Topical Report
INTERIM REPORT--PRELIMINARY STEAM GENERATOR CONCEPT SELECTION STUDY
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August 5, 1968

SODIUM TO STEAM HEAT EXCHANGER ELEMENTS AND RESEARCH

AEC Contract AT(11-1)-1280 Task II
B&W Contract 596-3559-55

THE BABCOCK & WILCOX CO.
POWER GENERATION DIVISION

Barberton, Ohio

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BARBERTON, OHIO
ABSTRACT

In order to select the most optimum steam generator design for the Liquid Metal Fast Breeder Reactor Program, ninety-six possible designs were considered. From these, five alternates and a reference design were selected for further study. The selected designs were:

No. 1 Modular, Forced recirculation, Drainable, Vertical Straight Tube Unit
No. 2 Modular, Once-through, Drainable, Vertical and Horizontal Straight Tube Units
No. 3 Modular, Once-through, Drainable, Horizontal, U-Tube Unit
No. 4 Large, Once-through, Drainable, Vertical, Return Bend Unit
No. 5 Large, Once-through, Drainable, Vertical, Helical Coil Unit
No. 6 (Reference Design) – Large, Once-through, Undrainable, Vertical, Helical Coil Unit.

The program plan for the preliminary analysis of the selected designs has been made and included in the report. The result of this analysis will be the selection of the most optimum sodium heated steam generator design.

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I. Introduction

In line with the USAEC's overall program for the development of components for Liquid Metal Fast Breeder Reactor Systems, the Babcock & Wilcox Company has been conducting a study program on sodium to steam heat exchangers under AEC Contract AT (11-1)-1280. Task I of this contract includes the design of both a prototype and full-size steam generator of the helical coil, once-through concept. The objective of Task II of the contract is to study a number of alternate heat exchanger concepts and develop the most optimum sodium heated steam generator design for the commission's LMFBR Program. The work included for this task is divided into four phases: (1) design criteria, (2) concept trade-off studies, (3) optimization of selected design, (4) preliminary design. Previous work on the first phase of this task was reported in BAW 1280-46. This report covers the preliminary work done under concept trade-off studies—the selection of the concepts for further study.

The initial work required for the concept trade-off studies included the formulation of many possible designs that were different in major features but were based on one set of design conditions and certain common design factors. The selection of five alternates and a reference design was made with the aid of specified design criteria, preliminary sizing and layouts, preliminary cost estimates, etc.
2. **Scope**

The scope of work under this section of the contract consisted of selecting, from many possible designs, three or more alternates for further study.

The formulation of the possible designs was made with the aid of the following common design factors:

1. Single wall tube
2. Shell and tube design with high pressure water and steam inside tubes and liquid sodium on the shell side.
3. Counter-current flow between sodium and water.
4. Croloy 2-1/4 material

With the limitations imposed by the common design factors and specified design conditions listed in Table 1 certain design parameters were developed for use in the formulation of the designs to be considered. The design conditions used were based on the previous system design study. Using the resulting design parameters, 96 possible designs were formulated.

The selection of three or more designs from these alternatives was made with the aid of the following:

1. Ability to withstand tube failures and subsequent sodium water reaction
2. Tube bundle accessibility for maintenance and repair
3. Protection of tube sheets, shells and other heavy metal parts from thermal shock
4. Freedom from damaging tube vibrations and wear distortion.
5. Freedom from sodium stratification or recirculation
The program for the selection of the alternate designs proceeded in three major phases.

**Phase I - Preliminary Analysis**

A preliminary analysis of all the designs was made and certain designs were eliminated on the basis of being obviously impractical or having apparent disadvantages as compared to other similar designs.

**Phase II - Sizing and Layouts**

A preliminary sizing was made of the remaining units to determine the unit size and the number of units required for 1000 MWe plant. Layouts and drawings were made for preliminary visualization of conceptual designs. The sizing and layouts were made only for once-through designs since the general logic used for the elimination of certain geometries would be similar for recirculated designs.

**Phase III - Evaluation of Recirculated and Once-Through Designs**

A comparison of the different types of secondary flow was conducted to evaluate the advantages and disadvantages of each. A representative design was selected and a cost estimate made for each type of system. On the basis of this cost estimate the final selection of promising concepts were made.

A program plan was prepared for the detailed design study of the selected concepts.
3. **Formulation of Possible Designs**

There are a large number of designs that are possible for sodium heated steam generators. These designs are different from each other in major parameters or aspects that characterize a steam generator design. However, for all designs that would be studied in this project, some common design factors have been established. These are:

1. Single-wall tube
2. Water and steam inside the tubes and sodium on the outside of tubes
3. Counter-current flow of Na and H₂O
4. Material of construction for steam generator Croloy 2-1/4

In the recent designs of sodium heated steam generators, single wall tube separating the sodium and water, has been adopted as the best choice. There are various reasons for this choice. For one, using concentric tubes, as was done in the earlier designs of sodium steam generators, does not absolutely prevent a sodium-water reaction. There are some reported instances in which Na-H₂O reaction took place with concentric tube as the barrier between Na and H₂O. Na-H₂O reaction data obtained by APDA, KAPL and AI revealed that a steam generator shell designed for relatively low steady state pressure can safely withstand the high transient pressure generated in a Na-H₂O reaction when proper relief system is designed for quick removal of the reaction products. The fabrication of concentric tube steam generators is difficult, and the inspection procedures would not lead to as high assurance of a defect free boundary as a single wall unit. In addition,
there is a significant cost savings for single wall steam generators as compared to those built with double wall tube. These reasons clearly favor single wall tubes for sodium steam generators and led to their choice for the designs in this study.

The tube side fluid was chosen as water and steam because of its high pressure, which is about 3,000 psi after allowing for pressure drop in the unit for the design conditions of this study, as compared to 40 psia operating pressure of sodium. The required tube wall thickness for water on the outside of tubes at these high pressures is large. For example, the inside diameter of 1-1/2" O.D. tubes in the B&W helical coil sodium steam generator, in the superheater section would be 0.45" for steam on the outside of tubes. The large number of tubes, steam generator size, and cost of material and fabrication for each tube circuit for these extremely thick tubes obviously makes the design with water and steam outside the tubes impractical. Further, if the steam and water pressure (3000 psi) is used outside of the tubes all surfaces of the pressure boundary (pressure vessel) enclosing the tubes is subjected to this high pressure resulting in a very thick and expensive pressure boundary.

For the high temperature difference that exists between sodium inlet and feedwater inlet temperatures in the sodium steam generators, using a co-current or mixed co-current and counter-current flows would impose severe thermal stresses on the tubes because of large temperature gradient across the tube-wall. Furthermore, thermal effectiveness of the system for counter-current flow is much higher than that for co-current flow.
For the temperatures of this study, ferritic alloys are suitable and among those Croloy 2-1/4 appears to be a good choice, as pointed out in BAW-1280-46, issued under this contract. Since the study reported here and the next phase of this contract involves comparative evaluation of different steam generator designs, the choice of material should not affect the selection of best design. For use in subsequent phases of this contract, data from materials development programs in progress or planned will be reviewed as they become available. If there is reasonable assurance of safe and reliable operation of steam generator with better or less expensive materials than Croloy 2-1/4, they will be integrated into this study.

Having established the common design factors, it is necessary, in formulating the various possible designs, to identify those major parameters that can be varied and variation of which makes a significant difference in the steam generator design. The following are the design parameters that were chosen for this study:

1. Tube Geometry
   a. Straight Tube
   b. U-Tube
   c. Return bend tube
   d. Helical coil tube

2. Types of Secondary (water side) Flow
   a. Once-through
   b. Natural recirculation
   c. Forced or pumped recirculation

3. Size of Units
   a. Large
   b. Module
4. Equipment orientation
   a. Horizontal
   b. Vertical

5. Tube configuration
   a. Drainable
   b. Undrainable

Combinations of the above design parameters produced a total of 96 designs. The process of combination and the resulting 96 designs are shown on Figure 1. Each design has a number. The design numbers listed in this report refer to Figure 1. For example, design number 37 is a large, forced recirculated, drainable horizontal straight tube unit.

The meaning of the design parameter terms, as used in this report, are defined in Appendix A. For example, the term straight tube would also include tubes that have expansion loops similar to sine-wave tubes used in the ALCO prototype sodium steam generator.
4.0 Phase I - Preliminary Analysis

In evaluating the 96 design concepts listed on Figure 1 the general approach used was to discard the concepts that were either impractical or have major draw-backs and do not compare favorably with other designs. Preliminary evaluation consisted of examination to eliminate impractical designs and qualitative analysis of remaining geometries as to major technical problems.

4.1 Impractical Design Elimination Process

Drainable or undrainable tube arrangement of certain tube geometries is not practical. These are:

1. It is not practically possible to have a drainable horizontal helical coil. To be able to drain a horizontal helical coil by gravity, a separate drain line is necessary on each tube at the low point of each complete coil turn. This makes this design obviously impractical. (Eliminate Design No. 8, 24, 40, 56, 72, and 88)

2. A horizontal straight tube is drainable. It can be undrainable only when it has an expansion loop with a tube portion lower than the elevation of the draining side of the tube. A horizontal straight tube unit with an expansion loop that is undrainable does not have any significant advantages over that of the drainable unit. Therefore the undrainable horizontal straight tube unit is not desirable. (Eliminate Design No. 13, 29, 45, 61, 77, 93)

3. An undrainable vertical straight tube is not possible. (Eliminate Design No. 9, 25, 41, 57, 73, 89)
A horizontal U-tube unit is drainable. By making this unit undrainable, no significant advantages can be gained.

(Eliminate Design No. 14, 30, 46, 62, 78, 94)

There are six designs, for each one of the four impossible or impractical types discussed above, in the 96 design concepts listed on Figure 1. Each one of the four types discussed has 3 types of secondary flow (once-through, natural recirculation, and forced recirculation), and two sizes of units (large and module). Thus 24 designs are eliminated from further consideration.

4.2 Evaluation of Horizontal and Vertical Units

Twenty four design concepts were studied in a group independent of the type of secondary flow, because the general geometric considerations and problems related to each design concept would be similar whether the secondary flow was once through or recirculated. Although once-through designs were referred to in this section, the reasons given for eliminating certain concepts were equally valid for recirculating flow systems. A comparison of the different types of secondary flow would be investigated later in Section 6.0. The design concepts in Section 4.0 and 5.0 are listed without regard to the water/steam flow of these 24 design concepts, ten are horizontal units and 14 are vertical units. These are listed below separately for horizontal and vertical orientations and organized by tube geometry. For each tube geometry, the units are classified by size and drainability of tube side fluid.

