order to relieve any potential thermal expansion problems between the tubesheet and the tube, the tube is rolled into the tubesheet so that the friction force between the two bears the load of thermal expansion instead of the tube-to-tubesheet welds. This particular design requires that two welds in the same row fail before a sodium-water reaction can occur. No single weld failure can allow sodium and water to mix.

The procedure required to put the helium ports in the tubesheet is not impossible, however, the costs and time requirements of such a procedure should be carefully studied. The benefits of this concept are experienced in the case where the welds are the weakest part of the sodium-water boundary. Should reliability studies presently being conducted, show that tubes or tubesheets are less reliable than the welds, this helium port concept incurs a great expense that does not aid in solving the problem of sodium-water reactions.

Figure 3.4.2.1 Double Tube Single Tubesheet with Leak Detection System. Leak detection ports connect gaps of all tubes in one row.

Figure 3.4.2.2 Single Tube -- Single Tubesheet With Leak Detection For Tube-To-Tubesheet Welds. Leak detection ports connect the gaps of all tubes in one row.

3.5 A CONCEPTUAL DESIGN USING DOUBLE TUBES, DOUBLE TUBESHEETS AND LEAK DETECTION

The double tube, double tubesheet concept has been applied to the design of a steam generator using the Hockey Stick configuration. (See Drawing Number 261R166). This steam generator has been designed to Low Temperature cycle conditions, since the double tubesheet arrangement seems more feasible under these conditions (for further discussion of High and Low Temperature cycles, see Section 5.0).

3.5.1 DESIGN FEATURES

The steam generator of Drawing Number 261R166 is designed to use a variable pressure helium leak detection system. The gap is provided by grooves on the outside of the inner tubes. The maximum helium pressure, applied when an inner tube leak is detected, is 1300 psi. All tubesheets and tubes are designed to this pressure requirement. The unit is designed to be operated with leaks in sodium and/or steam tubes at full power until the time of a scheduled outage while minimizing the potential for the occurrence of a sodium-water reaction. Many of the other features are similar to the Hockey Stick steam generator discussed in Section 2.2.1.

3.5.2 ASSEMBLY PROCEDURE

The Hockey Stick evaporator shown in Drawing 261R166 is assembled in the following manner. The sodium tubesheets, one half of the shroud and most of the tube support plates are placed in position relative to each other. Tube support plates in the bend region and below to the height of the sodium inlet nozzle are not installed; they are build-up supports that are assembled as each row of tubes is installed.

The insertion of the tubes begins with those on the inside of the 90° bend. Since a length of the tube must be slipped through the sodium tubesheet, the tubes are deflected near the top and guided into the upper sodium tubesheet. Passing the tubes through the lower

tubesheet presents no problem. Each outer tube is fillet welded to the sodium tubesheet and inspected.

With the tubes welded to the sodium tubesheet, the assembly proceeds as in Section 2.1.5.

Upon completion of the vessel assembly, the steam tubesheets are placed in their respective positions. Row by row, the short inner tube extensions are inserted through the steam tubesheet until they butt against the longer tubes that protrude from the sodium tubesheet. An internal bore weld that can be inspected between the tubesheets, joins the extension piece to the entire inner tube. A fillet weld on the accessible side of the steam tubesheet and inspection of those welds completes the tube insertion and welding process. The rings that fit in between each set of tubesheets are clamshelled in place and welded. The assembly is then complete and the unit is prepared for shipment.

4.0 SMALL VS LARGE STEAM GENERATOR MODULES

Current estimates are that the capital cost of a steam generating system decreases with the increased size of the module. Large units, however, may impose difficult engineering and technological problems. One such problem is the fabrication of a large tubesheet. Furthermore, the reliability of large units might provide sufficient incentive to consider small modules. Such a design might improve the plant availability, but special attention should be given to maintenance philosophy and repair procedures before a final conclusion is reached. Further study of the options is required in order to make the right decision. To begin such a study, some of the advantages of large and small modules are presented in the next two sections. The sections do not propose to be complete.

4.1 ADVANTAGES OF SMALL MODULES

- a. Easier fabrication, assembly, and shipping and handling.
- b. Potential reduction of capital cost as mass production techniques are utilized.
- c. Lower development costs; a prototype can be built and tested in a shorter time with less investment.
- d. Cheaper to have a spare module on site for a fast replacement.
- e. Increase the capacity factor by not having to shut down a large unit in case of a leak.
- f. Simpler to isolate a leak.
- g. Smaller valves

4.2 ADVANTAGES OF LARGE MODULES

- a. Lower plant capital cost.
- b. Easier flow control (regulation)
- c. Simple header and piping arrangement
- d. Fewer valves resulting in a cheaper and a more reliable systems.
- e. Fewer dump and relief systems.

