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MASTER

DESIGN, PERFORMANCE, AND ECONOMICS EVALUATION
OF SODIUM-HEATED, MODULAR,
SUPERCRITICAL, STEAM GENERATORS

AEC Research and Development Report

ATOMICS INTERNATIONAL

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OF SODIUM-HEATED, MODULAR,
SUPERCRITICAL, STEAM GENERATORS

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ABSTRACT

In May of 1962, authorization from the U. S. AEC was received to design and develop fabrication techniques for a sodium-heated, modular, supercritical, steam generator; and, upon completion of the work, submit an interim report. The following report summarizes the engineering and design phases of the project.

An IBM 7090 digital computer heat transfer code for a supercritical, once-through, sodium-heated, steam generator was developed. A water-side fouling factor was determined, based on published data. Detail designs of 37-tube and 61-tube modular steam generators were completed. Designs showing the installation of the modules, including their interconnecting piping, supporting structures, etc were completed and price estimates obtained. A reevaluation of previous economic studies continued to indicate cost savings resulting from the use of supercritical steam conditions.

Three other reports cover the development and test phase of the project. One pertains to the welding development, NAA-SR-8541; and the others, NAA-SR-8414 and NAA-SR-8415, pertain to the experimental stress programs.

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I. INTRODUCTION

In the nuclear energy field today, the sodium-cooled reactor holds a unique position. It may be designed as a thermal reactor when a moderator is used in the core, or it may be designed as a fast reactor when unmoderated. In both of these concepts, however, the nuclear energy generated in the core appears as high temperature sodium exiting from the core. Since sodium has a low vapor pressure (boiling point 1621°F) and excellent heat transfer properties, this source of high temperature sodium offers the capability for generating high temperature steam. Since the reactor, primary loop, intermediate heat exchanger, and secondary piping loop contain only sodium, they are relatively independent of the steam pressure developed in the steam generators. Therefore, the problems associated with steam pressure are basically limited to the steam generators.

One of the major problems associated with sodium-cooled reactor power plants has been the design of reliable and economical sodium-heated steam generators for high quality steam (above 900 psi/900°F). Problems encountered due to caustic stress corrosion, resulting from sodium-water reaction and chloride stress corrosion resulting from condenser leakage have been previously circumvented by the use of expensive noncorrosive linings, double-wall-tube construction, or the reduction of steam temperatures to levels where lower strength alloys not subject to the corrosion problem, may be used. These solutions, however, do not lend themselves to lower steam generator prices, and they do not offer the promise of fully exploiting the more advanced steam cycles which are currently being used in fossil-fired power-generating stations.

From the above considerations, the design criteria for sodium steam generators may be outlined as follows:

- a) Detail design features must minimize the possibility of caustic stress corrosion.
- b) Designs should allow the generation of 950 to 1050°F steam with the lowest possible cost consistent with reliable performance.
- c) The design should be adaptable to high pressures to exploit the associated lower plant heat rates.

- d) The design should allow isolation and removal from service of the units without a major plant outage.
- e) The design should allow steam generator fabrication and installation schedules which will not govern the plant construction schedule.

In order to determine optimum steam conditions for a sodium-cooled reactor power plant, based on economic considerations only, a preliminary economics study was conducted considering steam conditions of 1400 psi (condensing and single reheat), 1800 psi (single reheat), 2400 psi (single reheat), and 3500 psi (single and double reheat). The results of the preliminary economics study indicated an incentive to use supercritical steam conditions.

Supercritical steam conditions with the resulting high steam-side heat transfer coefficients allows a reduction of the steam generator and intermediate heat exchanger heat transfer surface areas and costs while giving an increase in overall plant performance. A conventional 2400-psi steam generator has a steam side heat transfer coefficient of about $750 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ for the superheater section which comprises over one-half of the total surface area. In comparison, at 3500 psi, the steam-side heat transfer coefficient is $2200 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$. Since the sodium-side heat transfer coefficient and the tube wall have very little thermal resistance, the majority of the overall thermal resistance in the subcritical steam region is due to the steam-side coefficient; therefore, any increase in the steam-side coefficient due to higher pressure results in a substantial increase in the overall heat transfer coefficient and a decrease in the required heat transfer surface area; in the supercritical region, the reverse is true. As the steam pressure increases, the overall heat transfer coefficient decreases due to the effect of greater wall thickness.

With the incentive to use supercritical steam for a sodium-cooled reactor power plant, a development project was proposed to the U.S. AEC to design, develop fabrication techniques for, and have fabricated two modular supercritical-pressure, once-through, sodium-heated steam generators for testing in the Sodium Components Test Installation.

In May of 1962, authorization was received to design and develop fabrication techniques for the supercritical modular steam generators and, upon completion of the work, to submit an interim report. This report summarizes the engineering and design phases of the project. Design details for 37-tube high-

and low-temperature modules applicable for testing in the Sodium Components Test Installation (SCTI) (with no reheat) are included. In addition, designs for 37-tube modules applicable for a 450-Mwe power plant with single reheat and 61-tube modules applicable for a 350-Mwe power plant with single reheat are also included. Three other reports cover the development and test phase of this work. One pertains to the welding development¹ and the others pertain to the experimental stress^{2,3} programs.

II. CURRENT MECHANICAL DESIGN CRITERIA

The basic requirement for the sodium-heated modular steam generators is to show the capability of furnishing 3500-psi, 1050°F steam at the turbine throttle utilizing an Advanced Sodium-Cooled Reactor (ASCR) as the source of hot sodium. With the ASCR as the heat source, the design criteria for the primary and secondary sodium systems must be adhered to and be the basis for the steam generator design criteria. Within these limits, there are various alternatives for designing and operating the overall system. These alternatives are discussed and the tentative steam generator design criteria are developed in the following pages.

A. STEADY-STATE FULL- AND PART-LOAD DESIGN CRITERIA

A reference ASCR system is shown in Figure 1 with representative full-load steady-state temperatures. Adhering to current ASCR system design criteria,

Figure 1. ASCR System With Balanced Primary and Secondary Sodium Flows and Additional Feedwater Heater

it is required that the primary inlet and outlet sodium temperatures be limited to changes of less than 100°F/hour or 50°F over a short time period. This requires that a load reduction of 4%/minute from 100 to 20% be accomplished within a maximum decrease of 50°F in both primary inlet and outlet sodium

temperatures. This requires that secondary sodium temperatures be held relatively constant with the result that steam is produced by the steam generators at about 1081°F. In addition, the requirement of having relatively constant steam generator sodium outlet temperatures over the load range requires the feedwater temperature be increased as the load is reduced. Normally, the feedwater temperature would drop from 600 to about 500°F as the load is reduced to 20%.*

The steam temperature of 1081°F would require attemperation which for sodium-heated steam generators is usually after the steam generator outlet. However, this does not reduce the steam generator tube sheet design temperatures. In order to allow a lower tube sheet design temperature, feedwater may be injected between the low- and high-temperature steam generator modules. This would reduce the steam temperatures leaving the high-temperature modules; however, excessive temperatures (greater than 875°F) could still be experienced by the low-temperature modules.

A second method of system operation is to unbalance sodium flows; that is, increase the secondary sodium flow and lower the secondary sodium temperature entering the steam generator to give 1055°F steam, see Figure 2. This would alleviate the requirement of attemperation; however, the secondary sodium temperature leaving the steam generator would still have to be maintained relatively constant and the feedwater temperatures would still have to be increased as the load is reduced.

Increasing the feedwater temperature as the load is reduced can be accomplished by an additional feedwater heater utilizing throttle steam. However, this does not alleviate high temperatures in the low-temperature modules at part load conditions. To overcome these conditions, recirculation of feedwater through the low-temperature modules may be employed by the addition of recirculation pumps. This should then maintain the water and sodium temperatures leaving the low-temperature modules constant for all load conditions.

In order to alleviate the requirement of increasing the feedwater temperature at reduced loads, the low-temperature steam generators may be designed

---

*If operation at 20% load is desired for an extensive period of time, the primary and secondary sodium temperatures could be reduced to produce 1055°F steam with 500°F feedwater; however, load pickup from this condition would then be limited to less than 1%/minute.

However, this possibility was not considered in establishing the steam generator design criteria since it exceeded the current established design criteria for the primary and secondary sodium systems.

Since use of any of the above methods to obtain part load performance requires either additional equipment or subsection of radioactive primary structures to severe temperature changes, further alternatives were sought. A fourth possibility based on the assumption that there are at least two Intermediate Heat Exchangers (IHX's) per loop, is to unbalance the secondary flows through the IHX's. This would allow the secondary sodium temperatures to be varied to control steam temperatures while the primary sodium temperatures could be held relatively constant. Relatively large temperature differences would be experienced across the IHX tube sheet, but the IHX's themselves are not radioactive and they could readily be designed to withstand such differences. This method of system operation, shown in Figure 4, has been used for determining the steam generator design criteria and part load performance.