HORIZONTAL UNITS

A. Straight Tube (2)

1. Large drainable unit
2. Module drainable unit
B. U-Tube (2)
   1. Large drainable unit
   2. Module drainable unit
C. Return Bend Tube (4)
   1. Large drainable unit
   2. Large undrainable unit
   3. Module drainable unit
   4. Module undrainable unit
D. Helical Coil Tube (2)
   1. Large undrainable unit
   2. Module undrainable unit

VERTICAL UNITS
A. Straight Tube (2)
   1. Large drainable unit
   2. Module drainable unit
B. U-Tube (4)
   1. Large drainable unit
   2. Large undrainable unit
   3. Module drainable unit
   4. Module undrainable unit
C. Return Bend Tube (4)
   1. Large drainable unit
   2. Large undrainable unit
   3. Module drainable unit
   4. Module undrainable unit
D. Helical Coil Tube (4)
   1. Large drainable unit
   2. Large undrainable unit
3. Module drainable unit
4. Module undrainable unit

4.2.1 **Horizontal Design Elimination Process**

One of the major problems in the horizontal sodium heated steam generators is the tendency for stratification of sodium in the shell side. Cold sodium settles in layers at the bottom and hot at the top. This large difference in temperature from top to bottom imposes severe thermal stresses on the shell and tube sheets. The heat transfer performance will also be lowered because of the stratification. A good example of a plant size steam generator that operated with this trouble is the SRE once-through horizontal U-tube unit. Severe stratification in this unit produced temperature differences from the top to the bottom of the shell at a given cross section of about 300°F. One of the factors causing this problem was water-side maldistribution at low loads. Although correcting the water side maldistribution problem by installing 1/16 inch diameter orifices in the water inlet side tubes reduced the magnitude of temperature gradients, sodium stratification and temperature gradients still remained severe. The reason for this severe stratification is the absence of baffles, which promote cross flow on the sodium side, in this SRE steam generator.

It is believed that proper design of baffles, causing the cross flow of sodium to be up and down as it flows along the length of the shell, would minimize and possibly eliminate the stratification problem. However, the placement of baffles for overcoming stratification problem poses some other practical
problems in a horizontal unit. The baffle design could interfere with the relief of sodium-water reaction products. In order to overcome this problem, it might be necessary to have several rupture diaphragms. Another problem is present in draining the sodium from shell side. In a vertical baffled unit, the shell side can be drained by gravity flow. Horizontal units may require drainage taps between alternate baffles.

In view of the above discussed disadvantages, two minimum requirements were set for the horizontal units to be considered in further evaluation of the designs. These are:

1. The particular tube geometry being considered in horizontal unit should facilitate the placement of the type of baffles needed for up and down flow of sodium in order to minimize sodium stratification.

2. Horizontal unit should have special advantages over vertical unit of the same tube geometry. This requirement is set up in view of the disadvantages of horizontal baffled unit.

The above two requirements were applied for each one of the possible horizontal units listed on pages 9 and 10. Remarks on each of these designs are:

A. Straight Tube

1. Although baffling against sodium stratification is possible in the large drainable horizontal straight tube unit, it does not have any significant special advantage over vertical unit of the same tube geometry
in support structure, flow stability, etc. Consequently, the large, drainable, horizontal straight tube unit is eliminated from further consideration. (Eliminate design no. 5, 21, 37)

2. Support structure against earth quake loadings is considerably simpler for long and slender module drainable horizontal straight tube units as compared to the tall vertical modules. Baffles for minimizing sodium stratification can be designed. Consequently, it is felt that this unit should be evaluated further.

B) U-Tube

1. & 2. Vertical units of this tube geometry have special problems that do not exist in horizontal units. These problems are discussed later in this section. Baffles for minimizing sodium stratification can be installed in both the straight legs of U-tube. Since the horizontal unit offered some advantages and was considered capable of being baffled, it should be evaluated further.

C) Return Bend Tube

1. A sketch of large drainable horizontal return bend unit is shown on Figure 2. A practical baffle arrangement for this geometry to produce up and down flow of sodium for minimizing stratification is not possible. In addition, the relative flow of sodium and water is not countercurrent. This geometry is
eliminated from further consideration. (Eliminate design no. 7, 23, 39)

2. A sketch of large undrainable horizontal return-bend unit is shown on Figure 3. Baffle arrangement for minimizing sodium stratification is possible in this geometry by placing baffles integral with tube supports at each return bend. This unit does not have any special advantage over vertical unit of the same geometry which is drainable. This geometry is eliminated from further consideration. (Eliminate design no. 15, 31, 47)

3. Horizontal return-bend shell and tube module with long straight section, as shown in Figure 4 can be baffled against sodium stratification in the straight section. For a module size unit, the return bend shell and tube unit is preferable compared to straight shell and return bend tube arrangement shown on Figure 2. The concept shown on Figure 4 is similar to the steam generator design being considered for the Phenix Reactor in France. Further comments regarding this concept are given in Section 5.3.4.

4. An undrainable module unit of the return bend shell and tube concept does not have any special advantages compared to the drainable unit. The modular undrainable horizontal return bend unit is eliminated from further consideration. (Eliminate 63, 79, 95)

D. Helical Coil Tube
1. & 2. A practical baffle arrangement for horizontal helical coil tube geometry producing up and down flow of sodium to minimize stratification is not possible. Furthermore, horizontal helical coil units do not have any significant special advantages over vertical units. These horizontal units are eliminated from further consideration. (Eliminate Design No. 8, 16, 24, 32, 40, 48, 56, 64, 72, 80, 88, 96)

The remaining units that should be evaluated further are:

a. Modular drainable horizontal straight tube unit (53, 69, 85)
b. Large drainable horizontal U-Tube unit (6, 22, 38)
c. Modular drainable horizontal U-tube unit (54, 70, 86)
d. Modular drainable horizontal return bend shell and tube unit (55, 71, 87)

The four units listed above include both once through and recirculated types.

4.3 Preliminary Evaluation of Vertical Units

Among vertical units listed on pages 10 and 11, the initial analysis showed special problems with U-tube units. First, U-tube units considered are those with straight shell as shown on Figure 5. These units were eliminated primarily because of large thermal gradients imposed on the tube sheets, shell and head, which cause high thermal stresses. Large thermal gradients arise from the differences in feed
water inlet and steam outlet temperatures, and sodium inlet and outlet temperatures. U-tube U-shell design, shown on Figure 9 would eliminate these problems.

Further consideration of vertical U-tube units showed that there would be severe problems of flow instability on the water side because of downflow boiling in tubes. There were a number of operating units that had instability problems, particularly at low loads, because of boiling in downflow heated parallel tubes. For example, water side instability problems in Fermi steam generator were thought to have been the result of boiling in downcomer tubes. A recent technical paper by Krasyakova and Glusker* on the experimental hydraulic study of six parallel heated three pass tubes showed that largest flow oscillations occurred for the cases where boiling started at the top of downflow leg. The oscillations were also pronounced when the mass velocity is lowered below a certain value determined by the hydraulic characteristic curve. The degree of subcooling of feedwater has strong influence on these oscillations.

Another potential problem area in vertical U-tube design is associated with the cooled upflow on the sodium side. This flow configuration is basically unstable as an increase in heat transfer would decrease the flow. This is due to the increase in static head loss for cold sodium flowing upward. This tendency toward vertical stratification of sodium is not considered to be as difficult a problem compared to the water side instability.

In view of the strong possibility of instability on the water side in vertical U-tubes, which would be difficult to overcome even with orifices

at the feedwater inlet for low loads, all vertical U tube designs are
eliminated from further consideration. (Eliminate design no. 2, 10, 18,
26, 34, 42, 50, 58, 66, 74, 82, 90)

4.4 Remaining Designs To Be Evaluated
The remaining concepts from those listed on page 11 and 12 which should
be evaluated further are:

1. Large drainable vertical straight tube unit (1, 17, 33)
2. Modular drainable vertical straight tube unit (49, 65, 81)
3. Modular drainable horizontal straight tube unit (53, 69, 85)
4. Large drainable horizontal U-tube (6, 22, 38)
5. Modular drainable horizontal U-tube (54, 70, 86)
6. Large drainable vertical return bend unit (3, 19, 35)
7. Large undrainable vertical return bend unit (11, 27, 43)
8. Modular drainable horizontal return bend shell and tube
   unit (55, 71, 87)
9. Modular drainable vertical return bend unit (51, 67, 83)
10. Modular undrainable vertical return bend unit (59, 75, 91)
11. Large drainable vertical helical coil unit (4, 20, 36)
12. Large undrainable vertical helical coil unit (12, 28, 40)
13. Modular drainable vertical helical coil unit (52, 68, 84)
14. Modular undrainable vertical helical coil unit (60, 76, 92)

This list includes 42 designs since each concept includes both once
through and forced and natural recirculated units. Forced and natural
recirculated are evaluated in Section 6.0.
5.0 Phase II - Sizing and Layouts

After the feasible design concepts were selected through the preliminary analysis in Section 4, sizing and layout work was performed in order to further evaluate each design. Although once-through designs were used as the basis for study in this section, the reasons given for eliminating certain concepts are equally valid for once-through and recirculating secondary flow designs.

Functional calculations were made for each design to determine the heat transfer surface required and to set the tube bundle size and geometry. At this time, layout work necessary to determine the physical size or arrangement of the tube bundle was performed. The functional analysis also set the number of units required for 1000 MWe output for a full size plant. Additional layout drawings were made to define outstanding problem areas unique to any one of the design concepts and to gain better visualization of the overall dimensions of each unit. Major problem areas that were identified in any particular design were investigated to determine the extent to which they affect the feasibility of the design. The data and drawings for each of the designs is included at the end of this report. Comments on each of the designs that were remaining after the analysis in Section 4 are given below.

5.1 Straight Tube Design

The characteristics of two straight tube designs are presented below.

