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VERY LARGE FAST BREEDER REACTOR (VLFBR) SECONDARY

SODIUM AND STEAM GENERATING SYSTEM

FEASIBILITY STUDY

Contract No. 31-109-38-1891
With Argonne National Laboratory

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ABSTRACT

The work performed by Westinghouse Electric Corporation under sponsorship of the Argonne National Laboratory (ANL Contract 31-109-38-1891) is described. A description of the conceptual design, estimated cost and development program of the secondary sodium system of the Very Large Fast Breeder Reactor (VLFBR) is given, together with the basis for selection of system parameters, including turbine cycle.

The capital cost of the secondary system installed is estimated to be from 13.00 to 15.40 \$/Kwe with an extreme of 18.80 \$/Kwe, based upon a plant output of 3900 MWe net. Also included in the above is the installed cost of the primary sodium pumps. Not included is building cost, system engineering, interest during construction and prime contractor's G & A, overhead and profit.

It is concluded that 2400 psia and 900°F turbine throttle steam with live steam reheat is a reasonable reference steam cycle for further more detailed studies.

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1. SUMMARY

General

Argonne National Laboratory granted Westinghouse Electric Corporation a contract to study the secondary sodium system of a Very Large Fast Breeder Reactor (VLFBR) concept.

The Atomic Power Division of Westinghouse was assisted in this study by Westinghouse Steam Divisions and the Atomic Equipment Division.

To provide a consistent basis for evaluating and comparing the information developed in this study, reference conditions and ground rules were established and mutually agreed upon with the Reactor Engineering Division of the Argonne National Laboratory. All work reported in this document is based on the reference conditions and ground rules which are listed in detail in Section 3.

The site is assumed to have no unusual conditions to complicate the design and increase cost. The work consists of turbine cycle and steam conditions selection, secondary sodium system design, cost estimation, and development program definition.

Preliminary Analyses

Because of the difficulties involved in optimizing turbine cycle and steam conditions of a plant of this size, at this stage of development, various alternatives were selected and examined for their effect on power costs. Sodium reheat was examined first. As a result of previous Westinghouse studies, and because of the technical simplification and improved reliability of the plant, it was decided to eliminate sodium reheat. Steam throttle pressure was then examined. As a result of a differential power cost comparison, a 2400 psia throttle pressure was chosen. Then the steam throttle temperature was examined. Again, as a result of a differential power cost comparison, a 900°F throttle temperature was chosen. Finally,

the turbine cycle was analyzed. After examination of condensing steam reheat, external moisture separation only, and live steam reheat cycles, the live steam reheat cycle, which had the lowest heat rate, was chosen as the preferred cycle.

To select the best conditions for the secondary sodium heat transfer system, an analysis was made using the primary sodium flow and temperature specified by ANL, and the steam conditions selected by Westinghouse. The analysis resulted in the selection of 620°F and 1000°F secondary terminal sodium temperatures, and 298×10^6 lb/hr sodium flow. Predicted future equipment sizes led to the selection of six as the number of primary and secondary loops with two loops paired to each of the three turbo-generators.

Plant Layout and Piping Arrangement

The reactor, with the six primary loops approximately equally spaced radially around it, is located in a 240 ft. diameter spherical container. In the arrangement selected, being one of several feasible possibilities, the steam generators and secondary sodium pumps are housed in pairs around the reactor building to minimize sodium piping runs. Each of the three, 60 ft. wide by 100 ft. long, steam generator buildings contains the auxiliary equipment for two secondary loops. The turbine generator building, 400 ft. long by 280 ft. wide, contains three turbine generators and is located adjacent to one steam generator building. In the primary system, the pump and intermediate heat exchanger are rigidly mounted, and the piping has sufficient bends to accommodate expansion stresses. In the secondary system, the pump and steam generator are suspended by tie-bars that allow lateral motion due to piping expansion, and thus permit more direct piping runs. All piping is fabricated of type 304 stainless steel.

Secondary Sodium System Description

The function of the secondary sodium system is to transfer heat from the primary sodium system to the steam system. The secondary sodium system has six identical loops, each loop consisting of a pump, a steam generator,

an intermediate heat exchanger, connecting piping, and operational control instrumentation. In each loop, cool (620°F) sodium is transmitted by a 113,000 gpm pump, through a single 42 inch pipe, to the intermediate heat exchanger. Hot (1000°F) sodium leaves the intermediate heat exchanger in two 30 inch pipes and flows to the steam generator. Sodium leaves the steam generator through a single 42 inch line and returns to the pump, where the cycle is repeated. In this manner, 1667 MWt of heat per loop are transmitted to the power generation system.