Figure 4. ASCR System With Unbalanced Secondary Flow Through IHX's

In any of the above methods, the remote possibility exists that a tube becomes partially plugged at one end with the result that the tube would be subjected to the full pressure and maximum sodium temperature. For this reason, there seemed to be no alternative but to use the maximum sodium temperature

as the design temperature for the tubes and tube sheets. Therefore, the high-temperature steam generator modules were designed for 1105°F and the low-temperature modules were designed for 875°F.

In order to furnish 3500 psi steam at the turbine throttle, steam should be produced at 3600 psi to allow 100 psi for main steam line and throttle valve pressure drop. Allowing for a pressure sensing and control error of 150 psi, the maximum operating pressure should be 3750 psi. However, the design pressure based on the setting of the relief valves would be 4000 psi for the high-temperature modules.

The maximum operating pressure for the low-temperature steam generators would then be 3850 psi which allows for a 100 psi drop in the high-temperature section. The maximum sodium temperature expected under part load conditions will be 875°F or less. The design pressure based on the setting of the relief valves would be 4100 psi for the low-temperature modules.

The above criteria for steady-state full and part load operation are summarized in Table I below:

TABLE I
OPERATION CRITERIA

Criteria	Modules			
	High Temperature		Low Temperature	
	Design	Nominal	Design	Nominal
Steam Pressure (psi)	4000	3600	4100	3700
Steam Temperature (°F)				
Tube Sheet	1105	1055	875	723
Tube	1105	1095	875	780
Sodium Pressure (psi)				
Shell	300	100	300	100
Rupturable membrane	200		200	
Sodium Temperature	1105	1105	875	875
Steam velocity (ft/sec)	120 maximum			
Sodium velocity (ft/sec)	15 maximum			

B. TRANSIENT DESIGN CRITERIA

The modular steam generators, when used in power plants for a period of 30 years, could experience various transient conditions resulting from uncontrolled variables. To ensure performance, these transients have to be anticipated, the number of times the transient may occur has to be estimated, and the steam generators designed accordingly.

The following are representative transients which might be expected during the 30-year period. The number of times these transients might occur will be highly dependent on the maintenance policy in effect at the plant, the alertness of the operator, and many other intangible items. In actuality, transients one to five as listed below should not occur during the life of the plant. However, in order to arrive at a conservative design and allow for transient conditions not ever thought of, the number of cycles were increased to the values shown below. Therefore, these transients establish the preliminary transient design criteria for the supercritical modular steam generators.

- 1) Reactor Scrammed, Turbine Throttle Valve Closed, Primary Outlet Sodium Temperature Maintained. Feedwater flow is essentially reduced to zero and steam at 1150°F is produced. This is a casualty condition and 20 such transients are assumed. Corrective action should be taken within 5 minutes by relieving pressure with the steam dump system. The conditions of the steam generator units will be:

High-Temperature Steam Generator

Steam Pressure	4000 psi
Steam Temperature	1150°F

Low-Temperature Steam Generator

Steam Pressure	4000 psi
Steam Temperature	1150°F
Feedwater	500°F

- 2) Turbine Throttle Valve Closed, Normal Pressure Control, Power Relief, and Steam Dump System do not Operate. Steam at 1105°F is produced and the pressure rises to 4000 psi before the safety valves

are actuated and feedwater flow stopped. This is a casualty condition and five such transients are assumed. Corrective action should be taken within 5 minutes by stopping sodium and feedwater flow in the steam generator bank effected. Steam generator conditions:

High-Temperature Steam Generator

Steam Pressure	4000 psi
Steam Temperature	1105° F

Low-Temperature Steam Generator

Steam Pressure	4000 psi
Steam Temperature	1105° F
Feedwater Temperature	500° F

- 3) Reactor Scrammed, Primary and Secondary Sodium Systems Continue at Full Flow. This is a casualty condition and 30 such transients are assumed. Steam generator conditions:

High-Temperature Steam Generator

Steam Pressure	4000 psi
Sodium inlet temperature ramped from	1105° F to 700° F at 35° F/sec

Low-Temperature Steam Generator

Steam Pressure	4100 psi
Sodium inlet temperature ramped from	875° F to 700° F at 35° F/sec

- 4) Secondary Sodium Flow Lost, Feedwater Flow Continues. This is a casualty condition and thirty such transients are assumed. Steam generator conditions:

High-Temperature Steam Generator

Steam Pressure	4000 psi
Steam outlet temperature ramped from	1050 to 600 at 35° F/sec

Steam inlet temperature
ramped from about 700 to 600
at 35°F/sec

Low-Temperature Steam Generator

Steam Pressure 4100 psi
Steam outlet temperature
ramped from about 700 to 600
at 35°F/sec

5) Reactor, Primary Sodium System and Secondary Sodium System

Operates at Full Power, Feedwater Lost. This is a casualty condition and 30 such transients are assumed. Steam generator conditions:

High-Temperature Steam Generator

Steam Pressure 4000 psi
Sodium outlet temperature
ramped from 875 to 1105
at 35°F/sec

Low-Temperature Steam Generator

Steam Pressure 4000 psi
Sodium outlet temperature
ramped from 700 to 1105
at 35°F/sec

6) Steam Generators Containing No Sodium, Preheated From Ambient

Temperature to Sodium Loading Temperature. This condition will exist every time the steam generators are preheated; one hundred and twenty such transients are assumed. Steam generator conditions:

Water heated from 60 to 350°F
at 100°F/hr.

III. THERMAL PERFORMANCE

Prediction of the performance of the steam generators under steady-state full- and part-load conditions requires extensive calculational time for each case. In order to reduce these calculations and still allow investigation of many different cases, the entire calculation procedure was programmed for the IBM 7090 digital computer.

Since the designs are based on the use of supercritical water as the cooling fluid with sodium as the heating fluid, the complexity associated with phase changes within the steam generator could be omitted. The problem, therefore, was one of defining heat transfer coefficients for the water and sodium sides, defining the tube wall thermal resistance, defining a water-side fouling factor, and incorporating these into the energy equation.

Considering a unit length ΔX , the following energy balance may be made:

then:

$$W_w C_{p_w} t'_{wi} + UP(\Delta X)(t'_N - t'_w) = W_w C_{p_w} t'_{wo} ,$$

and

$$W_N C_{p_N} t'_{Ni} = W_N C_{p_N} t'_{No} + UP(\Delta X)(t'_N - t'_w) ,$$

where:

$$t'_N = \frac{t'_{Ni} + t'_{No}}{2}$$

and

$$t'_w = \frac{t'_{wi} + t'_{wo}}{2} .$$

The overall heat transfer coefficient (U) based on the outside tube surface area is:

$$U = \frac{1}{\frac{D_o}{D_i h_w} + \frac{1.05(D_o) \ln(\frac{D_o}{D_i})}{2k_t} + \frac{1}{h_N} + \frac{D_o}{D_i h_{ff}}} .$$

The sodium-side film coefficient may be defined by the Lubarsky Equation 4 with the shell-side diameter being defined by the equivalent diameter concept

$$h_N = 0.625 \left(\frac{k_N}{De} \right)^{0.6} \left(\frac{G_N}{C_{pN}} \right)^{0.4} .$$

The use of the equivalent diameter concept in the Lubarsky equation for non-circular geometries may possibly be somewhat optimistic. However, for the present studies no correction factor was applied.

The fouling factor for supercritical water has been discussed in detail in Appendix A and the recommended value of 1×10^{-4} obtained. This gives a fouling factor equivalent film coefficient of:

$$h_{ff} = \frac{1}{1 \times 10^{-4}} = 10,000 \text{ Btu/hr-ft}^2 \text{-}^\circ\text{F} .$$

The film coefficient for supercritical water was based on experimental data obtained by Dickinson and Welch,⁵ and confirmed by Marchaterre and Petrick.⁶

This data indicated three separate relationships for the water-side film coefficient, dependent on the wall temperature as follows:

For

$$t_{\text{wall}} \leq 660^{\circ}\text{F} ,$$

$$h_w = \frac{(G_w)^{0.8} k_w (P_{rw})^{0.4} (0.023)}{(D_i)^{0.2} (\mu_w)^{0.8}} ;$$

for

$$660 < t_{\text{wall}} < 800^{\circ}\text{F} ,$$

$$h_w = 0.0025 (G_w) .$$

The coefficient was based on a Stanton number of 0.00161 and an average value for $C_{pw} = 1.55$ over the temperature range.⁷

For

$$t_{\text{wall}} \geq 800^{\circ}\text{F} ,$$

$$h_w = 0.00189 C_{pw} G_w .$$

Evaluation of the equivalent heat transfer coefficient for the tube wall included a correction factor of 1.05 to allow for an increase in wall thickness. The design specified a minimum wall or a thickness variation of $-0.0 + 10.0\%$; therefore, on an average, the wall thickness was assumed to be 5% thicker which gave the correction factor of 1.05.