5.1.1 Large Drainable Vertical Straight Tube Unit

For an analysis of the large straight tube design, 1/2" O.D. tubes were selected on the basis of unit height limitation and
the selection of a design with a reasonable number of units for 1000 MWe output. This design consisted of six units with a vessel I.D. of 65-1/2 inches and a total vessel height of seventy feet (see Table 2 and Figure 6). The straight tube design calls for compensation of differential expansion between tubes and shell, and because of simplicity of design, the sine wave expansion loop was selected. This technique for expansion is the same as that used in the Alco steam generator design. It is most favorable since it provides the ability to maintain a constant bundle diameter and, therefore, a minimum shell diameter.

The Alco sine wave design has a total tube length of approximately 39 feet. However, in order to reduce the number of units required per 1000 MWe in the straight tube design, a total tube length of sixty feet was used in the present study. A question which requires some further investigation is whether or not this additional tube length could pose support problems due to the possibility of buckling in a bundle of this height. In the Alco design, analytical methods of predicting stresses in the sine wave expansion area proved inadequate, and as a result, the question of whether or not the sine wave tubes were adequate to withstand stresses was answered experimentally. Similarly, if the straight tube design with a tube length of sixty feet is selected on further study, it most probably will require experimental analysis to verify that these tubes are within stress limits.

Although the design presented in Table 2 utilizes the segmental baffle arrangement, the disc and donut type of baffle was also
considered. It was found that the type of baffle used (segmental or disc and donut) has an insignificant effect on the size of the vessel diameter. If the straight tube design is selected and further study indicates that one type of baffle is better than the other in promoting good flow distribution or in the relief of the products of sodium-water reaction, then that type of arrangement will be selected. The baffles placed at 2-1/2 foot intervals will also serve as supports. Further consideration should be given to the unsupported tube length due to the possibility of vibration problems arising from high sodium velocities and pressure drop.

From a manufacturing point of view, one of the initial problem areas needing analysis was the limitations of maximum size for manufacture of tubesheet forgings. For this design it was determined that an outlet tubesheet of twenty inch thickness and sixty-seven inch diameter is not a limiting factor. In the Alco design, approximately six feet was considered to be the maximum practical tubesheet diameter. A manufacturing area that requires further investigation for this design are the difficulties in welding the 1/2" O.D. tubes to the tube sheets with provisions for the x-ray inspection of the welds.

The large straight tube concept, similar to the Alco design, appears to be favorable and should be further evaluated.

5.1.2 Module Drainable Vertical Straight Tube Unit

In the module design of a straight tube heat exchanger, no expansion loop, similar to the sine wave in large straight tube design is provided. Previous analysis by Atomic International
in their module straight tube design showed that thermal transients arising from incidents such as loss of feedwater and loss of sodium flow can be withstood adequately by straight tube and straight shell design without having a loop in the tube for differential expansion. For a module concept to have favorable comparison with large steam generator concept, it is felt that the module steam generator should have as simple fabrication as possible.

There is one major difference in the module design contemplated in this study and that designed by Atomics International. The design in this study is for one steam generator of Croloy 2-1/4 material with 484°F feedwater inlet and 955°F steam outlet temperatures. In the A.I. design there are separate evaporators of Croloy 5 material and superheaters of stainless 321, with interconnecting headers and piping. Lower design temperatures (1025°F) of this study permitted usage of Croloy 2-1/4 in a single steam generator fabrication. Design temperatures of 1150°F used in A.I. study required the usage of two materials, Croloy 5 for evaporator, which is economical and has better resistance against stress corrosion; and stainless 321 for superheater, which has higher allowable stresses at 1150°F. Combining the evaporator and superheater into a single steam generator results in the elimination of interconnecting piping, headers, several tubesheets, welds, etc. Consequently, the design is less complex. It might be noted here that the reduction in capital cost at the expense of lower thermal efficiency at lower temperatures is justified by the system designers on the basis of anticipated low fuel costs in fuel breeder reactor.
Sizes obtained from preliminary straight tube module design in this study are given in Table 2 and illustrated on Figure 7. A length of 100 ft. was chosen for the modules with the view of minimizing the number of modules. It is felt, however, that the support structure required for the tall and slender vertical modules to withstand earth quake loadings is going to be large and expensive. The support structure for the horizontal modules is expected to be much simpler. However, horizontal modules occupy a much larger area and have other disadvantages mentioned in the previous section. Further analysis is needed to select the orientation and the length of straight tube modules.

For the preliminary sizing, a 10" diameter shell was selected for the modules. Further evaluation is necessary as the diameter of modules would have considerable influence on the cost and the flexibility of modules concept. It is contemplated in this study that the modules would be preassembled in the shop in groups and connected to headers at the inlet and outlet on both sodium and water side before shipment. This technique is expected to result in considerable savings as the field work is more expensive than that in the shop. Furthermore, it would be less expensive and less complicated to isolate groups of modules by valves, rather than individual modules.

For example, the 84 modules obtained in the preliminary sizing can be divided into 14 groups of 6 each. These groups will be assembled in the field and connected to IHX's. The isolation required would be only for 14 groups rather than 84 modules. The loss of power by removing one or two groups of modules from the line in case of need for repair will not be significant.
Module straight tube concept is regarded as being one of the promising ones that require further study.

5.2 U-Tube Designs

Discussion on the large and module U-tube designs are given below.

5.2.1 Large Drainable Horizontal U-Tubes Design

The large horizontal U-tube design consists of three units for 1000 MWe output, each unit being 58 inches in diameter and 60 feet long (see Table 3 and Figure 8). The most serious problem areas associated with the horizontal U-tube design occur with the large radius bend of the unit and how this bend region will affect baffle arrangement, tube bundle support, and sodium flow distribution.

FWR units of similar geometry have had problems with tube supports in the U-bend region. There were a number of tube failures in the U-bend region possibly due to vibration. Because of the large unsupported length in the large U-tube design (22 feet), tube supports will have to be placed in the U-bend region to guard against vibration problems. It will also be necessary to provide adequate baffle arrangement in this region to minimize sodium stratification. In the sodium heated steam generator design, the problem of baffle arrangement and tube bundle support would be further complicated by provisions that would have to be made for differential thermal expansion between hot leg and cold leg and the tube bundle and the vessel shell in the U-bend region.

Due to the severe nature of these problems in the large U-bend region this design will be eliminated from further consideration.

(Kllimate Design No. 6, 14, 22, 30, 38, 46)
5.2.2 Modular Drainable Horizontal U-Tube

The module horizontal U-tube design consists of 84 module units per 1000 MWe output, each unit having a shell diameter of 10" and a length of 60 feet (see Table 3 and Figure 9). The return bend of the module unit is not expected to cause a severe problem as does the return bend of the large U-tube design because in the module unit the unsupported length would be less than 5 feet as compared to 22 feet in the large unit.

Baffles in the return bend region will not be required. Sodium stratification is not expected to present a serious problem since the bend is small and the shell diameter is only 10 inches. Due to the short length of the unsupported region, tube supports will be minimized or omitted. For example, in the SRE U-tube steam generator, which has a 19" diameter shell, one tube support is used in the center U-bend region, and it has operated without any known vibration problems. However, further analysis is required on this concept regarding thermal expansion between the hot and cold legs of U-tube and U-shell.

In the fabrication of U-tube modules, welding of tubes to the back side of tube sheets is expected to be less complicated than that in straight tube modules. In straight tube modules, after welding the tubes on one tubesheet, it is difficult to weld the tube to the back side of the other tube sheet due to alignment and weld shrinkage. Also it would be necessary to deflect the other tubes from the welded tube area to allow x-ray inspection of the weld.
For U-tube modules, placement of tube support in the bend region, if necessary, can be a difficult fabrication step. Further study should be made regarding the proper selection of tube and shell sizes in the U-tube modules. As in straight tube modules, it is expected that groups of U-tube modules of rail shippable size will be assembled in the shop.

U-tube modules is one of the steam generator concepts, that require further study.

5.3 Return Bend Tube Designs

There are five return bend tube designs remaining to be considered after the preliminary analysis in the last section. Two of these five designs are of large size. Prior to the evaluation of the two large return bend designs, analysis was made of the possible tube geometry patterns and also the effect of tube diameter.

5.3.1 Tube Geometry Patterns in Large Return Bend Tube Designs

Three tube geometry patterns were analyzed for the return bend design: the square pattern (see Figure 10); the involute pattern (see Figure 11); and the hexagonal pattern (See Figure 12). As a basis for comparison of these three tube geometry patterns, one and a half inch O.D. tubes were selected, an undrainable design was used, tube bundle height was kept below twenty-three feet, and vessel I.D. was limited to 156 inches for a possible rail shipment. Using this data, tube bundle arrangement drawings were made for each of the tube patterns to determine the number of plattens per unit and the number of tubes per platten (See Figure 13 for a typical platten). This information made possible
an analysis of tube geometry pattern using the number of units necessary for 1000 MWe plant output, under the specified conditions, as a basis. The comparison of the three tube geometry patterns shows that the square pattern and the involute pattern compare favorably with nine and eight units per 1000 MWe output respectively, while the hexagonal return bend pattern requires fourteen units per 1000 MWe output (Ref. Table 4). On this basis, the hexagonal return bend pattern was eliminated.

In order to compare the tube packing density of the square return bend pattern and the involute pattern using 1-1/2" O.D. tubes for larger units, the number of units was limited to three and the vessel I.D. was allowed to vary. The tube bundle arrangement for the square pattern required a 270 inch diameter vessel while the involute arrangement required a 220 inch vessel (Ref. Table 5). The conclusion being that the tube packing density of 1-1/2 inch O.D. tubes becomes more favorable with respect to the involute pattern as the shell diameter is increased beyond 156 inches, which is approximately the maximum diameter vessel shippable by rail.

5.3.2 Effect of Tube Diameter For Large Return Bend Tube Designs

In order to determine the effect of a smaller tube O.D. on the number of rail shippable units required per 1000 MWe output for the involute pattern and for the square return bend pattern, an analysis was made using 5/8" O.D. tubes. The 5/8" O.D. tubes were selected because of their use in Fermi steam generator return bend design, which has an involute pattern.