Intermediate Heat Exchanger Conceptual Design

Six intermediate heat exchanger units are required to meet the plant rating of 10,000 MWt. These units are the counter-flow, shell and tube type, with primary sodium on the shell side and secondary sodium in the tubes. They are approximately 14 feet in diameter and 42 feet long, and contain 54,000 ft² of effective heat transfer area.

Sodium Heated Steam Generator Conceptual Design

The proposed steam generator is a once-through, vertical, shell and tube type unit. The once-through type of heat exchanger was selected for its simplicity of construction and operation, lower cost, compactness, and very low water retention in the event of leakage. Six units are required to meet the plant rating of 10,000 MWt. The materials of construction, which represent a reasonable extrapolation of current technology, are type 316 stainless steel for the steam generator shell, tube sheets, and internals, and Incoloy 800 for the tubes. Using Incoloy 800, which is compatible in both sodium and water systems, eliminates many manufacturing problems and expense associated with bi-metal or double wall tubes. The serpentine tubes are bundled into a basic tube bank module. Six banks are nested in the 14 foot diameter by 52 foot long steam generator to give 75,500 ft² of effective heat transfer area.

Primary and Secondary Pumps Conceptual Design

The pumps, proposed as a result of this study, are electrically driven, shaft sealed, variable speed, sump-type pumps, employing single suction and discharge nozzles. Conventional thrust and radial bearings are located at the upper end of the pump shaft, and a sodium lubricated radial bearing is employed near the impeller end of the shaft. Each primary pump unit consists of a volute-type centrifugal pump driven by a 10,000 SHP, 450 rpm, wound rotor, induction motor. Six primary pumps are required, each with a capacity of 143,000 gpm and a head of 232 ft. The secondary pump unit consists of an axial flow pump driven by a 3,200 SHP, 600 rpm, wound rotor induction motor. Six secondary pumps are required, each with a capacity of 113,000 gpm and a head of 80 ft.

Secondary Sodium Auxiliary Systems

The following auxiliary systems have been provided for the secondary sodium heat transfer system: the sodium service system, the auxiliary coolant system, the cover gas system, the preheating system, and the control system. The sodium service system provides facilities for filling, draining, and purifying the secondary sodium coolant. The NaK auxiliary cooling system provides auxiliary cooling of the secondary sodium, primarily cold-trap cooling. Distribution supply and venting lines are supplied for the cover gas system to maintain a protective, inert atmosphere for the secondary sodium coolant. All sodium piping and components have heating equipment for preheating, and in some cases for intermittent or continuous heating during operation, to insure that the sodium will remain liquid and circulate freely. A secondary control system has been developed conceptually, based on the once-through steam generator and live steam reheater concept being used in this plant.

Operation and Maintenance of Steam Generators

An auxiliary starting system is required to startup the once-through steam generating system. Its principal function is to protect the steam generating system and the turbine generators, from abnormal temperatures and

operating conditions. Although it is an integral part of the turbine and feedwater plants, a brief description of the system was developed because of its necessity for startup of the once-through steam generator. The once-through steam generator also places demanding requirements upon the feedwater treatment system to obtain reliable and long life operation. Minor steam generator leaks can be repaired by tube plugging, but large leaks may require replacement of a whole bundle, a major operation. Extensive analyses and tests of the sodium water reaction are required for the steam generator.

Equipment Cost Data

Order of magnitude cost estimates were developed for the secondary system. These estimates are based on current labor and material costs, but assume that one or more 1000 MWe plants, with design features consistent with the VLFBR design, have been operated prior to designing the VLFBR equipment. No development costs are included in the prices. The Westinghouse divisions which normally design and manufacture pumps and steam generators prepared the conceptual design and cost estimate of the major equipment. Installation costs were estimated by Nuclear Power Services Group of Westinghouse Atomic Power Division. Items excluded from the cost estimate are: 1) Plant and System Engineering, 2) Architect-Engineer services, 3) Building Structures, 4) Equipment foundations, 5) Interest during construction and 6) Prime Contractor's G&A, overhead and profit. The capital cost of the secondary system installed is estimated to be from 13.00 to 15.40 \$/Kwe with an extreme of 18.80 \$/Kwe, based upon a plant output of 3900 MWe net. Also included in the above is the installed cost of the primary sodium pumps.

Research and Development Program

Based on a review of the performance requirements and design features outlined for the secondary system components, no further research and development on these components will be required to construct and operate the 10,000 MWt plant, if a development program is successfully completed for the 1000 MWe plant. Extrapolations of proven technology by less than a factor of three would be required for the 10,000 MWt plant, and this should be within the capability of the manufacturing industry.