Sodium properties were taken from Reference 8. Values for the thermal conductivity, viscosity, and Prandtl number for water were taken from Reference 9. Specific heat and Enthalpy values for water were taken from Reference 7.

Figure 5 is a schematic of the steam generator complex with reheaters.

In general, the digital computer solutions were obtained by dividing the steam generators into a number of axial sections, initiating the solutions from known or assumed values at the bottom (t_{No} , W_{Nk} , w_w , t_{wi}), and then obtaining solutions for each axial length or node. At the top of the steam generators, the end points were compared to desired values and in the case of disagreement, the initial values were modified and the calculations repeated.

Figure 5. Steam Generator Complex

The results obtained from the computer for the three cases of interest are shown in Figures 6, 7, and 8. Based on the assumption that the sodium temperatures may be varied as desired, part-load calculations were performed for the three steam generator designs considered. Results of the calculations are shown in Figures 9 through 14. These results should be considered as representative characteristics of the steam generators when they are operated under the assumed method of control.

Under this method of control, the sodium inlet temperature to the steam generator was controlled as a function of load. The sodium flow was controlled by maintaining the sodium temperature at the midpoint (between the low and high temperature units) constant. The sodium temperature out of the steam generators was allowed to swing with load. The feedwater temperature was assumed to vary with load as shown, and a constant steam outlet temperature was maintained.

Figure 6. Predicted Performance for 37-Tube Modular Steam Generator for SCTI (Throttle Steam Pressure = 3600 psia, Fouling Factor = 0.0001)

Figure 7. Predicted Performance for 37-Tube Modular Steam Generator for 450-Mwe-Gross Plant (Throttle Steam Pressure = 3600 psia)

Figure 8. Predicted Performance for 61-Tube Modular Steam Generator for 350-Mwe-Gross Plant (Throttle Steam Pressure = 3600 psia)

Figure 9. Part-Load Predicted Performance for 37-Tube Modular Steam Generator for SCTI-Sodium and Feedwater Flow Rates (Steam Pressure = 3600 psia)

Figure 10. Part-Load Predicted Performance for 37-Tube Modular Steam Generator for SCTI-Sodium and Water Temperatures (Steam Pressure = 3600 psia)

Figure 11. Part-Load Predicted Performance for 37-Tube Modular Steam Generator for 450-Mwe-Gross Plant Sodium and Feedwater Flow Rates (Steam Pressure = 3600 psia)

Figure 12. Part-Load Predicted Performance for
37-Tube Modular Steam Generator for 450-Mwe-
Gross Plant Sodium and Water Temperatures
(Steam Pressure = 3600 psia)

Figure 13. Part-Load Predicted Performance 61-Tube Modular Steam Generator for 350-Mwe-Gross Plant Sodium and Feedwater Flow Rates

Figure 14. Part-Load Predicted Performance 61-Tube Modular Steam Generator for 350-Mwe-Gross Plant Sodium and Water Temperature (Steam Pressure - 3600 psia)

Other methods of part-load operation were considered as discussed earlier; however, the method used in the analysis appeared to be representative of what may be used in future plants. No part-load calculations were performed on the reheaters; however, control of the reheat steam temperature would be by variations of sodium flow through the reheaters.

IV. MECHANICAL DESIGN

The design of steam generators for pressures greater than 1400 psi requires provision for steam reheat. When sodium is used as the heating fluid, it is necessary to separate sodium from the IHX through the reheaters and through the superheaters. It is also necessary to recombine the two sodium flows at some appropriate point downstream of the superheaters and reheaters. An appropriate place to recombine the sodium from the reheaters, with the sodium from the superheaters, is at the evaporator-superheater junction. In this manner less expensive material is utilized and corrosion resistant ability of the evaporator is improved by using ferritic materials. With these criteria as a basis, designs were obtained for the high temperature modules (superheaters), reheater modules, and low temperature modules (evaporators) which are described in Section A below. Additional designing was done on the installation of the high- and low-temperature modules and reheater modules incorporating the interconnecting piping and auxiliary equipment. This is described in Section B.

A. MODULE DESIGN

The modular design permits generation of high pressure steam with relatively thin tube sheets. This is important since under transient conditions, sodium can impose severe thermal stresses on thick sections. The modular concept should also result in lower fabrication and installation costs since semi-mass production fabrication techniques may be used.

The high temperature (superheater) modules will be fabricated of austenitic steel with forged tube sheets and butt-welded single-wall tubes containing steam. In this manner, the caustic corrosion problem associated with crevices in the tube sheet region is alleviated. Further, to improve the reliability of the tube-to-tube-sheet joint, a butt-weld away from the tube-sheet surface will be used. Specifically, a joint similar to that in the HNPF steam generator units will be used, except the tubes will be smaller in diameter (≈ 0.625 in.). The austenitic steel used in this unit will be susceptible to chloride stress corrosion. However, this problem is common to conventional power plants and is usually minimized by closely controlled water treatment and monitoring of condenser in-leakage.

The low-temperature (evaporator) modules will be fabricated of chrome-molybdenum steel. They will furnish slightly superheated steam to the high

temperature modules and utilize forged tube sheets and single-wall tubes containing water or steam. The tubes could be butt-welded or they could pierce the tube sheets and be welded in the conventional manner. The use of chrome-molybdenum steel will alleviate the corrosion problems since this material is not susceptible to caustic or chloride corrosion.

The use of bellows in the module shells was considered at one time; however, investigation of the temperature difference between the tubes and the shell indicated that the temperature differences were not excessive; thus, the need for bellows is eliminated.

Design of the modules will include provisions for rupturable membranes at the top and bottom (adjacent to the sodium inlet and outlet nozzles) of each module. Since the shell would be capable of withstanding relatively high pressures for short periods of time, a water-to-sodium reaction should rupture the membranes and relieve the pressure to a pressure relief system (described later) without damaging the module shell.

The shell side of the steam generators contains sodium which has excellent heat transfer properties; therefore, the need for cross flow is minimized. On this basis, the sodium flows countercurrent to the water or steam and parallel to the tubes. Tube spacers or supports are to be located about every three feet to prevent vibration. The tube spacers will either be brazed rings or possibly investment castings. This type of spacer offers a minimum flow restriction in the event of a water-to-sodium reaction; that is, a sudden acceleration of the shell side fluid due to a tube rupture would not be restricted by baffles. The spacers will be supported and located longitudinally by rods and other spacers located next to the shell.

The module will be designed to meet the requirements of the ASME Boiler and Pressure Vessel Code, Sections I, III, and VIII. All welds in the modules will be 100% penetrant inspected, radiographed, and helium leak-tested in accordance with the code. Each high temperature module (superheater) and each low temperature module (evaporator) will be pressure tested on the tube side to meet the requirements of these sections. These test pressures will be held for a minimum of 10 minutes.

The spacing of the tubes within the shell was determined on the basis of the heat transfer ability of each tube; that is, the spacing was varied so that

theoretically equal flow would be obtained around each tube, with a result that a uniform temperature should exist across the tube bundle at any axial position. The design of the 37-tube tube-sheet was proved by an experimental stress program.^{2, 3} The ability to make the internal tube-to-tube-sheet butt-welds was developed in a welding program.¹

Two module designs were investigated for the high- and low-temperature units: a 37-tube module utilizing a 6-in. pipe as the shell, and a 61-tube module utilizing an 8-in. pipe as the shell. The 37-tube design was chosen for the initial investigation since this was the easiest to develop in a short time.

Design details for 37-tube high- and low-temperature modules were obtained for units to be tested in the SCTI. Since the SCTI has no provision for steam reheat the SCTI module designs could not be applied to a power plant installation with reheat. Therefore, detail designs of 37-tube high- and low-temperature steam generators and 102-tube reheaters applicable to a 450-Mwe steam generator complex with single reheat were made. In addition, in order to investigate the effect of using larger modules, a design study was made for a 350-Mwe steam generator complex with single reheat using 61-tube high- and low-temperature steam generators and 102-tube reheaters. The data obtained from the experimental stress program² had indicated that the 61-tube design for 4000 psi was feasible with a small development program.

Summary of the pertinent data for the above modular design are given in Tables II, III, and IV. In addition, a 37-tube tube-sheet is shown in Figure 14, and a 37-tube module assembly is shown in Figure 15.

Since the assembly procedure for a module is important, a suggested assembly procedure is given in Appendix B.

B. MODULE INSTALLATION

The steam generator complex consists of four banks of high-temperature (superheater), low-temperature (evaporator), and reheater modules. The modules in each bank are manifolded together in a vertical configuration with the high temperature and reheater modules located above the low temperature modules. This arrangement provides stable temperature gradients through the system which aids in the control of sodium flow through the system at low load conditions. Each module contains two shell rupturable membranes.