The data for 5/8" O.D. tube return bend design are given in Table 6
and illustrated on Figures 16 and 17 for square and involute patterns. The number of rail shippable vessel size units required for 1000 MWe output were reduced from 8 or 9 units with 1-1/2" O.D. tubes to three units for both tube bundle patterns with 5/8" O.D. tubes. There was considerable increase in the number of tubes required per 1000 MWe output with the decrease in tube diameter. This, however, was more than offset by the reduction in total heat transfer surface and the shorter tube length. It is possible to pack more heat transfer surface in a given volume with smaller diameter tubes. The net result was a large reduction in the number of units required for 1000 MWe plant output.

5.3.3 Large Vertical Return Bend Tube Designs Evaluation

Using the data of 5/8" O.D. tubes, a layout drawing of the top head was made for a rail shippable vessel size unit to examine the geometrical limitations of an undrainable unit (two sodium inlets and four steam outlets are shown in Figure 18). It is obvious that there is not enough room on the top head to locate 4 feed water inlet and 4 steam outlet tube sheets along with 2 sodium inlet nozzles and rupture disc for sodium-water reaction product relief. In addition, it should be noted that there would be 2438 downcomer and 2438 riser tubes for 5/8" O.D. tube design, which make it impossible to weld and fabricate the tube circuits on the top head. Even if the tube diameter were to be increased on the basis of further study, it is not expected that the above mentioned geometrical limitation would be relieved enough for an undrainable design. Because of this, the large undrainable vertical return bend designs were eliminated from further
consideration. (Eliminate design no. 11, 15, 27, 31, 43, 47)

A drainable tube configuration with feed water inlet tube sheets on the bottom head appears to be a promising design that should be investigated further in the detailed concept studies. For this concept, if the tube bundle is to be removable for maintenance purposes, it is necessary to design feed water inlet tube sheets that are removable from the bottom head. In the detailed study, further study should be made to select the proper tube diameter and tube bundle pattern. Manufacturing considerations would play an important role in the selection of these parameters. A conceptual drawing of drainable return bend steam generator with square bundle pattern is shown on Figure 19.

5.3.4 Modular Return Bend Tube Units

Of the three return bend modular units remaining after the preliminary analysis in the last section, one is a horizontal unit and two are vertical units. The horizontal unit has a return bend in both shell and tube. The return bend in the shell is not attractive for vertical units. It is desirable to keep long straight lengths between return bends in order to minimize the difficulty associated with the large number of return bends in the shell. If the long straight sections are placed vertically, the unit will not only be undrainable on water side and require drainage taps for sodium at each return bend, but would pose problems with regard to instability on the water side because of downflow boiling. Consequently, for vertical units, only straight shell and return bend tube designs are presented below.
The horizontal return bend shell and tube sizes from the preliminary design are given in Table 7. This concept, which was illustrated on Figure 4 was compared to U-tube U-shell design shown on Figure 9. The larger number of return bends on return bend shell and tube design as compared to U-tube design (3 vs 1) increases the complexity of fabrication for return bend design considerably. On the basis of complexity of fabrication, modular horizontal return bend shell and tube designs were eliminated from further consideration. (Eliminate design no. 55, 63, 71, 79, 86, 95)

Vertical straight shell and return bend tube module design information is given in Table 7 and tube bundle cross-section illustrated on Figure 20. There is considerable wasted space in this design as reflected in the large shell diameter (52") for the 30 modules required for 1000 MWe output. Each tube has about 36 return bends. This large number of return bends makes the fabrication more complex. For a module design to be practical, it is felt that the geometry and fabrication should be less complex than those for the large units. In view of the fabrication complexity and the wasted space in these modules, the modular drainable and undrainable vertical return bend tube units are eliminated from further consideration. (Eliminate design no. 51, 59, 67, 75, 83, 91)

5.4 Helical Coil Tube Designs

There were two large and two modular vertical helical coil tube designs remaining from the analysis in the previous section. These designs were separately evaluated.
5.4.1 Large Vertical Helical Coil Tube Designs

Of the two large helical coil tube designs, the undrainable configuration is the same as the design being pursued by B&W under Task I of AEC Contract AT(11-1)-1280. Because of the large amount of readily available information on the undrainable helical coil tube design, it will be used as the reference design for comparison with the other concepts selected in the present study. Design information for undrainable helical coil design is given in Table 8 and illustrated in Figure 21.

The large drainable helical coil tube design is a variation of the present B&W helical coil design. The drainable design is illustrated in Figure 22. The main physical difference between the drainable and undrainable designs is in the location of feed water inlet tube sheets. Water inlet tube sheets are located on the bottom head for drainable design whereas for undrainable design they are located on the top head. In addition to the drainability, some of the advantages offered by drainable design over undrainable design are:

1. Fabrication simplicity on the top head because of better accessibility for welds with the reduction of total number of tubes on the top head in half.

2. Better stability at low loads on the water side. This increases flexibility in the selection of tube bundle height.

3. Elimination of long downcomer tubes and the complexity of fabrication associated with them.
4. Elimination of outer shroud, which protects the downcomer tubes in undrainable design.

However, there are certain disadvantages in drainable design which are not present in undrainable design. The feed water inlet tube sheets in the drainable configuration need to be designed for removable feature without having any danger of sodium leaks, if it is desired to have removable bundle for maintenance purposes. There is some question regarding the sodium-water reaction near the feed water inlet tube sheet. If convection baffles are required near the tube sheets to minimize sodium recirculation, the baffles can obstruct the relief of sodium-water reaction products. In the undrainable configuration, similar problem with sodium water reaction is present in the downcomer region. However, the problem is not as severe as near the water inlet tube sheets in the drainable configuration. Also the tube sheets and other large metal parts exposed to sodium must be thermally protected against rapid temperature transients.

From the above evaluation, it is felt that large drainable helical coil is one of the promising concepts that should be investigated further in the subsequent detailed study.

5.4.2 Modular Vertical Helical Coil Tube Designs

Design information on module helical coil tube concept is presented in Table 8. For 1000 MWe output, it takes 30 modules of 82 inches shell diameter. The large diameter clearly indicates that there is considerable wasted space in this design, since there is a cylindrical center space which cannot be filled with coiled tubes.
In view of the large wasted space and the fact that the helical coil tube circuits require more physical access for fabrication, all modular vertical helical coil concepts are eliminated from further consideration. (Eliminate design no. 52, 60, 68, 76, 84, 92)

5.5 Remaining Units

The remaining concepts from those listed in Section 4.4 which should be evaluated further are:

1. Large drainable vertical straight tube unit (1, 17, 33)
2. Modular drainable vertical straight tube unit (49, 65, 81)
3. Modular drainable horizontal straight tube unit (53, 69, 85)
4. Modular drainable horizontal U-Tube unit (54, 70, 86)
5. Large drainable vertical return bend tube unit (3, 19, 35)
6. Large drainable vertical helical coil unit (4, 20, 36)
7. Large undrainable vertical helical coil unit (12, 28, 44)

This list includes 21 designs since each concept includes both once-through and forced and natural recirculation units. The relative merits of once-through, natural and forced recirculation units are given in the next section.
6. Phase III - Evaluation of Recirculated and Once-Through Designs

A general comparison of recirculated units and once-through units was made to explore the advantages and disadvantages of the different secondary flow systems. To aid in the comparison study, preliminary design and cost estimates were made.

Some of the advantages and disadvantages of recirculated units compared to a once-through unit are:

A. Advantages

1. More water inventory for stable operation and to prevent rapid transient during loss of feedwater.

2. Steam drum provides location for solids removal to help maintain water purity. However, in present day recirculated fossil fired boilers, at high operating water pressures of 2800 psi, the water quality required is being upgraded equivalent to that of once-through boilers.

3. Only dry steam enters superheater.

4. Not as sensitive to load changes. Easier to control. Fluctuations are not reflected rapidly back to the reactor.

5. No complicated start-up system.

6. Can be used for decay heat removal.

B. Disadvantages

1. Large steam drum and risers and downcomers required, leading to additional cost.

2. Separate superheater bundle required.

3. Drum operating pressure limited to approximately 2800 psi, which limits the pressure drop in the superheater.
4. More number of welds and points of possible leaks.
5. Longer load response time.

From the list of these advantages and disadvantages of recirculated versus once-through units, it appeared that a preliminary comparative design and cost study would be useful in arriving at a conclusion regarding the merits of recirculation units.

In order to compare recirculated and once-through designs, a representative design was selected from the six remaining concepts listed in the last section. It was felt that a general comparison could be obtained by studying any of the remaining concepts, but more cost estimating had been done on large helical coil units, which is reported in BAW-1280-46. Therefore, this concept was selected for the representative design.

6.1 Preliminary Design of a Helical Coil Natural Circulation Boiler (Large Unit)

The design of a natural circulation boiler was based on the conditions shown in Table 9.

The selection of the diameter of the tubing was made with the aid of Figure 23. The number of circuits required could be reduced by almost fifty per cent by using 2 inch diameter tubes rather than 1-1/2 inch diameter. The larger diameter tube was a thicker wall tube and would have additional difficulties in fabrication which would result in a higher cost per circuit. It was considered that reducing the number of circuits by one half would more than compensate for the increased cost per circuit and on this basis the 2 inch diameter tube was selected.

Circulation ratio is an important factor since it affects the size of boiler significantly. Careful consideration was given for its selection.
In examining the present designs of fossil fuel fired recirculation boilers, it was found that they use circulation ratios near 4 to 5. The main objective in using these high circulation ratios is to maintain lower steam qualities at the outlet of boiler, which in turn prevents departure of nucleate boiling (DNB) in the tubes. DNB in fossil fuel boilers would result in the overheating failure of tubes because of high gas temperatures. In sodium boilers, the maximum temperature that the tube will see is equal to the sodium temperature, which is below the useable limit of the tube material. Another problem that is connected with DNB is corrosion near DNB zone. This problem can be overcome by maintaining high purity water. Water chemistry requirements for high pressure recirculation boilers now being specified are equivalent to those in once-through steam generators. It is concluded that the high circulation ratios used in fossil fuel recirculation boilers are unnecessary in sodium boilers.

There is considerable incentive in reducing the circulation ratio to as low as possible for sodium boilers. Because of more stringent quality control requirements, the cost per each tube circuit is high in sodium boilers. The number of tube circuits increase with the increase in circulation ratio. This effect can be seen on Figure 24 for 2" diameter tubes.