2. PURPOSE AND SCOPE OF WORK

The purpose of this engineering study is to develop a conceptual design and cost estimate for the primary sodium pumps, secondary sodium loops, (including pumps, IHX, and auxiliaries) and steam generating equipment for a 10,000 MWt sodium fast breeder reactor plant designed to provide steam at conditions suitable for electric power production. No specific limitations on site, cycle or owner conditions are considered in this study. The choices of equipment and arrangement are those which are believed to provide economic and operational features attractive to the largest group of potential utility operating companies. The engineering and cost analyses performed for this study have recognized as principle guidelines the necessity for reliable and economic operation of such a large capacity system.

Westinghouse has performed the following sub-tasks established for this contract:

1. In cooperation with Argonne National Laboratories, established the plant reference conditions and the ground rules to be employed in the study.
2. Performed a preliminary evaluation of reheat versus non-reheat cycles and selected a preferred cycle.
3. Prepared a conceptual design of the secondary sodium loop, secondary loop equipment items, IHX, and the preferred steam generating equipment for a 10,000 MWth Fast Breeder Reactor Plant to generate steam at conditions suitable for electric power production. Outlined strategy for steam generator leak detection, isolation and repair. Determined probable effect of failure on plant availability.
4. Prepared a conceptual design of primary pumps based on ANL requirements.
5. Prepared a preliminary capital cost estimate of the equipment conceived under subtasks 3 and 4. Stated cost estimating basis and scope.

6. Identified the principle problem areas in the development of the major components and systems. Outlined a program to perform this development.
7. Prepared and submitted to ANL a final report incorporating the results of subtasks 1 through 6, including conceptual drawings of major equipment.

3. GROUND RULES, GUIDELINES AND ASSUMPTIONS

The following plant reference conditions and ground rules for the study have been established and mutually agreed on with the Reactor Engineering Division of the Argonne National Laboratories:

1. Primary System Characteristics

Reactor output, MWt	10,000
Bulk sodium outlet temperature from reactor, °F	1050
Bulk sodium inlet temperature to reactor, °F	720
Sodium flow, 10 ⁶ lb/hr	343
Reactor pressure drop, psi	80
Number of primary loops	6
Absolute reactor seal pressure, psia	15
Primary system material	304 SS

2. Reactor General Arrangement

The general arrangement of the reactor and the primary system in reactor building is as shown in Argonne National Laboratory drawings of the VLFBR.

3. Economics Evaluation Basis

Economics are to be evaluated on a basis characteristic of publicly owned utilities; namely:

Annual carrying charge, %/year	7
Annual load factor, %	80
Fuel cycle cost, at a plant heat rate of 8000 Btu/kwh, mills/kwh	0.25

4. Site

It is assumed that the plant site is suitable for a large nuclear power system of this type, i.e. the site has adequate soil conditions, adequate water availability, adequate undeveloped acreage, reasonable stream and air pollution ordinances, accessibility to highway and railroad systems, and other features commonly sought for the installation of major electric generating plants.

5. Unusual Conditions

It is assumed that no unusual design features need to be incorporated in this plant because of specifically local conditions, i.e., there are no seismic zoning, peripheral land use, nearby habitation, meteorological or other requirements that require unusual design and construction features.

6. Previous Sites Developed

It is assumed that no previous site development has taken place, and that this plant is to be installed on a completely new site with all of the components services and facilities required for a first unit installation.

7. Future Extension

The general arrangement for both the sodium systems and the steam generators would not interfere with the location of a similar adjacent unit on the same site. In sizing the components and service facilities for this plant, no provisions are made for possible future plant expansion.

8. Electric System

It is assumed that an existing major electric system can provide at least one dependable incoming source of electric power that can be used for station power during an outage.

9. Test Facilities

It is assumed that this plant would be developed as a commercial installation. Therefore the use of this plant as a test facility is not considered in developing the plant design, layout, instrumentation, and functional arrangements.

10. Geographical Location

It is assumed that this equipment will be installed in the United States on a site having reasonable access to highways, railroads, and labor supply, and that major components can be shipped by ship or barge.

11. Capital and Fuel Costs

To provide a basis for equipment and heat cycle evaluation of the secondary sodium loop and steam generating units, capital cost ranges and fuel cycle costs have been supplied by ANL from their study of the reactor.