TABLE II
DESCRIPTION OF MODULES FOR SCTI

Parameter and Units	High Temperature Module	Low Temperature Module
Design Pressures (psig)		
Steam	4000	4100
Sodium	300	300
Design Temperature (°F)	1105	900
Rating (Btu/hr)	26.2×10^6	20×10^6
Operating Pressures (psig)		
Steam	3600	3700
Sodium	≈ 40	≈ 30
Operating Temperatures (°F)		
Steam or water in	726	600
Steam out	1050	726
Sodium in	1105	875
Sodium out	875	705
Operating Flow Rates (lb/hr)		
Steam	54,300	54,300
Sodium	379,750	379,750
Number of Modules	1	1
Effective Length (ft)	50.4	36.6
Number of Tubes per Module	37	37
Material		
Shell	6-in. Sched-10 pipe 304 SS	6-in. Sched-10 pipe 5 chrome, 1/2-moly-Ti
Tube sheet	347 SS	2-1/4 chrome, 1-moly
Tubes, OD x wall (in.)	347 SS 5/8 x 0.095	2-1/4 chrome, 1-moly 5/8 x 0.083

TABLE III
DESCRIPTION OF MODULES FOR 450-Mwe PLANT

Parameter and Units	High Temperature Module	Low Temperature Module	Reheater Module
Design Pressures (psig)			
Steam	4000	4100	1200
Sodium	300	300	300
Design Temperature (°F)	1055	900	1055
Rating (Btu/hr)	22.6×10^6	16.5×10^6	29.6×10^6
Operating Pressures (psig)			
Steam	3600	3700	1050
Sodium	≈ 40	≈ 40	≈ 40
Operating Temperatures (°F)			
Steam or water in	729	600	645
Steam out	955	729	955
Sodium in	1055	850	1055
Sodium out	850	705	850
Operating Flow Rates (lb/hr)			
Steam	59,400	42,400	150,500
Sodium	366,000	374,000	472,000
Number of Modules	60	84	20
Effective Length (ft)	39.4	39.6	30.4
Number of Tubes per Module	37	37	102
Material			
Shell	6-in. Sched-10 pipe 304 SS	6-in. Sched-10 pipe/5-chrome, 1/2-moly, Ti	10-in. Sched-10 pipe 304 SS
Tube Sheet	347 SS	2-1/2-chrome, 1 moly	347 SS
Tubes, OD x wall (in.)	5/8 x 0.083 in. 347 SS	5/8 x 0.083 in. 2-1/4-chrome, 1 moly	5/8 x 0.049 in. 347 SS

TABLE IV
DESCRIPTION OF MODULES FOR 350-Mwe PLANT

Parameter and Units	High Temperature Module	Low Temperature Module	Reheater Module
Design Pressures (psig)			
Steam	4000	4100	1200
Sodium	300	300	300
Design Temperature (°F)	1100	900	1100
Rating (Btu/hr)	43.1×10^6	31.4×10^6	26.1×10^6
Operating Pressures (psig)			
Steam	3600	3700	1050
Sodium	≈ 40	≈ 40	≈ 40
Operating Temperatures (°F)			
Steam or water in	728	550	660
Steam out	1005	728	1005
Sodium in	1100	875	1100
Sodium out	875	700	875
Operating Flow Rates (lb/hr)			
Steam	102,580	68,390	138,000
Sodium	633,300	593,000	384,000
Number of Modules	24	36	16
Effective Length (ft)	43.0	35.9	23.3
Number of Tubes per Module	61	61	102
Material			
Shell	8-in. Sched-10 pipe, 304 SS	8-in. Sched-10 5-chrome, 1/2-moly, Ti	10-in. Sched-10 pipe 304 SS
Tube Sheet	347 SS	2-1/4-chrome, 1 moly	347 SS
Tubes, OD x wall (in.)	5/8 x .095 347 SS	5/8 x 0.083 in. 2-1/4 chrome, 1 moly	5/8 x 0.049 in. 347 SS

Figure 15. High Temperature Module
Head Supercritical Steam
Generator (7519-449310)

The outlets from the pressure relief nozzles are manifolded together and piped to the pressure relief tanks where an inert atmosphere is maintained. A representative Modular Steam Generator Installation is shown in Figure 16. A brief description of the complementary equipment considered in the installation of the modules is given below.

1. Piping

High and intermediate temperature sodium piping, headers, and manifolds are of Type 304 stainless steel. Low temperature sodium piping, headers, and manifolds are of ASTM A-106 Grade B carbon steel material.

High temperature steam piping, headers, and manifolds are fabricated from Type 316 stainless steel. Intermediate temperature manifolds and piping are A355-P22, 2-1/4% chrome, 1% moly steel. Feedwater piping and manifolds are of A-106, Grade B carbon steel. Pressure relief piping is fabricated from A53, Grade B carbon steel material.

Bellows type expansion joints are used where required to reduce effects of thermal expansion on the sodium and pressure relief piping systems. Steam and feedwater piping systems are designed so that thermal expansion stresses are within the allowable stress ranges.

All piping and manifolds are designed in accordance with the requirements set forth in the Code for Pressure Piping, ASA-B 31.1, Section 1.

2. Valves

Single block valves are provided on the inlet and outlet sodium headers to each bank of modules. Each reheater group has a sodium flow control valve actuated by outlet steam temperature in the outlet header. A single block valve and appropriate relief valves are provided on the main steam outlets from each bank of high temperature modules. There is a single block valve in the inlet and in the outlet header of each group of reheater modules. Each feedwater header to a bank of low temperature modules contains a block valve and a check valve.

3. Insulation

All piping and manifolds are insulated as required for their temperature ranges. Modules are individually insulated to facilitate removal and replacement. All insulation is waterproof and fire resistant.

Figure 16. High Temperature Module
Assembly Supercritical Steam
Generator (7519-449308)

4. Supports and Supporting Structure

The steam generator is supported on the bottom headers and permitted to expand vertically upward. Constant-support hangers carry the weight of the modules, manifolds, and piping throughout the height of the generator. Modules are restrained by guides. Anchors, stops, and guides are used as required. Standard structural steel columns, beams, foundations, and ties comprise the support structure. Grated walkways, catwalks, and platforms are provided where access is required. Access to higher levels is by means of protected ladders.

5. Leak Detection

A hydrogen leak detector is located in the sodium outlet of each module. The outlet header of each bank also contains a hydrogen leak detector. Shell or sodium-pipe leaks would be detected visually; i.e., by observation of smoke in vicinity of leak.

6. Preheating

All sodium piping and headers are preheated by electrical resistance heaters. The modules are preheated by circulating hot water.

7. Erection

Depending on location, site, and handling equipment available, there are several ways of erecting the steam generator. Whole or partial banks can be prefabricated on the ground and then raised into place on the structure, or the modules and headers can be put in place and all connecting piping welded in place.

8. Maintenance

The structure has been designed to permit the removal and replacement of any one module or group of modules. The modules are cut from their respective headers, lifted up, moved out away from the structure, and lowered to the ground. Replacement follows the reverse procedure.

V. COST ESTIMATES

A. STEAM GENERATORS USING 37-TUBE MODULES FOR SCTI

Estimates for the 37-tube high temperature modules and the 37-tube low temperature modules capable of generating 3500 psi, 1050°F steam from 600°F feedwater were made, based on information from typical vendors and AI's prior experience. The cost estimate for the low and high temperature modules are shown below:

High Temperature module (300 ft ²)	\$21,200
Low Temperature module (217 ft ²)	15,500

B. STEAM GENERATOR USING 37-TUBE MODULES AND REHEATERS

Since the SCTI has no provision for steam reheat, the SCTI module designs could not be applied to a power plant installation incorporating reheat. Therefore, a design study was made and estimated prices obtained for a 450-Mwe steam generator complex providing 3500-psi steam at the turbine throttle. The complex utilized 37-tube steam generator modules and 102-tube reheater modules. Steam at 955°F was generated from 600°F feedwater and 1055°F sodium. These cycle conditions were based on preliminary economics studies using fuel costs of 20¢/10⁶ Btu, a capitalization rate of 14% and a plant load factor of 0.8. The feedwater temperature of 600°F was maintained constant in accordance with AEC steam generator specifications.¹⁰ The estimated prices are as follows:

High Temperature Modules	60 x 11,600 = 696,000
Low Temperature Modules	84 x 10,050 = 845,000
Reheaters	20 x 19,400 = 388,000
Interconnecting piping, supporting structures, insulation, installation of modules, pre-heating, hydrogen detectors* (valves not included)	<u>2,300,000</u>
Total installed cost	4,229,000

This gives an average installed cost of \$94.50/ft² or \$9.40/kwe.