The number of tubes required was approximately 25 per cent less for a circulation ratio of 1.25 as opposed to 1.75. Considering the high cost per circuit a circulation ratio of 1.25 was selected. It was felt that this low circulation ratio was necessary for recirculated units to compare favorably with once-through units.
Circulation ratio of 1.25 gives an average steam quality of 80% leaving the boiler. Previous experimental data on steam separation showed that the water level in steam drum can be maintained stable at these steam inlet qualities. At higher inlet qualities there can be a problem in maintaining stable water level, resulting in unstable flow in the boiler.

A steam drum height of sixty-five feet was selected for the preliminary design study. The increase in height required for each psi of pressure head was approximately 4.5 feet. Reducing the number of circuits below that selected increased the pressure drop significantly causing the height required for recirculation to increase rapidly. This effect is shown in Figure 25. The details of the selected design are given in Table 10 and the unit is illustrated in Figure 25.

6.2 Study of Forced Recirculation Boilers

The design of a forced recirculation boiler was based on the conditions shown in Table 9.

The diameter selected was 1-1/2 inch O.D. Unlike the natural circulation unit, this unit was designed with approximately 50 psi pressure drop in the circulation loop. The cost savings of using a 2 inch O.D. tube with less circuits would be counterbalanced by the additional costs due to the increase in the required tube length and the manufacturing difficulties associated with the larger tube. The diameter comparison between natural and forced recirculation units, as selected here, is similar to that in fossil fired boilers. Smaller diameter tubes are used in forced recirculation boilers as being economical in comparison
to larger O.D. tubes which are used in natural circulation boilers.

A circulation ratio of 1.25 was used since the previous study of natural circulation boilers showed that the number of circuits increased substantially with an increase in circulation ratio.

The details of the selected design are given in Table 11 and the unit is illustrated in Figure 26. The pumping system for the boiler consisted of two pumps so that if one pump failed the other would be adequate for safe operation at a reduced load of approximately 75 per cent of full load. The pump data was as follows:

- 275 hp
- 45 psig
- 7000 GPM
- 2850 psi inlet

The details of the pump system were similar to those in forced recirculation fossil fired boilers.

6.3 Comparison of Forced Recirculation Unit with Natural Circulation Boiler (Helical Coil)

Comparisons between forced recirculation and natural circulation boilers were made on the basis of size and preliminary cost estimates. The cost estimating procedure was similar to that used in BAW 1280-46. The cost estimates should be interpreted as having a tolerance of ± 20%. The cost of one design relative to another should have a tolerance of ± 5%. Therefore, if the cost difference is less than 5% the decision on the best design should not be made on the basis of cost.

Comparing the size of the two boilers showed that the forced recirculation was the smaller of the two. The number of tubes and the length of each tube was approximately the same for each
but the natural circulation boiler had 2 inch diameter tubes whereas the forced recirculation boiler had 1-1/2 inch tubes. This was the reason for the natural circulation unit being larger. The inside diameter of the vessel for the natural circulation unit was 161 inches and for the forced recirculation unit it was 140 inches. The diameter of the natural circulation unit was such that it might be difficult to ship by rail but the forced recirculation vessel was small enough for rail shipment. The height of the boiler drum was 65 feet for natural circulation and approximately 49 feet for forced recirculation.

The preliminary cost estimates of the two types of recirculation boilers showed that for a full size plant the natural circulation design would cost approximately $1,60/KWe more to build than the forced recirculation unit. The difference in the boiler cost was approximately 18%.

The cost of the pumps, motor, valves, etc. required for forced circulation was considered in the preliminary cost estimate. The additional pumping power cost was considered on the basis of the present worth of this cost distributed over the full plant lifetime. This was the same procedure as described in BAW 1280-46.

For this comparison of the two types of boilers, cost estimates were not made for the steam separator system and superheater, since they would be the same for each concept.

The support system for the boiler drum was not included in the cost estimate but since it was less expensive for the forced recirculation system it would cause the cost difference to be greater. Therefore, it was not considered necessary to estimate this cost. The higher
cost of the support structure and downcomer and riser pipes for natural circulation were considered as offsetting the capital cost for the maintenance of pumps, motors, valves, etc., for the forced recirculation system.

The results of this study show that on the basis of size and a preliminary cost estimate, the forced recirculation concept was the better of the two. Therefore, the natural circulation concept was eliminated and the forced recirculation design was selected for comparison with the once-through design. (Eliminate design no. 17, 19, 20, 28, 65, 69, 70)

6.4 Comparison of Forced Recirculation Unit With Once-Through Design

In order to compare the forced recirculation unit with the once-through design a cost estimate was made for a complete recirculation unit. This involved designing and pricing a superheater and steam drum for the forced recirculation boiler, in addition to the boiler costs figured for the comparison in the previous section.

The design of a superheater was based on the conditions shown in Table 12. A 1-1/2 inch diameter tube was selected since the steam conditions were similar to those in the once-through superheater sections and previous analysis, given in BAW-1280-46, showed this to be the optimum tube size for helical coil sodium to steam heat exchangers. The superheater except for its size is similar to the helical coil once-through unit shown in Figure 22. Steam pipe from the top of the steam drum connects to the inlet header of the superheater.

The once-through design used for this comparison study was similar to the 2400 psi, stepped tube design given in BAW-1280-46. The only
difference was that the feedwater inlets were located in the lower head, as shown in Figure 22. This difference was not considered to change the cost of the unit significantly.

Comparing the size of the two systems showed that the once-through unit required a vessel with a 196 inch I.D. compared to two vessels of 140 inch and 132 inch I.D. for forced recirculation system. One advantage to the two smaller vessels was that they were small enough to be shipped by rail. This was not the case for the once-through design.

The preliminary cost estimate for the forced recirculation unit, including the boiler and superheater, resulted in a price of $17.90/KWe. The cost for the helical coil once-through design (BAW-1280-46) was approximately $9.50/KWe. The cost of the recirculation unit was almost twice that of the once-through design. The major reason for this was the difference in the total number of circuits (high cost per circuit) and the number of vessels.

The results of this study showed that on the basis of cost, the recirculation units did not compare well with the once-through steam generator. The principal advantages listed for recirculated boilers, such as in the start-up system and decay heat removal were not sufficient to overcome this big cost differential. The additional cost of the required systems for the once-through unit was less than $1.00/KWe. It was felt that the high cost of large steam generators should not be tied up with decay heat removal which can be accomplished by an auxiliary unit at lower cost.
Since the high fabrication cost per circuit for helical coils was one of the major factors that caused the recirculation units to be so expensive, another alternate with simpler circuitry was considered. The straight-tube module was selected as a possible alternative. Some of the advantages of this unit were as follows:

1. They offered the possibility of being mass produced due to the size requirements for the modules and the design simplicity. (Preliminary sizes shown in Table 13)

2. In the case of a sodium-water reaction in one of the modules or module groups, it could be taken out of service and repaired without seriously affecting the plant output.

3. The wasted space for straight tubes in modules was small compared to other geometries.

Even though modules have these advantages, cost factors should be considered before arriving at a conclusion regarding the merits of this design. The principal reason for suggesting further study of this design is to evaluate the potential of the recirculated concept in more detail than was possible in the preliminary analysis presented in this report.

The results of this study of the various types of secondary flow showed that the once-through concept offered a cost advantage over the recirculated units. On this basis all but one of the recirculated units were eliminated. (Eliminate design no. 33, 35, 36, 44, 85, 86)

6.5 Remaining Units

The remaining units to be considered are as follows:
1. Modular forced recirculated drainable vertical straight tube unit (81)
2. Modular once through drainable vertical straight tube unit (49)
3. Modular once through drainable horizontal straight tube unit (53)
4. Large once through drainable vertical straight tube unit (1)
5. Modular once through drainable horizontal U-tube unit (54)
6. Large once through drainable vertical return bend unit (3)
7. Large once through drainable vertical helical coil unit (4)
8. Large once through undrainable vertical helical coil unit (12)
   (Reference design)
7.0 Final Selection and Recommendations

The analysis in this study resulted in the eight concepts selected for further evaluation shown in Section 6.5.

7.1 Final Selection

In order to limit the number of concepts to be studied in detail, it is recommended that the large once-through drainable vertical straight-tube unit be dropped from those concepts selected for further evaluation. Although there are some significant differences in design details, the large once-through drainable vertical straight-tube unit discussed in this report was previously studied by ALCO. It is felt that more information can be gained by studying the other concepts rather than the variations of this previously studied straight-tube once-through unit.

The modular once-through drainable vertical or horizontal straight-tube units are very similar in design fabrication and performance areas. The main differences exist in field orientation, i.e., vertical or horizontal. This orientation affects the support structure required for the units. In order to provide an opportunity to study these structural problems, the vertical unit will be retained as one of the alternates to be studied. The horizontal unit will not be eliminated from consideration, since most of the work necessary for this unit is contained in the vertical design. However, the horizontal unit will not be carried forward as a separate design effort.

Merge design no. 53 into design no. 49.
The recommended concepts for further study are the following:

1. Modular, Forced recirculation, Drainable, Vertical Straight-Tube Units.
2. Modular, Once-Through, Drainable, Vertical and Horizontal Straight-Tube Unit.
3. Modular, Once-Through, Drainable, Horizontal, U-Tube Unit.
4. Large, Once-Through, Drainable, Vertical, Return Bend Unit.
5. Large, Once-Through, Drainable, Vertical, Helical Coil Unit.
6. (Reference Design) - Large, Once-Through Undrainable, Vertical, Helical Coil Unit.

These above concepts cover the following important design variations:

a. Tube geometry
   (1) Straight tube
   (2) U-Tube
   (3) Return bend tube
   (4) Helical Coil Tube

b. Type of secondary flow
   (1) Once-through
   (2) Recirculated
c. Orientation
   (1) Horizontal
   (2) Vertical

d. Size
   (1) Modular
   (2) Large
8.0 **Program Plan for Concept Trade-Off Studies**

A program plan has been prepared for further study of the concepts selected in this report. The work in this plan is divided into two categories: one includes work that should be done for each design, and the other covers the work that is common for all designs. This program outlines the work in these two categories. The schedule of work for the concept trade-off studies is a part of the general schedule for Task II of AEC Contract AT(ll-l)-1280. This general schedule chart will be supplied at a later date.

8.1 **Analysis Planning** - The objective of this section is to establish the ground rules for engineering work on each selected design.