12. Equipment Availability

In a study of this nature, the ground rules for applying and costing component equipment must be clearly identified. A distinction is made between two different types of equipment. For equipment which is not specific to sodium, for example, electric motors and steam turbines, costs will be based on equipment which is either currently available or which may be available within the foreseeable future. For the case of the components specific to sodium, such as the intermediate heat exchangers, pumps, and steam generators, there is no equipment currently available in sizes which would be appropriate for the system under study. Therefore, for the purpose of this study, the components specific to sodium will be based upon capacities and design configurations which the contractor's engineers believe can be developed to the reliable service stage by an engineering development program. The engineering development required for these components, beyond that needed to achieve 1000 MWe plants, is outlined in Section 13 of this report.

13. Multiple Units

As a result of limiting unit capabilities to those for which there is reasonable certainty of availability, either now or through an engineering development program, there are multiple units serving similar or identical functions. To minimize original equipment cost, spare parts inventory cost, and maintenance costs, such units are interchangeable.

14. Cost Estimates

Because the major component items have not yet been developed, the cost estimates are the best engineering estimates. The basis for the estimates is given in the appropriate sections of this report.

15. Structures

The sodium steam generating system begins in the reactor building and ends in the steam turbine hall. Thus, the structures and foundations for the sodium steam generating system are intimately related to the total integral plant design and may well be included entirely within the reactor and turbine structures. Therefore, structures have not been considered in this study.

16. Reliability

A nuclear facility of this size will represent a large portion of the energy capacity of the utility system. Therefore, this plant must perform with an availability factor consistent with the other large units of the utility or within an interconnected area. The design and selection of equipment assumes that this system will be required to operate at a load factor at least comparable with that of other large systems. To achieve this end, the selection of non-sodium component equipment has been limited to the capacity and rating conditions for which manufacturers have current design and operating experience or can project such a design and operating experience on a logical basis.

Capacities and design configurations for the sodium components have been selected on the basis that these items can be developed to the reliable service stage by an engineering development program.

17. Operation

The design philosophy for the operation of this system presumes a centralized control operation of the reactor, sodium primary and secondary loops, steam generator and electric generation plant. This is necessary to provide integrated control for effective unit operation and for safety. The centralized control system and facilities are not within the scope of this study.

Because of the very large energy capacity of this system, it is presumed to be necessary to provide for partial load operation of the system during a period of forced or planned outage of certain components and auxiliary systems. These considerations are included in the design. To the extent consistent with the efforts of this study, the conceptual design represents an economic balance between investment costs and operating and maintenance costs.

18. Maintenance

The quality and design features of the operating equipment and components were chosen to provide maximum in-service availability and to minimize maintenance time and cost.

Maintenance and service facilities at the plant site are presumed to be provided where required for the reactor and the steam utilization equipment.

4. PRELIMINARY ANALYSES

4.1 Cycle and Steam Conditions Selection

The proposed level of effort for the study did not permit, nor would the accuracy of the available cost data justify, a complete optimization study at this time. Justification for the use of reheat and high throttle steam temperature and pressure should be based primarily on economic gains. Technical considerations would in theory be reflected by their effect on costs; however, in this study where cost differentials are small, engineering judgment will be used.

The selection of plant cycle and steam conditions was first performed in several separate steps as follows:

1. Decision on whether sodium reheat should be used.
2. Selection of throttle steam pressure.
3. Selection of throttle steam temperature.

Then, based upon a United Engineers and Constructors study of turbine plants for Argonne National Laboratory⁽¹⁾, a further estimate of the economics of steam conditions and cycle alternatives was made. Lastly, the selection of the plant heat cycle type was made, based upon the selected throttle steam conditions. The details of this procedure can be found in Appendix A. It should be noted, however, that a number of approximations and assumptions were made. The selection of the steam cycle and steam conditions therefore are only indicative of reasonable choices. These suffice for the end of this study, namely, feasibility.

The comparison of sodium reheat case to the condensing steam reheat case for initial steam conditions of 3500 psia and 1050°F indicated that no great incentive existed for either type of reheat. However, technically, the simplification and improved reliability due to elimination of the sodium reheater is appreciable. Based upon the above, it is reasonable to eliminate sodium reheat.

Three steam throttle pressures were selected for study of 1800, 2400, and 3500 psia with 1000°F temperature. The 1800 psia condition gave higher energy cost than the other two pressures. The 2400 psia and 3500 psia gave about equal energy costs. Based on this indication, the 2400 psia pressure was selected.

At 2400 psia steam pressure, temperatures of 800, 900, and 1000°F were picked to study differential energy costs holding the reactor inlet temperature at 720°F and outlet temperature 1050°F. The variation with temperature was small and 900°F was selected as the temperature. In all of the above analyses an annual charge on capital of 7% was used and an annual plant factor of 80% was held constant.