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*For a more detailed description see Section IV-B

C. STEAM GENERATOR USING 61-TUBE MODULES AND REHEATERS

In order to investigate the effect of using larger modules, an additional design study was made and estimated prices obtained for a 350 Mwe steam generator complex using 61-tube steam generator modules and 102-tube reheater modules. Steam at 1005°F was generated from 550°F feedwater and 1100°F sodium. These cycle conditions were based on preliminary economic studies using fuel costs of 35¢/10⁶ Btu, a capitalization rate of 14% and a plant load factor of 0.8. The estimated prices are as follows:

High Temperature Modules	24 x 20,100 = 483,000
Low Temperature Modules	36 x 14,350 = 516,000
Reheaters	16 x 16,000 = 256,000
Interconnecting piping, supporting structure, insulation, installation of modules, preheating, and hydrogen detectors* (valves not included)	<u>1,410,000</u>
Total installed cost	\$2,700,000

This gives an average installed cost of \$91.80/ft² or \$7.72/kwe.

D. COST ESTIMATES SUMMARY

Based on the above two studies, the 61-tube design costs slightly less than the 37-tube design. Therefore, one may be led to consider a 91-tube design in order to achieve further cost reductions. However, the design of a 91-tube tube-sheet for supercritical pressures may well result in excessive tube sheet thicknesses and lead to problems in thermal stresses during the various transients. In addition, the incremental savings which may be realized by using a 91-tube design rather than a 61-tube design would undoubtedly be less than that obtainable by using a 61-tube design rather than a 37-tube design.

A different concept utilizing toroidal tube-sheets and having 150 to 300 tubes per steam generator may also cost less; however, this concept would require an extensive development program.

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* For a more detailed description see Section IV-B

On the basis of cost, the following conclusions may be made.

- 1) The 37-tube modular steam generator complex for supercritical pressures may be built and installed today for prices that are competitive or more economical than present day subcritical sodium heated steam generators.
- 2) The 61-tube modular steam generator complex for supercritical pressures would cost less and appears to be entirely feasible. However, a short development program would be required on the tube sheet.
- 3) For the long range, a 91-tube modular or a toroidal steam generator complex for supercritical pressures may offer further savings. However, extensive development work would be required on the tube-sheets and the cost savings would have to be determined.

VI. OPERATION AND MAINTENANCE

From an operational standpoint, the modular steam generator offers many advantages. In the event of a minute leak of water into the sodium, the excess hydrogen could be detected by hydrogen detectors developed under a previous AEC project. These hydrogen detectors¹¹ can monitor the system as banks of modular steam generators and as individual modules. Amounts of hydrogen as low as 3 ppm can be routinely detected.

With the modular concept, the ability to detect a small leak of water into sodium is improved. The water or steam leak from a defective tube is mixed with the sodium adjacent to 37 or 61 tubes; therefore, the dilution is greatly reduced, and the ability to detect a leak greatly improved. With the use of large units (2000 or more tubes per shell) the leak from one tube is mixed with the sodium adjacent to 2000 or more tubes and the water or steam diluted with the result that the ability to detect a leak is greatly reduced. In the event a water or steam leak is detected, the bank of modules containing the leaking module can be isolated, drained, and when time permits, the faulty module can be replaced. In the event of a major rupture, it is believed that only one module would be damaged; therefore, the affected bank of modules could be blocked off, drained, the defective module removed and replaced by a spare, or the pipe ends of the manifolds could be capped off. The remaining modules could then be brought back to operating conditions. In this event, the loss of one unit should not have serious consequences on the load factor of a large plant.

VII. ECONOMIC EVALUATION

The economics pertaining to the steam cycle portion of a sodium-cooled reactor is quite different than those pertaining to a conventional fossil fired power plant. In general, when one is talking 20¢ fuel (20¢/10⁶ Btu) for a conventional plant, one does not consider the more efficient high pressure steam cycles. This is due to the fact that as the steam pressure increases, the cost of the fossil fired boiler increases and offsets the capitalized fuel cost savings. However, for the case of sodium-cooled reactor power plants, the cost of the reactor, primary loop, and secondary loop (excluding steam generators) is virtually independent of the steam pressure. The only components in the sodium portion of the plant that are affected by the steam pressure are the steam generators. On this basis, a preliminary economics study on the steam cycle portion of a sodium cooled reactor power plant was conducted. The steam conditions studied in the preliminary evaluation were:

- 1) 1400-psi (nonreheat, and single reheat)
- 2) 1800-psi (single reheat)
- 3) 2400-psi (single reheat)
- 4) 3500-psi (single and double reheat)

The results of the preliminary economy study indicated an incentive to use supercritical steam conditions.

With the estimated installed prices for the modular steam generators available and better price information on the feedwater heaters, steam piping, etc. available, a review of the preliminary economy study was warranted. Since the preliminary study indicated the trend to higher pressures, only 2400- and 3500-psi cycles were considered in the economic reevaluation.

A. CASES CONSIDERED AND ASSUMPTIONS MADE

The method used in the economics study was to combine the differential capital costs of the major pieces of equipment in the plant with the differential operating costs to obtain the optimum plant parameters.

The following steam cycles were considered:

<u>Steam Pressure (psig)</u>	<u>Steam Temperature (°F)</u>
2400	1050 - 1050
	1000 - 1000
	950 - 950
3500	1050 - 1050
	1000 - 1000
	950 - 950
3500	1050 - 1050 - 1050
	1000 - 1000 - 1000
	950 - 950 - 950

1) The following major equipments were included in the cost analysis:

- a) Steam generator and intermediate heat exchanger surface,
- b) Main steam turbine generator plus extra extraction bleed points,
- c) Main steam piping and valves,
- d) Feedwater heater, feedwater piping, and valves,
- e) Main condenser, and
- f) Reactor,

2) The operating costs included were based on:

- a) The annual differential capitalized fuel cost based on cycle heat rates,
- b) The annual differential capitalized boiler pump operating cost, and
- c) The annual differential capitalized sodium pump operating cost.

B. BASIS FOR COMPARISON

The ground rules that applied to this study were:

1) Sodium System

- a) Fix the reactor sodium outlet temperature at 1150°F.
- b) Vary the sodium temperature differential across the reactor at 350, 400, and 450°F, and vary the Log Mean Temperature Difference (LMTD) across the intermediate heat exchanger.

- c) For each $\pm 1\%$ difference in reactor thermal power required, credit or debit reactor capital costs $\pm \$50,000$.
- d) For steam generator (high and low temperature modules) and first reheater incremental surface area costs use:

Steam Pressure (psig)	High Temperature Module (\$/ft ²)	Low Temperature Module (\$/ft ²)	First Reheater (\$/ft ²)
2400 single reheat	46	37	35
3500 single reheat	50	40	35
3500 double reheat	50	40	40

For second-reheater and IHX incremental surface area costs use $\$35/\text{ft}^2$.

The prices for the 3500 psig low- and high-temperature modules were based on quotations received by AI from outside vendors as discussed in Section V. The prices for the 2400-psig low- and high-temperature modules and reheaters were based on AI estimated pricing.

- e) Assume an 80-psi pressure drop for the primary sodium loop and the secondary sodium loop, and evaluate pumping power as being directly proportional to total sodium flow.

2) Steam and Feedwater System

- a) Main steam turbine prices were handbook costs plus the cost for extra bleed points for feedwater heaters.
- b) Feedwater heater prices were quotations for 2400- and 3500-psig cycles.
- c) Feedwater piping and valve costs were based on an Edward Valves Co. cost study comparing 2400- vs 3500 psig.¹²
- d) Main steam piping costs were based on using 75¢/lb (AI estimating price) for 2-1/4 moly pipe based on the weight of the solid forged billet before boring. The reheat steam piping costs were based on using the finished weight of the hollow

forged piping at 78¢/lb for 1-1/2 chrome - 1/2 moly. Main steam valves and steam safety valves were based on list prices. The main steamlines were sized for 10,000 ft/min velocity; the reheat steam lines were sized for ~15,000 ft/min velocity. Pipe wall thicknesses were calculated in accordance with power code requirements.

- e) The cost of the main steam condenser was \$4.50 per ft² of surface, based on cost estimates for this size unit.
- f) The value of the capitalized incremental heat rate based on 20¢/10⁶ Btu fuel cost, 14% capital charge rate, and 80% capacity factor was \$4000/heat rate differential. The value of the capitalized incremental heat rate for 7% capital charge rate was \$8000/heat rate differential, other items being equal.
- g) The capitalized pumping cost for 14% capital charge rate was \$75. per differential kilowatt pumping power. The capitalized pumping cost at 7% capital charge rate was \$150 per differential kilowatt pumping power.
- h) The net turbine cycle heat rates were calculated from General Electric heat rate curves for performance of large steam turbine generators based on:
  - (1) 1-1/2-in. Hg (abs) exhaust pressure operation.
  - (2) Motor driven boiler feed pump; the discharge pressure equaling 1.25 times the throttle pressure; 75% pump efficiency; 90% motor drive efficiency.
  - (3) The net turbine cycle heat rate includes the boiler feed pump power only in accordance with (h-2). The remaining plant auxiliary power requirements were assumed at 3.5% to arrive at the reactor thermal power requirements.