8.1.1 Determine material and properties to be used.

8.1.2 Determine steady-state design conditions.

8.1.3 Part load operation and design conditions.
   a. Operating conditions that can influence design, i.e. decay heat removal, hot restart.

8.1.4 Identify critical areas for analysis.
   a. Critical area - Success of solving problems here can determine outcome of entire design.
   b. Define reasons why areas are critical - Subject to thermal shock, etc.

8.1.5 Specify transient conditions to be used in analysis.
   a. List all transients. Indicate which one to be considered for study.

8.1.6 Determine major parts to be sized.

8.1.7 Determine variables to be studied - range and number, i.e. tube O.D., bundle height.
8.1.8 Number and capacity of units for 1000 MWe plant.
8.1.9 State design criteria which each unit will meet.
8.1.10 Make detail work schedule.
8.1.11 Summarize in letter - approval by Project Engineering and Reliability Engineering.

8.2 Preliminary Analysis - The objective of this phase of work is to examine the important sections of each design. The end result is an assurance that each design can be engineered and built.

8.2.1 Functional sizing calculations to span range of selected variables.
8.2.2 Stress rough sizing calculations on major parts.
8.2.3 Study critical areas (success of solving problems here can determine outcome of entire design). Study critical parts of design in sufficient depth to determine feasibility of design. Develop necessary solutions to problems.
8.2.4 Layouts of problem areas.
8.2.5 Drawing - start preliminary arrangement drawing.
8.2.6 Coordinate and discuss with manufacturing about the manufacturing problems and the effect of design parameters on costs. This includes a feasibility study of processing to determine if the unit can be built.
8.2.7 Summarize calculations. Letter on results of work which recommends final variables and arrangement of each unit. Check to see all critical areas have been noted and investigated.
8.2.8 Preliminary review - Basic question to be resolved is whether each unit is promising enough to proceed into design analysis.
8.3 Design Analysis - This phase covers the work necessary to resolve important outstanding problems in sufficient detail to serve as a basis for cost estimates and schedules. Details that will not affect cost, schedule, or engineering evaluation need not be resolved unless they will affect the choice of a final steam generator design.

8.3.1 Performance sizing calculations based on the final selected variables.
8.3.2 Stress analysis
   a. Steady-state calculations (pressure parts, supports, etc.)
   b. Thermal transients on critical parts (pressure parts and major supports)
8.3.3 Develop proposed solutions to critical areas. If more than one solution, select best solution.
8.3.4 Layout and sizing of important parts of steam generator if required, i.e., tube bundle geometry, tube supports, top head, and bottom head.
8.3.5 Determine effect of operation conditions on design.
8.3.6 Shipping problems, if any, with solution.
8.3.7 Functional examination of potential problem areas.
   a. Stability
   b. Sodium stratification
   c. Provision for level variation
   d. Evaluation of effects of sodium water reaction on design.
   e. Water side circulation
   f. Water side unbalance calculations
   g. Water dump times
   h. Part load calculations
i. Start up considerations and type of start up systems, if required
j. Sodium water reaction relief systems

8.3.8 Finish arrangement drawing.

8.3.9 Identify any required R&D - cost estimate and schedule.

8.3.10 Cost estimates, span times and tooling requirements. Sufficient accuracy for comparison of alternate concepts.
   a. Cost of steam generator and support structure
   b. Shipping costs
   c. Erection
   d. Cost of space and building
   e. Manufacturing and erection span time
   f. Interest on customer loan
   g. Special tooling

8.3.11 Additional process feasibility study in sufficient detail to show unit can be built.

8.3.12 Design review and summary.
   a. Functional calculation completed.
   b. Stress calculations completed.
   c. Preliminary arrangement drawing completed.

8.4 Development of Evaluation Criteria - The objective of this phase is to develop the evaluation procedures and criteria, other than cost, and schedule which will be used to evaluate each design and select the one concept which best meets B&W's objectives and the LMFBR program objective.

8.4.1 Operation
   a. Operating procedures for each concept, i.e., response to load, start up, normal and fast shut down.
b. Comparison of operating procedures for different concepts.
c. Procedures for shutting down the unit, cleaning and putting the
unit back in operation.
d. Costs of operation.

8.4.2 Maintenance and Repair

a. Ease and accessibility for routine inspection and repair.
b. Identify areas needing periodic maintenance.
c. Cost of down time - number of units down at one time.

8.4.3 Emergency shutdown resulting from sodium water reaction.

a. Postulation of shutdowns, interruptions and curtailment of full
power operation arising from Na H2O reactions.
   (1) Major damage
   (2) Minor damage
b. Operation after a sodium water reaction.

8.5 Evaluation - The objective of this phase is to evaluate each alternate and
select the design that best meets the design criteria and has the greatest
assurance of producing safe, reliable, and economical power.

8.5.1 Areas to be considered:

a. Cost
b. Schedule
c. Required R&D
d. Operation
e. Maintenance
f. Inspection and repair
g. Safety

8.6 Evaluation results and report.
TABLES
<table>
<thead>
<tr>
<th>TOTAL PLANT REQ'TS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steam Conditions</strong></td>
</tr>
<tr>
<td><strong>At Turbine Inlet</strong></td>
</tr>
<tr>
<td>Feedwater Temperature, F</td>
</tr>
<tr>
<td>Steam Outlet Temperature, F</td>
</tr>
<tr>
<td>Steam Outlet Pressure, psi</td>
</tr>
<tr>
<td>Steam Flow, lb/hr</td>
</tr>
<tr>
<td>Steam Outlet Enthalpy, B/lb</td>
</tr>
<tr>
<td>Sodium Inlet Temperature, F</td>
</tr>
<tr>
<td>Sodium Outlet Temperature, F</td>
</tr>
<tr>
<td>Sodium Flow, lb/hr</td>
</tr>
</tbody>
</table>
## TABLE 2
STRAIGHT TUBE STEAM GENERATOR DESIGN INFORMATION
(LARGE AND MODULE SIZE)

### LARGE DRAINABLE UNIT

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell Diameter</td>
<td>65-1/2&quot;</td>
</tr>
<tr>
<td>Number of Units/1000 MWe</td>
<td>6</td>
</tr>
<tr>
<td>Tube Diameter</td>
<td>1/2&quot; O.D.</td>
</tr>
<tr>
<td>Height of Bundle</td>
<td>60'</td>
</tr>
<tr>
<td>Effective Tube Length</td>
<td>50'</td>
</tr>
<tr>
<td>Number of Tubes/Unit</td>
<td>2450</td>
</tr>
<tr>
<td>Height of Unit</td>
<td>70'</td>
</tr>
<tr>
<td>Outlet Tube Sheet Thickness</td>
<td>20&quot;</td>
</tr>
<tr>
<td>Expansion Loop</td>
<td>Sine Wave</td>
</tr>
<tr>
<td>Baffle Arrangement</td>
<td>Segmental</td>
</tr>
<tr>
<td>Length Between Baffles</td>
<td>2-1/2'</td>
</tr>
</tbody>
</table>

### MODULE DRAINABLE UNIT

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell Diameter</td>
<td>10&quot; Schedule 20 Pipe</td>
</tr>
<tr>
<td>Number of Units/1000 MWe</td>
<td>84</td>
</tr>
<tr>
<td>Tube Diameter</td>
<td>5/8&quot; O.D.</td>
</tr>
<tr>
<td>Effective Tube Length</td>
<td>100'</td>
</tr>
<tr>
<td>Number of Tubes/Unit</td>
<td>73</td>
</tr>
<tr>
<td>Height of Unit</td>
<td>120'</td>
</tr>
<tr>
<td>Number of Rupture Discs/Unit</td>
<td>4</td>
</tr>
<tr>
<td>Type of Baffle Assembly</td>
<td>Segmental</td>
</tr>
<tr>
<td></td>
<td>Shop Assembled</td>
</tr>
<tr>
<td></td>
<td>Shippable Module Group</td>
</tr>
</tbody>
</table>
TABLE 3
U-TUBE STEAM GENERATOR DESIGN INFORMATION
(LARGE AND MODULE)

**LARGE HORIZONTAL U-TUBE**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell Diameter</td>
<td>58&quot;</td>
</tr>
<tr>
<td>Number of Units/1000 MWe</td>
<td>3</td>
</tr>
<tr>
<td>Tube Diameter</td>
<td>5/8&quot; O.D.</td>
</tr>
<tr>
<td>Tube Length (Avg.)</td>
<td>100'</td>
</tr>
<tr>
<td>Number of Tubes/Unit</td>
<td>2040</td>
</tr>
<tr>
<td>Length of Unit</td>
<td>60&quot;</td>
</tr>
</tbody>
</table>

**MODULE HORIZONTAL U-TUBE**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell Diameter</td>
<td>10&quot; Schedule 20 Pipe</td>
</tr>
<tr>
<td>Number of Units/1000 MWe</td>
<td>84</td>
</tr>
<tr>
<td>Tube Diameter</td>
<td>5/8&quot; O.D.</td>
</tr>
<tr>
<td>Tube Length (Avg.)</td>
<td>100'</td>
</tr>
<tr>
<td>Number of Tubes/Unit</td>
<td>73</td>
</tr>
<tr>
<td>Length of Unit</td>
<td>55'</td>
</tr>
<tr>
<td>Number of Rupture Discs/Unit</td>
<td>4</td>
</tr>
<tr>
<td>Type of Baffle</td>
<td>Segmental</td>
</tr>
<tr>
<td>Assembly</td>
<td>Shop Assembled</td>
</tr>
<tr>
<td></td>
<td>Shippable Module Group</td>
</tr>
</tbody>
</table>
## TABLE 4

**RETURN BEND TUBE BUNDLE PATTERN COMPARISON**

(1-1/2" TUBE O.D.)