5.0 LOW AND HIGH TEMPERATURE CYCLES

The distinction between these two cycles is based on the level of technology required for each cycle. Generally, the Low Temperature Cycle uses lower pressures and temperatures than the High Temperature Cycle (See Figure 5.1), thus requiring fewer developments in the areas of materials, weld procedures and thermal transient protection. The choice of the high or the low temperature cycle will be made after reactor manufacturers have adequately studied the two alternatives and the implications of each to the overall plant. For this reason, this section presents some of the advantages and limitations of each cycle.

5.1 LOW TEMPERATURE CYCLE

The Low Temperature Cycle (LTC) can be used with any of the steam generator concepts discussed in Section 2.0. The use of the J-Module, however, generates a special problem. In this particular case, the length of the heat exchanger from the beginning of the active tube length to the point at which nucleate boiling begins may be shorter than the minimum possible length from the inlet water tubesheet to the bottom of the long leg, causing boiling to occur in the bend.

The LTC can use either single or double tubes and single or double tubesheets. The lower pressures and temperatures of the LTC allow thinner tubes and tubesheets. The use of double tubes and double tubesheets is not difficult because the thicknesses of the added components is not as great as in the case where the temperatures and pressures are higher.

5.2 HIGH TEMPERATURE CYCLE

The higher temperatures and pressures of the High Temperature Cycle (HTC) require the use of thicker components than the LTC. The use of either

Parameter	HTC	LTC
Heat Input, MWe	2984	3740
Net Output, MWe	1174	1258
Overall Efficiency, %	39.36	33.63
Max. Steam Temperature, °F	900	775
Steam Pressure, psig	2400	1100
Steam Flow, 10 ⁶ lb/hr	9.38	14.9
Feedwater Temperature, °F	480	420
Core Outlet Temperature, °F	1000	875
Core Inlet Temperature, °F	725	610
Primary Na Flow, 10 ⁶ lb/hr	124	147
IHX Inlet/Outlet Temp., °F	935/648	820/540
Secondary Na Flow, 10 ⁶ lb/hr	120	142
Loops/Plant	4	4
Evaporators/Loop	2	3**
Superheaters/Loop	1	0
Reheaters/Loop	2	0
Material	2½ Cr-1 Mo	2½ Cr-1 Mo

** Denotes an evaporator that generates steam with approximately 30°F superheat.

Figure 5.1 Representative High and Low Temperature Cycles for a 1200 MWe LMFBR. Assumes the use of EM sodium pumps.

double or single tubes and tubesheets is possible, however, the impact of double tubesheets may be great due to the high temperatures and pressures. The incentive to use single tubesheets with either single or double tubes is large. Single tubesheets, with helium ports (Figure 3.4.2.1 & 2) combine the HTC with the advantages of leak detection.

The cost of the additional work required on each tubesheet compared to the availability and reliability gained by doing so must be carefully evaluated.

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UNLESS OTHERWISE SPECIFIED TO USE THE FOLLOWING		TITLE OUTLINE	
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FIRST MADE FOR		SUNNYVALE	
ECF-227			

REV	NO	DATE	BY	APP
1		1/1/55	W. B. M.	F. E. D.
2		6/17/55	SUNNYVALE	

857

EVAPORATOR DATA

TOTAL PLANT POWER -	1500MW
NO. OF LOOPS -	4
NO. OF UNITS/LOOP -	2
HEAT LOAD/UNIT -	294.9 MW

TUBE DATA

TYPE -	DUPLEX TUBE W/LINER
NUMBER -	1003
TUBE I.D./O.D. -	529/693 IN
LINER I.D./O.D. -	431/529 IN
ACTIVE TUBE LENGTH -	82 FT
PITCH -	14.323 IN

SODIUM DATA

TEMPERATURE (IN/OUT) -	867/648°F
OPERATING PRESSURE -	50 PSI
PRESSURE DROP/UNIT -	11.6 PSI
FLOW RATE/UNIT -	1505 x 10 ³ LBm/HR

STEAM DATA

TEMPERATURE (IN/OUT) -	489/702°F
OPERATING PRESSURE -	2700 PSI
PRESSURE DROP/UNIT -	80 PSI
FLOW RATE/UNIT -	1.428 x 10 ⁶ LBm/HR