C. CONCLUSIONS

From past studies, it has been evident that the selection of the type of steam turbine generator greatly affected the optimum system costs. The minor differences in turbine heat rates have had small influence on the steam generator

exchanger costs (differences ranging from about \$40,000 to \$80,000) as compared to differences in turbine generator costs (ranging from about \$100,000 to \$2,000,000) in the 400-Mw size turbine generator.

Therefore, the initial phase of the study covered the selection of the optimum turbine based on balancing the cost of the turbine and the capitalized value of the turbine cycle heat rate.

The results of the turbine study are as follows for a 400-Mw size plant:

- 1) The tandem, compound, four-flow, 30-in. turbine is the optimum turbine selection for plant systems using 14% capital charge rates, 80% load factor, and $20¢/10^6$ Btu fuel cost, for the 2400-psig, and 3500-psig steam cycles.
- 2) The cross-compound, two-flow, 43-in. turbine is the optimum turbine selection for plant systems using 7% capital charge rates, 80% load factor, and $20¢/10^6$ Btu fuel cost for the 2400-psig, and 3500-psig steam cycles.

By use of this information, the remaining major equipment and operating cost figures as outlined in the ground rules for various reactor sodium temperature differentials and intermediate heat exchanger LMTD were totalized to arrive at the plant with the lowest combined cost for each steam cycle condition.

The results of this preliminary study provided for the selection of the sodium parameters which were:

- 1) That the optimum reactor sodium temperature differential is about 350° F for the steam cycles studied.
- 2) That for 2400 psig steam cycles, the optimum intermediate heat exchanger LMTD is about 75° F while for 3500 psig steam cycles the optimum LMTD is about 95° F.

In addition, it was evident that at capital charge rates of 14% the optimum steam temperature condition was 950° F while at capital charge rates of 7% the optimum steam temperature was 1000° F.

The attached summary sheet, Table V tabulates the optimum conditions for each steam pressure condition based on 14% and 7% capital charge rates.

TABLE V
OPTIMUM CONDITIONS SUMMARY

Capital Charge Rate (%)	Steam Pressure (psig) S = Single D = Double Reheat	Steam Temp (° F)	Reactor Sodium Outlet Temp (° F)	Reactor Sodium Outlet Diff. (° F)	Interm. Heat Exc Temp Drive (° F)	Reactor Thermal Power (Mw)	Gross Turbine Cycle Heat Rate (Btu/kw-hr)	Interm. Heat Exc Surface (ft ²)	Low Temp Module Surface (ft ²)	High Temp Module Surface (ft ²)	1st Reheater Surface (ft ²)	2nd Reheater Surface (ft ²)	Increment Cost IHX Surface (\$)	Increment Cost L. T. M. Surface (\$)	Increment Cost H. T. M. Surface (\$)	Increment Cost 1st Reheat. Surface (\$)	Increment Cost 2nd Reheat. Surface (\$)	Increment Reactor Cost (\$)	Increment Turbine Cost (\$)	Increment Condenser Cost (\$)	Increment Main Steam Piping, Valves, Safties, Cost (\$)	Increment Feedwater Piping Valve Cost (\$)	Increment Feedwater Heater Cost (\$)	Increment Boiler Feedpump Pumping Cost (\$)	Increment Sodium Pump Pumping Cost (\$)	Increment Heat Rate Cost (\$)	Extra Extract Point in Turbine Cost (\$)	Total Columns 14 thru 28 (\$)
14	2,400-S	955/955	1,150	350	65	1,049	7,845	50,400	24,750	13,300	9,050	—	Base	Base	Base	Base	—	Base	Base	Base	Base	Base	Base	Base	Base	Base	Base	Base
14	3,500-S	955/955	1,150	350	95	1,022	7,645	33,400	20,400	12,100	11,690	—	-595,000	-99,000	-7,000	+92,000	—	-120,000	-75,000	+39,000	+176,000	+120,000	+330,000	+437,000	-14,000	-800,000	+40,000	-476,000
14	3,500-D	955/955/955	1,150	350	95	955	7,435	32,500	23,800	11,250	8,030	13,200	-626,000	+37,000	-50,000	+4,000	+462,000	-250,000	+375,000	-40,000	+371,000	+120,000	+276,000	+321,000	-28,000	-1,640,000	+40,000	-628,000
7	2,400-S	1005/1005	1,150	350	65	1,025	7,655	49,500	23,630	16,420	11,290	—	Base	Base	Base	Base	—	Base	Base	Base	Base	Base	Base	Base	Base	Base	Base	Base
7	3,500-S	1005/1005	1,150	350	95	999	7,454	32,650	22,800	17,600	14,800	—	-590,000	+41,000	+124,000	+123,000	—	-125,000	-75,000	+32,000	+175,000	+120,000	+330,000	+814,000	-31,000	-1,608,000	+40,000	-630,000
7	3,500-D	1005/1005/1005	1,150	350	95	970	7,244	31,800	24,600	14,680	11,320	20,200	-620,000	+110,000	-22,000	+58,000	+707,000	-270,000	+425,000	-40,000	+395,000	+120,000	+276,000	+588,000	-63,000	-3,288,000	+40,000	-1,584,000

Although the single- and double-reheat supercritical steam conditions appear to indicate a savings at 14% capital charge rate, (savings of \$292,000 and \$444,000 respectively over the 2400 psig steam cycle) additional detailed analysis would be required to verify this trend.

For the 7% capital charge rate though, the savings available with a double-reheat supercritical plant are clearly substantial, \$1,485,000 over the 2400 psig plant.

Future studies based on capital charge rates between 7 and 14% plus variations in fuel costs and load factors would firmly establish those additional cases for the application of the supercritical steam cycle using the module steam generator design concept.

VIII. APPENDICES

APPENDIX A

WATER SIDE FOULING FACTOR

The fouling factor generally applied to heat transfer equipment is usually obtained from "Standards of Tubular Exchanger Manufacturers' Association." Representative values are given in Table A-I. These values are for general commercial process equipment; however, there seems to be no consideration for the type of material and the present-day once-through subcritical and supercritical steam generators using super-pure water.

Deviations from the recommended values have been noted in the past: For example, the Hallam steam generators (850 psig, 850°F), using boiler feedwater of 600 ppm total solids, used fouling factors of 0.0005 and 0.001 for the evaporators and superheaters respectively. The Enrico Fermi once-through steam generators (900 psig, 780°F), utilizing boiler feedwater of 1.0 ppm total solids, used a fouling factor of 0.0005.

These plants are subcritical, and in the case of Hallam, double-wall tubes are used. In both cases, since the superheat region comprises approximately two thirds of the heat transfer area due to the low steam side film coefficient, the fouling factor represents an increase in heat transfer surface of only about 10 to 15%. Commercial fossil-fired steam generators with a gas-side film coefficient of about $30 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ can use a fouling factor of 0.001 with ease since it represents an increase in heat transfer surface of only about 3%.

In the case of sodium-heated supercritical steam generators where the overall heat transfer coefficient varies from about 700 to 1000 $\text{Btu/hr-ft}^2\text{-}^\circ\text{F}$, an arbitrarily added fouling factor of 0.0005 represents a heat transfer area increase of 35 to 50%. Since the fouling factor now represents an important factor, one should not arbitrarily use values that may not be applicable. Therefore, the published literature was reviewed and analytical work performed to determine a realistic fouling factor for supercritical steam generators.

SUPERCritical WATER

Supercritical water, when compared to subcritical water, exhibits many interesting characteristics. Dr. E. P. Partridge in his paper¹⁵ discusses the increased ability of supercritical water to absorb silica, sodium chloride,

TABLE A-I
HEAT EXCHANGER FOULING FACTORS
($r = 1/h$ in. °F-ft²-hr/Btu)