<table>
<thead>
<tr>
<th>Return Bend Pattern</th>
<th>Vessel I.D.</th>
<th>Number of Units/1000 MWe</th>
<th>Tube Diameter</th>
<th>Height of Bundle</th>
<th>Tube Length</th>
<th>Number of Tubes/Unit</th>
<th>Number of Tubes/Platten</th>
<th>Number of Plattens/Unit</th>
<th>Number of Return Bends/Tube</th>
<th>Smallest Bend Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SQUARE RETURN BEND PATTERN</strong></td>
<td>156 inch</td>
<td>9</td>
<td>1-1/2&quot; O.D.</td>
<td>23'-0&quot;</td>
<td>350'-0&quot;</td>
<td>156</td>
<td>3</td>
<td>52</td>
<td>41</td>
<td>2&quot;</td>
</tr>
<tr>
<td><strong>IN VOLUTE RETURN BEND PATTERN</strong></td>
<td>156 inch</td>
<td>8</td>
<td>1-1/2&quot; O.D.</td>
<td>23'-0&quot;</td>
<td>350'-0&quot;</td>
<td>174</td>
<td>3</td>
<td>58</td>
<td>35</td>
<td>2&quot;</td>
</tr>
<tr>
<td><strong>HEXAGONAL RETURN BEND PATTERN</strong></td>
<td>152 inch</td>
<td>14</td>
<td>1-1/2&quot; O.D.</td>
<td>20'</td>
<td>350'-0&quot;</td>
<td>96</td>
<td>1</td>
<td>96</td>
<td>58</td>
<td>2&quot;</td>
</tr>
</tbody>
</table>
### TABLE 5

**SQUARE AND INVOLUTE RETURN BEND TUBE BUNDLE PATTERN COMPARISON**

*(1-1/2” TUBE O.D.)*

<table>
<thead>
<tr>
<th></th>
<th>SQUARE RETURN BEND PATTERN</th>
<th>INVOLUTE RETURN BEND PATTERN</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vessel I.D.</strong></td>
<td>270</td>
<td>220&quot;</td>
</tr>
<tr>
<td><strong>Number of Units/1000 MWe</strong></td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>Tube Diameter</strong></td>
<td>1-1/2”</td>
<td>1-1/2”</td>
</tr>
<tr>
<td><strong>Height of Bundle</strong></td>
<td>23’</td>
<td>23’-4”</td>
</tr>
<tr>
<td><strong>Tube Length</strong></td>
<td>350’</td>
<td>350’</td>
</tr>
<tr>
<td><strong>Number of Tubes/Unit</strong></td>
<td>452</td>
<td>450</td>
</tr>
<tr>
<td><strong>Number of Tubes/Platten</strong></td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td><strong>Number of Plattens/Unit</strong></td>
<td>113</td>
<td>75</td>
</tr>
<tr>
<td><strong>Number of Return Bends/Tube</strong></td>
<td>23</td>
<td>19</td>
</tr>
<tr>
<td><strong>Shortest Bend Radius</strong></td>
<td>2”</td>
<td>2”</td>
</tr>
</tbody>
</table>
TABLE 6
SQUARE AND INVOLUTE RETURN BEND TUBE BUNDLE PATTERN COMPARISON
(5/8" TUBE O.D.)

<table>
<thead>
<tr>
<th></th>
<th>SQUARE RETURN BEND PATTERN</th>
<th>INVOLUTE RETURN BEND PATTERN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vessel I.D.</td>
<td>156 inch</td>
<td>156 inch</td>
</tr>
<tr>
<td>Number of Units/1000 MWe</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Tube Diameter</td>
<td>5/8&quot; O.D.</td>
<td>5/8&quot; O.D.</td>
</tr>
<tr>
<td>Height of Bundle</td>
<td>22' - 4&quot;</td>
<td>21'</td>
</tr>
<tr>
<td>Tube Length</td>
<td>91'</td>
<td>91'</td>
</tr>
<tr>
<td>Number of Tubes/Unit</td>
<td>2438</td>
<td>2600</td>
</tr>
<tr>
<td>Number of Tubes/Platten</td>
<td>23</td>
<td>25</td>
</tr>
<tr>
<td>Number of Plattens</td>
<td>106</td>
<td>104</td>
</tr>
<tr>
<td>Number of Return Bends/Tube</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Smallest Bend Radius</td>
<td>1-3/16&quot;</td>
<td>1-3/16&quot;</td>
</tr>
</tbody>
</table>
### TABLE 7
**RETURN BEND MODULE DESIGN INFORMATION**

#### HORIZONTAL RETURN-BEND SHELL AND TUBE

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell Diameter</td>
<td>10&quot;</td>
</tr>
<tr>
<td>Number of Units/1000 MWe</td>
<td>84</td>
</tr>
<tr>
<td>Tube Diameter</td>
<td>5/8&quot; O.D.</td>
</tr>
<tr>
<td>Tube Length</td>
<td>100'</td>
</tr>
<tr>
<td>Number of Tubes/Unit</td>
<td>73</td>
</tr>
<tr>
<td>Number of Rupture Discs/Unit</td>
<td>4</td>
</tr>
<tr>
<td>Number of Return Bends</td>
<td>3</td>
</tr>
<tr>
<td>Length of Unit</td>
<td>30'</td>
</tr>
</tbody>
</table>

#### VERTICAL STRAIGHT SHELL AND RETURN BEND TUBE

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shell Diameter</td>
<td>52&quot;</td>
</tr>
<tr>
<td>Number of Units</td>
<td>30</td>
</tr>
<tr>
<td>Tube Diameter</td>
<td>5/8&quot; O.D.</td>
</tr>
<tr>
<td>Tube Length</td>
<td>100'</td>
</tr>
<tr>
<td>Height of Tube Bundle</td>
<td>23'</td>
</tr>
<tr>
<td>Number of Tubes/Unit</td>
<td>204</td>
</tr>
<tr>
<td>Number of Tubes/Platten</td>
<td>6</td>
</tr>
<tr>
<td>Number of Plattens</td>
<td>34</td>
</tr>
<tr>
<td>Number of Return Bends/Tube</td>
<td>36</td>
</tr>
<tr>
<td>Smallest Bend Radius</td>
<td>1-3/16&quot;</td>
</tr>
<tr>
<td>TABLE 8</td>
<td></td>
</tr>
<tr>
<td>HELICAL COIL TUBE DESIGN INFORMATION</td>
<td></td>
</tr>
</tbody>
</table>

**FULL SIZE HELICAL COIL UNIT**

- Vessel I.D. for Drainable Unit: 196"
- Vessel I.D. for Undrainable Unit: 208"
- Number of Units/1000 MWe: 3
- Tube Diameter: 1-1/2" O.D.
- Tube Length: 337'
- Height of Tube Bundle: 23'
- Number of Tubes/Unit: 452
- Height of Unit (Approx.): 56'
- Number of Units for Rail Shippable Vessel: 6
- Size Limits/1000 MWe:

**MODULE HELICAL COIL UNIT**

- Vessel I.D.: 81"
- Number of Units/1000 MWe: 30
- Tube Diameter: 1-1/2" O.D.
- Tube Length: 350'
- Height of Bundle: 23'
- Number of Tubes/Unit: 47
- Height of Unit: 32'
<table>
<thead>
<tr>
<th></th>
<th>C.R. = 1.25</th>
<th>C.R. = 1.5</th>
<th>C.R. = 1.75</th>
<th>C.R. = 2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedwater Temp. (°F)</td>
<td>534</td>
<td>565</td>
<td>586.6</td>
<td>601.7</td>
</tr>
<tr>
<td>Steam Outlet Quality (%)</td>
<td>80</td>
<td>66.7</td>
<td>57.1</td>
<td>50</td>
</tr>
<tr>
<td>Steam Outlet Press. (psi)</td>
<td>2800</td>
<td>2800</td>
<td>2800</td>
<td>2800</td>
</tr>
<tr>
<td>Steam Flow (lb/hr)</td>
<td>3.76*10^6</td>
<td>4.51*10^6</td>
<td>5.27*10^6</td>
<td>6.02*10^6</td>
</tr>
<tr>
<td>Steam Outlet Enthalpy (B/lb)</td>
<td>998.1</td>
<td>960.1</td>
<td>933.1</td>
<td>912.5</td>
</tr>
<tr>
<td>Sodium Inlet Temp. (°F)</td>
<td>891</td>
<td>891</td>
<td>891</td>
<td>891</td>
</tr>
<tr>
<td>Sodium Outlet Temp. (°F)</td>
<td>658.6</td>
<td>658.6</td>
<td>658.6</td>
<td>658.6</td>
</tr>
<tr>
<td>Sodium Flow (lb/hr)</td>
<td>24.9*10^6</td>
<td>24.9*10^6</td>
<td>24.9*10^6</td>
<td>24.9*10^6</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Boilers for 1000 MWe</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circulation Ratio</td>
<td>1.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam Quality Leaving Unit (%)</td>
<td>80</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet Water Enthalpy (B/1b)</td>
<td>529</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube Diameter (in.)</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height of Steam Drum (ft.)</td>
<td>65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube Length (ft.)</td>
<td>194</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bundle Height (ft.)</td>
<td>23</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of Tubes</td>
<td>347</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vessel I.D. (in.)</td>
<td>161</td>
<td></td>
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</tr>
</tbody>
</table>
### TABLE 11

**DETAILS OF FORCED RECIRCULATION BOILER DESIGN**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of units for 1000 MWe</td>
<td>3</td>
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<tr>
<td>Circulation Ratio</td>
<td>1.25</td>
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<tr>
<td>Steam Quality Leaving Unit (%)</td>
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</tr>
<tr>
<td>Inlet Water Enthalpy (B/lb)</td>
<td>529</td>
</tr>
<tr>
<td>Tube Diameter (in.)</td>
<td>1.5</td>
</tr>
<tr>
<td>Height of Steam Drum (ft.)</td>
<td>49</td>
</tr>
<tr>
<td>Tube Length (ft.)</td>
<td>200</td>
</tr>
<tr>
<td>Bundle Height (ft.)</td>
<td>17</td>
</tr>
<tr>
<td>Number of Tubes</td>
<td>334</td>
</tr>
<tr>
<td>Vessel I.D. (in.)</td>
<td>140</td>
</tr>
</tbody>
</table>

**Pump Data**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Recirculation Pumps/Unit</td>
<td>2</td>
</tr>
<tr>
<td>Capacity (GPM)</td>
<td>7000</td>
</tr>
<tr>
<td>Head (psi)</td>
<td>45</td>
</tr>
<tr>
<td>Horsepower of Motors</td>
<td>275</td>
</tr>
<tr>
<td>Inlet Pressure (psi)</td>
<td>2850</td>
</tr>
</tbody>
</table>
### TABLE 12
SUPERHEATER DESIGN FOR FORCED RECIRCULATION CONCEPT