Temperature of heating medium	Up to 240°F		240-400°F	
Temperature of water	125°F or less		Above 125°F	
Water velocity (ft/sec)	3 and less	over 3	3 and less	over 3
Distilled water	0.0005	0.0005	0.0005	0.0005
Sea water	0.0005	0.0005	0.001	0.001
City or well water	0.001	0.001	0.002	0.002
Treated boiler feed water	0.001	0.0005	0.001	0.001
Mississippi River water	0.003	0.002	0.004	0.003
Liquid gasoline, organic vapors				0.0005
Refrigerating liquids, cooling brine, oil-bearing steam				0.001
Refrigerating vapors, distillate bottoms above 20° API, air				0.002
Fuel oil, salty crude oil, residual bottoms less than 20° API				0.005
Diesel exhaust gas, coke-oven gas, cracking unit residuum				0.010

sodium sulphate, and calcium indicating "that salt deposits are not likely to form on the heat transfer surfaces of a boiler generating supercritical fluid at 5000 psi and 1200°F from relatively pure water." He points out that, as the supercritical fluid is reduced in pressure in the turbine to subcritical steam as we know it, with a much lower ability for absorbing the salts, one could expect deposition in the turbine. The article further states "This silica problem has been met in current practice by keeping the silica in a 1400-psi circulating boiler down to as low as 1 to 2 ppm. Must we face the prospect of keeping not just silica alone but all dissolved solids continuously down to some such level or even lower in a once-through 5000-psi system? The solubility data, limited as they are, suggest that the answer is 'yes'." Iron oxide is extremely insoluble at ordinary temperatures, and Dr. Partridge states that "iron oxides become even less soluble as the temperature is increased towards the critical point;" however, he states other published data¹⁶ indicates that "At a pressure of 15,000 psi and a temperature of 932°F, pure water passing over the mineral hermatite, which is crystalline ferric oxide, picked up 90 ppm of Fe₂O₃." The question is then asked "How much iron oxide, and perhaps also the oxides of

chromium, nickel, and other alloy elements, will dissolve in the water under a pressure of 5000 psi as its temperature is increased to 1200°F, and what will happen to the metal oxides dissolved in the supercritical fluid as it passes into the domain of ordinary steam part way through the turbine." The final point which is noted from the paper is the transformation of Fe_3O_4 into Fe_2O_3 and vice versa. "The temperature at which these oxides are in equilibrium in air is calculated to be 1060°F." This would indicate "we might find Fe_2O_3 dissolving from the surfaces towards the hot end of the boiler circuit, but crystals of Fe_3O_4 depositing in the middle stages of the turbine."

The above references lead one to believe that for supercritical water of high purity, all the total dissolved solids pass through the steam generator.

The above comments may now be related to actual experience from information gained by operation of the Avon No. 8 plant. A paper by Gill and Flack¹⁷ describing the initial operation of Avon No. 8 stated the feedwater specifications and actual values obtained as follows:

Control Concentrations (Economizer Inlet)

Substance	Specifications	Actual
	9.0-9.5	8.9-9.2
Total solids	50 ppb max	-
Total iron	20 ppb max	10 ppb max
Total copper	10 ppb max	5 ppb max
Silica	20 ppb max	10 ppb max
Oxygen	7 ppb max	5-15 ppb max

With this feedwater, the following problems showed up:

1. "Inspection of the turbine revealed that major depositions started on the last wheel of the superpressure section and continued throughout the very high-pressure turbine. This covers the pressure range of approximately 2200 to 750 psia at full load. The deposits were extremely hard and very adherent with copper oxide being the predominant constituent. The average deposit thickness for wheels and diaphragms 5 through 15 was approximately 11 mil. The composition of the various deposits are approximately as follows:

Cu	62%	Na ₂ O	6%	Zn	3%
Fe ₃ O ₄	18%	SiO ₂	4%	Ni	1%

2. "Samples of tubes were taken from various sections of the steam generator for evaluation of deposition and corrosion characteristics. The area inspected showed no corrosion or abnormal buildup of corrosion products. Isolated cases of soft sludge were found at the inlet of some waterwall tubes, and also in the horizontal run of the radiant superheater."

Operation of the Breed Plant has given further insight into the previously discussed problems. A paper by E. B. Morris¹⁸ on the Breed Plant Chemical Control and Cycle Cleanup gave the feedwater specifications and actual values for normal operation as follows:

	<u>Specifications</u>	<u>Normal Operation</u>
Total dissolved solids	150 ppb max	50 ppb
Silica, SiO ₂	20 ppb max	2-5 ppb
Iron	10 ppb max	5 ppb
Copper	5 ppb max	5 ppb
Dissolved oxygen	7 ppb max	5 ppb

With this feedwater, the paper stated the following problems showed up:

1. "The Breed Plant has demonstrated the same characteristics as the Philo Plant with regard to iron oxide. At 500 to 550°F outlet temperature, almost all of the iron oxide in the feedwater passes through the steam generator. At 600°F and above, almost all of the entering iron oxide deposits within the steam generator. Since it is known that every major flow or temperature increase will result in peaks of iron content, the overall economies then dictate, within limits, depositing a high iron concentration for a short period, rather than a lower concentration for a long period. This has resulted in more rapid starts."
2. "At the present time, SiO₂ peaks occur at each startup, but only reach a level of 30 to 50 ppb. Values for full-load operation are 2 to 5 ppb."
3. Early operation of Breed showed that copper in the steam was in the low range of 1 to 4 ppb. It was also found that about 50% of the feedwater

copper apparently deposited in the steam generator. While this trend continues, there are indications that an equilibrium is being reached and that the rate of deposition is decreasing."

Pertaining to the Breed Plant operation, one factor should be considered. That is, there was no mention of the turbine being torn down and inspected, which leads one to speculate as to exactly where the deposition of the iron oxide, copper oxides, and SiO_2 really occurred. Could the deposition have occurred in the turbine rather than in the steam generator?

The above data is further borne out in Reference 13 which states "In the supercritical once-through boiler, there is no division between boiler water and steam, both being of the same density. Therefore, no concentration of boiler-water solids takes place and the boiler feedwater passes through the boiler and enters the turbine as a supercritical fluid, unchanged in concentration of solids."

In summary, for supercritical water of high purity, one may expect that except for the oxides of copper and iron, all the total dissolved solids pass through the steam generator.

CORROSION OR FOULING DATA

Experimental steam side corrosion data for steel tubes are given by Daman, Phillips, et al.¹⁹ Their experiment utilized feedwater of the following purity:

PH at 25°C	9.0-9.5
Dissolved oxygen	0.007 ppm
Iron as Fe	0.005-0.010 ppm
Silica as SiO_2	0.010-0.020 ppm
Ammonia as NH_3	1.5 ppm
Total dissolved solids	0.25 ppm
Copper as Cu	Trace

At the end of 3600 hours of operation at 4750 psi and 1050°F final steam temperature, inspection of the test section revealed the following:

1. "There was no evidence of localized corrosion (pitting)"
2. "The internal tube surface, irrespective of the material, was covered with fairly uniform, extremely thin coating of black iron oxide. The maximum thickness of the scale measured as follows."

- a) Carbon steel tubing (750°F max) 0.0009 in.
- b) Chrome moly (820°F max) 0.0007 in.
- c) Stainless steel (316) 0.0015 in.

Additional corrosion data are presented in a paper by Ulmer, Grabowski, and Patterson²⁰ using a model of the Eddystone No. 1 installation and operating in a simulated version of the Eddystone No. 1 water cycle with 50 ppb total dissolved solids. The results obtained after 7300 hours of operation are given below.

<u>Steel Water Wall</u>	<u>Approximate Temperature (°F)</u>	<u>Oxide Thickness (in.)</u>
SA 209 Tia	300	0.005
SA 209 Tia	315	No scale
SA 213 T11	735	0.006
SA 213 T11	750	0.001
<u>Screen Tube</u>		
TP-316	775	0.001
<u>Transition Zone</u>		
SA 209 Tia	800	0.002
SA 209 Tia	850	0.004
SA 209 Tia	900	0.004
<u>Radiant Superheater</u>		
TP 316	1000	0.004
TP 316	1015	No scale
<u>Convection Superheater</u>		
TP 316	1050	0.004
TP 316	1075	0.006

The article further states: "Comparison of unused TP-316 tubing taken from the same batch of tubing, revealed that the oxidation did not occur in service but during the annealing process prior to service."

Further data indicated that unmachined tubes of TP-347 material had a corrosion rate of about 10% that of TP-316. When the tubes were machined to remove any mill scale, the TP-347 material corrosion rate was reduced by a factor of 2-1/2, and the TP-316 corrosion rate was reduced by a factor of 30, making it then comparable to the TP-347 material.

Two additional papers, one by Eberle and Anderson⁷ on the "Scaling Behavior of Superheater Tubes" and the other by Solberg, Brock, and Rebello¹⁴ on the "Corrosion Effect on Heat Transfer Through Superheater Tubes," presented further data. Their papers utilized test specimens that had been located in the Phillip Sporn plant of the American Electric Power Company System. Steam at 1050°F and 2000 psig pressure from one of the boilers was passed through the specimens and suitably preheated by electric heaters so as to maintain the desired steam temperature levels. The ferritic steel specimens were held at steam temperatures of 1100 and 1200°F, and the austenitic specimens were held at 1200, 1350, and 1500°F.

The specimens were 2 in. OD by 1/2 in. wall by 42 in. long commercial tubing. At the end of the various testing periods, they were removed, sectioned, and various pieces of each specimen tested for various reasons. The two papers of interest gave measurements of the scale thicknesses and the effect the scale had on heat transfer. Many different materials were tested and the results reported; however, only the data pertaining to 2-1/4-chrome 1-moly, 9-Cr 1-Mo, TP-347, and TP-316 will be reiterated here.

Results on the average scale thicknesses (21) were as follows:

Material	Steam	Scale Thickness (in.) (ΔL)		
		6 months	12 months	18 months
2-1/4 Cr-1 Mo	1100	0.005	0.0072	-
	1200	0.0165	0.023	-
TP-347	1200	0.0006	0.0006	0.0007
	1350	0.0007	0.0007	0.0007
TP-321	1200	0.0021	0.00105	0.00225
	1350	0.0008	0.00075	0.0006
	1500	-	0.0023	-
TP-316	1200	-	0.0039	0.0035
	1350	0.0027	0.0028	0.0034
	1500	-	0.0019	0.0022
9 Cr-1 Mo	1100	0.004	0.0065	-
	1200	0.010	0.013	-

Results of the heat transfer tests were as follows:

Material	Steam Temperature (°F)	Time (hr)	Temperature Difference Due to Corrosion (°F) (Δt)
2-1/4-Cr 1-Mo	1098	4320	-1.2
	1097	8742	+7.4
	1197	4320	+10.6
	1199	8742	+19.1
9-Cr 1-Mo	1197	4320	+9.3
	1199	8742	+14.0
TP-316	1200	13138	-2.2
	1351	8742	-11.3
	1349	13138	-10.8
	1496	8742	-14.2
	1496	11376	-17.2
TP-321	1351	8742	-13.8
	1495	4320	-13.1

Since the test specimen had an inside heat transfer area of 0.338 ft and an average heat transfer rate of about 18,000 Btu/hr, an approximate value for the thermal conductivity of the corrosion film may be obtained.

$$k = \frac{18,000(\Delta L)}{(0.338)(\Delta t)(12)} = \frac{4430(\Delta L)}{\Delta t}$$

Correlating the above two sets of data, values of k equal to 4.3, 6.9, 5.34, 4.76, and 4.10 Btu/hr-ft-°F are obtained. Where the temperature drop due to corrosion was a negative value, the heat transfer actually improved. An explanation for this could be the scaling of the surface increased the surface roughness and increased the heat transfer.

APPLICATION OF CORROSION DATA TO SUPERCRITICAL STEAM GENERATORS

A representative steam generator complex producing 453 Mwe with a 3500-psi, 950/950°F steam cycle, has about 10,000 ft² of high-temperature steam generator surface, 15,000 ft² of low-temperature surface, and a throttle steam flow of 3.56 x 10⁶ lb/hr.

Assuming feedwater of the following purity,

Total solids	100 ppb max
Total Fe	10 ppb max
Total Cu	10 ppb max
Silica	20 ppb max
Oxygen	7 ppb max

the assumption may be made that all the Fe will be deposited out as Fe_3O_4 and 50% of the Cu will be deposited as CuO. Then the total amount deposited in one full power year would be:

$$W = (3.565 \times 10^6)(8760) \left[(10 \times 10^{-9})(1.38) + \frac{(10 \times 10^{-9})(1.25)}{2} \right]$$
$$= 625 \text{ lb/yr} \quad .$$

Assuming the scale deposit has a density of 100 lb/ft^3 , the volume deposited would be:

$$V = 6.25 \text{ ft}^3/\text{year} \quad .$$

The thickness of the film may then be, assuming uniform distribution,

$$l = \frac{6.25}{25,000} = 2.5 \times 10^{-4} \frac{\text{ft}}{\text{year}} \quad .$$

Since a representative value for the thermal conductivity of the scale has been previously shown to be about $5.0 \text{ Btu/hr-ft-}^\circ\text{F}$, a fouling factor may be determined:

$$R_s = \frac{2.5 \times 10^{-4}}{5.0} = 5.0 \times 10^{-5} \quad .$$

In order to allow for uncertainties in the analysis (and there are many), a factor of two should be applied to the fouling factor for design purposes; therefore, for design purposes:

$$R_s = 0.0001$$

The design value has added margins since it has been shown in the Breed Plant that for normal operation the Fe and Cu may be maintained at 5 ppb, in all probabilities the density of the scale is much greater than 100 lb/ft³, and for the austenitic alloys the effect of surface corrosion is to increase the heat transfer coefficient.

CONCLUSION

There apparently exists the twofold need to maintain superpure water in once-through subcritical and supercritical steam generators; namely, to reduce the deposits in the steam generators and also in the turbine. Since existing plants are operating and maintaining water of 100 ppb total dissolved solids or less, the same requirement would also apply to the water side of a sodium-cooled reactor steam-generating plant.

Published experimental data is reviewed and indications are that TP-347 SS is less susceptible to water-side corrosion than TP-316. Therefore, wherever austenitic steels are required, the use of TP-347 should be seriously considered.

A representative value for the thermal conductivity of the corrosion film deposited on chrome moly and austenitic steels has been determined from published data to be 5.0 Btu/hr-ft-°F.

The recommended fouling factor for sodium-heated supercritical steam generators is 0.0001.

APPENDIX B

SUGGESTED MODULE ASSEMBLY PROCEDURE

1. Assemble tubes (-5), spacers (-4), and spacer tie rods (-9) into one assembly leaving three spacers unattached to the tie rods at each end of the assembly.
2. Starting with the center tube of the assembly, make tube-to-tube sheet (-2) weld on lower end of assembly and inspect the weld. Continue welding tubes in sequence from the interior to the exterior of the tube pattern.
3. During step 2, it will be necessary to provide access space to the tube being welded. This may be done by displacing all unwelded tubes radially in the end regions not supported by spacers. (The yield stress of the material is not to be exceeded during this operation.)
4. After completion of step 3, the unfastened spacers at the lower end should be positioned and secured.
5. Slide lower shell (-7) over tube bundle assembly from the upper end.
6. Make tube-to-tube sheet welds on upper end of assembly in the same manner as outlined in step 2.
7. The lower shell can now be moved to the lower end and a split shell (-8) welded to the top end of the lower shell.
8. Inspect this weld. (This and step 3 can be accomplished by shifting unfastened spacers axially to more convenient positions.)
9. Weld the split halves of the upper shell (-6) in position and inspect the welds.
10. Position and secure the unfastened spacers at the upper end.
11. Fit and weld the split halves of both the upper and lower cross (-10) into position and inspect the welds, through the nozzles.
12. Weld reducer nozzles (-3) on both ends of module and inspect welds.

APPENDIX C

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APPENDIX D

NOMENCLATURE

- C_{p_N} = Specific heat of sodium (Btu/lb $^{\circ}$ F)
- C_{p_w} = Specific heat of water (Btu/lb $^{\circ}$ R)
- D_e = Equivalent diameter (ft)
- D_i = Inside diameter of tubes (ft)
- D_o = Outside diameter of tubes (ft)
- G_w = Flow rate of water per unit area (lb/hr-ft ^{2})
- h_{ff} = Equivalent heat transfer coefficient for fouling factor (Btu/hr-ft ^{2} - $^{\circ}$ F)
- h_N = Heat transfer coefficient for sodium (Btu/hr-ft ^{2} - $^{\circ}$ F)
- h_w = Heat transfer coefficient for water (Btu/hr-ft ^{2} - $^{\circ}$ F)
- k_N = Thermal conductivity of sodium (Btu/hr-ft/ $^{\circ}$ F)
- k_t = Thermal conductivity of tube wall (Btu/hr-ft/ $^{\circ}$ F)
- k_w = Thermal conductivity of water (Btu/hr-ft- $^{\circ}$ F)
- L_k = Effective length of low-temperature module (ft)
- L_m = Effective length of high-temperature module (ft)
- L_R = Effective length of reheater module (ft)
- p = Perimeter (ft)
- P_{rw} = Prandtl number of water dimensionless
- t_N = Temperature of sodium ($^{\circ}$ F)
- t_{NC} = Temperature of sodium at evaporator-superheater junction ($^{\circ}$ F)
- t_{Ni} = Temperature of sodium in ($^{\circ}$ F)
- t_{No} = Temperature of sodium out ($^{\circ}$ F)
- t_{RSi} = Temperature of reheat steam in ($^{\circ}$ F)
- t_{RSo} = Temperature of reheat steam out ($^{\circ}$ F)
- t_w = Temperature of water ($^{\circ}$ F)
- t_{wc} = Temperature of water at evaporator-superheater junction ($^{\circ}$ F)

t_{wi} = Temperature of water in ($^{\circ}\text{F}$)

t_{wo} = Temperature of water out ($^{\circ}\text{F}$)

U = Overall heat transfer coefficient ($\text{Btu/hr-ft}^2\text{-}^{\circ}\text{F}$)

W_N = Flow rate of sodium (lb/hr)

W_{Nk} = Flow rate of sodium through low-temperature module (lb/hr)

W_{Nm} = Flow rate of sodium through high-temperature module (lb/hr)

W_{Nk} = Flow rate of sodium through reheater module (lb/hr)

W_{RS} = Flow rate of reheat steam (lb/hr)

W_w = Flow rate of water (lb/hr)

ΔX = Incremental length of module (ft)

= Nodal point