<table>
<thead>
<tr>
<th>Performance Data</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam Inlet Enthalpy (B/lb)</td>
<td>1054.8</td>
</tr>
<tr>
<td>Steam Outlet Enthalpy (B/lb)</td>
<td>1427.8</td>
</tr>
<tr>
<td>Steam Inlet Pressure (psi)</td>
<td>2800.0</td>
</tr>
<tr>
<td>Steam Outlet Pressure (psi)</td>
<td>2500.0</td>
</tr>
<tr>
<td>Steam Flow (lb/hr)</td>
<td>3.01*10^6</td>
</tr>
<tr>
<td>Sodium Inlet Temperature (°F)</td>
<td>1025.0</td>
</tr>
<tr>
<td>Sodium Flow (lb/hr)</td>
<td>24.9*10^6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Details of Superheater</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Number of Units for 1000 MWe</td>
<td>3</td>
</tr>
<tr>
<td>Tube Diameter (in.)</td>
<td>1.5</td>
</tr>
<tr>
<td>Pressure Drop (psi)</td>
<td>300</td>
</tr>
<tr>
<td>Bundle Height (ft.)</td>
<td>25</td>
</tr>
<tr>
<td>Number of Tubes</td>
<td>526</td>
</tr>
<tr>
<td>Vessel I.D. (in.)</td>
<td>132</td>
</tr>
<tr>
<td>Tube Length (ft.)</td>
<td></td>
</tr>
<tr>
<td>A - 1st S.H. Section (1.053&quot; I.D.)</td>
<td>18.2</td>
</tr>
<tr>
<td>B - 2nd S.H. Section (0.850&quot; I.D.)</td>
<td>43.6</td>
</tr>
<tr>
<td>C - 3rd S.H. Section (0.692&quot; I.D.)</td>
<td>80.0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>141.8</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>---------------------------------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Shell Diameter (in.)</td>
<td>10</td>
</tr>
<tr>
<td>Number of Units for 1000 MWe</td>
<td>82</td>
</tr>
<tr>
<td>Tube Diameter (in.)</td>
<td>5/8</td>
</tr>
<tr>
<td>Effective Tube Length (ft.)</td>
<td>48</td>
</tr>
<tr>
<td>Height of Unit (ft.)</td>
<td>60</td>
</tr>
<tr>
<td>Circulation Ratio</td>
<td>1.25</td>
</tr>
<tr>
<td>Outlet Steam Quality (%)</td>
<td>80</td>
</tr>
<tr>
<td>Inlet Enthalpy (B/1b)</td>
<td>529</td>
</tr>
</tbody>
</table>
FIGURES
Sketch of Large Once-Through Drainable Horizontal Return Bend Tube Steam Generator (Design 7)
Sketch of Large Once-Through Undrainable Horizontal Return Bend Tube Steam Generator (Design IS)
STEAM OUT

SODIUM IN

SODIUM OUTLET

10'-SCH. 20 PIPE
24'-0''

73 - 5/8" O.D. TUBES ON 1" A PITCH

10" SCH. 20 PIPE

SECTION "A-A"

MODULAR - ONCE-THROUGH DRAINABLE
RETURN BEND SHELL AND TUBE
STEAM GENERATOR (DESIGN 55)

FIGURE 4
DRAINABLE
(DESIGNS 2 & 50)

UNDRAINABLE
(DESIGNS 10 & 58)

ONCE THROUGH VERTICAL U-TUBE STRAIGHT SHELL CONCEPT

FIGURE 5
2450 - \( \frac{1}{2} \)" O.D. Tubes on 1" Pitch

Enlarged Section "B-B"

Sodium Outlet

Large Once-Through Vertical Straight Tube Steam Generator (Design 1)
Module - Once - Through Drainable Straight Tube Steam Generator (Designs 49 853)

Figure 7
Figure 8

LARGE ONCE-THROUGH DRAINABLE HORIZONTAL U-TUBE U-SHELL STEAM GENERATOR (DESIGN B)
STEAM OUT

SODIUM IN

FEEDWATER IN

"A"

SODIUM OUTLET

10"-SCH. 20 PIPE

49'-0"

30"

73 - 8" O.D. TUBES ON 1' A PITCH

10"-SCH. 20 PIPE

SECTION "A-A"

Module Once-Through Drainable Horizontal U-Tube U-Shell Steam Generator (Design 54)

Figure 9
SQUARE RETURN BEND TUBE BUNDLE PATTERN
(1/2" TUBE O.D. RAIL SHIPPABLE UNIT SIZE)
58 Involute Plattens - 3 tubes each on 2" centers

174 - 1 1/2" O.D. tubes 350'-0" L.
Length of Plattens 10'-6"
Height of Plattens 23'-0"

Involute Return Bend
Tube Bundle Pattern
(1 1/2" O.D. tube rail shippable unit size)

Figure 11
NOTES:
56 PLATTENS -1 TUBE EACH
2' HORIZ. PITCH - 4' VERT. PITCH
36-1/2 O.D. TUBES X 350'-0" L.G.
LENGTH OF PLATTENS 6'-0"
HEIGHT OF PLATTENS 20'-0"
152" I.D. VESSEL

HEXAGONAL RETURN BEND TUBE
BUNDLE PATTERN
(1 1/2" O.D. TUBES RAIL SHIPPABLE SIZE)

FIGURE 12
NOTE
EACH LINE REPRESENTS ONE TUBE - 23 TUBES IN ONE PLATTEN

PLATTEN WITH $\frac{5}{8}$ o.d. TUBES

FIGURE 13
NOTES:
91 Plattens-5 tubes each.
455 tubes - 1 1/2" O.D. x 350'-0" L.G.
Length of Plattens 15'-0''
Height of Plattens 23'-0''

Outer Shroud

Square Return Bend Tube Bundle Pattern
(1 1/2" O.D. tubes, 3 units/1000 MWe)

Figure 14
75 INVOLUTE PLATTENS- 6" TUBES EACH ON 2" CENTERS

450 TUBES 1/2" OD. 356'-6" L.G.
LENGTH OF PLATTENS- 18'-5"
HEIGHT OF PLATTENS 23'-4"

INVOLUTE RETURN BEND
TUBE BUNDLE PATTERN
(1 1/2" O.D. TUBES,
3 UNITS/1000 MWE)

FIGURE 15
SQUARE RETURN BEND TUBE BUNDLE PATTERN
(5/8" O.D. TUBE, RAIL SHIPPABLE UNIT SIZE)

FIGURE 16
104 Involute Plattens - 25 tubes each on 1" centers

2600 - 5/8" o.d. tubes 91'-0" lg.
Length of Plattens 9'-6"
Height of Plattens 21'-0"

Involute Return Bend Tube Bundle Pattern
(5/8" o.d. tubes, rail shippable unit size)

Figure 17
Large Once-Through Drainable Vertical Return Bend Tube Steam Generator (Design No. 3) Figure 19
Module Return Bend Tube Bundle
Cross-Section

Figure 20
4 STEAM OUTLETS
SODIUM HEADER
452 - 1/2" DIA. TUBES 337-0.4G
SHELL 452 DOWNCOMERS
OUTER SHROUD
INNER SHROUD
LINER
4 FEEDWATER INLETS
2 SODIUM INLET NOZZLES
23'-0" TUBE BUNDLE

56'-0" OVERALL LENGTH (APPROX)

LARGE ONCE-THROUGH UNDRAINABLE VERTICAL HELICAL COIL TUBE STEAM GENERATOR (DESIGN 19)

Figure 21
LARGE ONCE-THROUGH DRAINABLE VERTICAL HELICAL COIL TUBE STEAM GENERATOR (DESIGN 4)

FIGURE 22
Natural Circulation Boiler Design

Effect of Tube Diameter on Number of Tubes and Boiler Height

Figure 23
NATURAL CIRCULATION BOILER DESIGN
EFFECT OF CIRCULATION RATIO ON NUMBER OF TUBES AND HEIGHT OF STEAM DRUM

FIGURE 24
STEAM OUTLETS

STEAM DRUM - 60% D.

16 RISERS

RUPTURE DISC

4 DOWNCOMERS

STEAM GENERATOR

SODIUM OUTLET

SODIUM INLET

LARGE NATURAL CIRCULATION DRAINABLE VERTICAL HELICAL COIL TUBE BOILER (DESIGN 20)

FIGURE 25
LARGE FORCED RECIRCULATION DRAINABLE VERTICAL HELICAL COIL TUBE BOILER (DESIGN 36)

FIGURE 26
APPENDIX A

DEFINITIONS OF TERMS
DEFINITIONS OF TERMS

The following are the definitions to be used in the steam generator selection study.

(a) Large Single Units - The estimated range is from 150 MWe to 500 MWe per unit.
(b) Modular Units - The estimated range is from 10 MWe to 30 MWe per unit.
(c) Once through - The water-steam circuit is continuous from economizer inlet to superheater outlet with no definable water level or steam drum. Headers can be used to collect and distribute the flow. The fluid is forced through the unit by pumps.
(d) Recirculated-Natural - The boiling circuit is a loop including a steam drum for steam separation, downcomers and risers circulating by density differences only.
(e) Recirculated-Forced - The boiling circuit is a loop including a steam drum for steam separation, downcomers and risers, circulating by density differences and by pumps.
(f) Drainable - A unit is considered drainable if the water can be removed by gravity.
(g) Undrainable - A unit is considered undrainable if the water cannot be removed by gravity. Boiling out of the water or using pressure or vacuum are the only methods of emptying the unit.
(h) Vertical - A vertical unit is one having the containment and the heating surface oriented in a vertical direction.
(i) Horizontal - A horizontal unit is one having the containment of the heating surface in a horizontal elevation.
(j) **Straight Tube** - This includes:

1) tubes with no bends

2) tubes with expansion bends such as sine wave, slightly 's' shaped tubes, etc.

3) bowed tubes.

(k) **U-Tubes** - This includes tubes bent in a U shaped with one return bend and straight legs. Legs do not have to be of equal length.

(l) **Return Bend** - A return bend is a platen with two or more U shaped tubes mounted continuously one after the other. The platen can be flat, circular, involute or any other geometric shape.

(m) **Helical Coil** - A helical coil is composed of spirally formed tubes with a fixed pitch and coil diameter to any desired length.