Three different turbine cycles based on 2400 psia/900°F throttle steam, without sodium reheat, were considered and heat balances were performed as a basis for selection of the preferred cycle. In all cases, seven stages of regenerative feedwater heating were employed, resulting in approximately 480°F final feedwater temperature. The computed heat rates include generator losses and boiler feedpump power. The steam expansion lines for the three cycles are presented in Figure 1.

The three cycles are described below:

1. Condensing steam reheat. Here exhaust steam from the high pressure turbine heats exhaust steam from the intermediate pressure turbine in external steam-to-steam heat exchanger and moisture separation units. The heat rate is 8654 Btu/kwh. This is the highest heat rate of the three cycles considered. Moreover, the terminal ΔT in the reheater is small resulting in large heat transfer surface. This cycle was, therefore, rejected.

2. Moisture separation only. In this case, although there is some internal steam separation, external steam separation between the intermediate pressure and low pressure cylinder is required. Otherwise, the maximum moisture would be above 13% and excessive blade erosion would occur. This cycle has an estimated heat rate of 8624 Btu/kwh and is close to the lowest of the three. However, there is a major drawback to this cycle in that the low pressure end expands steam from 75 psia to 1-1/2 in. Hg. Standard design low pressure turbine cylinders expand steam from between 150-200 psi to 1-1/2 in. Hg. Thus, removal of several sets of blading would be required, thereby drastically changing the standard low pressure turbine cylinder design. For the purposes of this study, this reason is sufficient to reject this cycle.
3. Live steam reheat. In this case, throttle steam is used to reheat exhaust steam from the intermediate pressure cylinder. A simplified heat balance diagram is presented in Figure 2. The resulting heat rate is 8615 Btu/kwh, the lowest of the three cycles. No moisture separation is required, and, because of the comparatively large steam-to-steam reheater ΔT , the required heat transfer area is a minimum. This is the preferred steam cycle.

Three independent tandem compound quadruple flow turbine generators are required. Each turbine-generator unit accepts steam in the high pressure cylinder at 2400 psia/900°F where it expands to 570 psia and 570°F. Expansion in the intermediate pressure cylinder is down to 200 psia and 380°F. This steam is then reheated with live steam to 660°F before the steam enters the quadruple flow low pressure ends where expansion is down to 1-1/2 in. Hg absolute. Each of the three identical turbine-generator assemblies has an overall length of 211 ft. and a gross output of 1320 MWe. A preliminary turbine-generator outline is presented in Figure 3.

$$\text{HEAT RATE} = \frac{12,253,000 (1392.2 - 464.5)}{1319.5} = 8615 \text{ BTU/KW HR}$$

Figure 2. VLFBR SIMPLIFIED HEAT BALANCE

TURBINE	
KW	1,320,000
TYPE	TC4F
LAST ROW BLADE LENGTH	52"
STEAM CONDITIONS:	
INITIAL PRESSURE, PSIA	2,400
INITIAL TEMP., FTT	900
REHEAT TEMP., FTT	-
EXHAUST PRESSURE, IN. HG. A.	1.5

GENERATOR	
KVA	1,600,000
POWER FACTOR	0.90
KW	1,320,000
S.C.R.	0.50
GAS PRESSURE, PSIG	75
RPM	1,800

* DIMENSIONS ARE APPROXIMATE

Figure 3. WESTINGHOUSE TURBINE-GENERATOR UNIT PRELIMINARY OUTLINE *

4.2 Secondary Sodium Loop

The physical characteristics of the secondary loop equipment and piping are in part determined by the primary circuit and the turbine-generator portion of the plant. The physical size of the sodium to-sodium heat exchanger and the size of the sodium heated steam generator are inter-related to some extent by the division of the available temperature driving force between the units.

It was decided that the units should be transportable to the site. The systems temperature distribution is illustrated in Figure 4.

In a plant of such large capacity, the number of secondary coolant loops used has a strong bearing on the economic and technical desirability of the plant. The principal means of achieving economic advantage is through the use of few large size reliable components rather than multiple duplication of current small components. In this way, maximum plant reliability may be maintained. The component size must not, however, be increased to the point where its cost per unit of capacity is increased due to necessary changes in fabrication techniques.

With flow and heat removal of the magnitude specified above, three to eight loops represent the practical extremes. Three single shaft 1800 rpm turbines-generators of between 1300 and 1400 MWe output are considered feasible by the Westinghouse Steam Divisions and East Pittsburgh Large Rotating Apparatus Division.

Hence, from three to eight single shaft machines could be used, but the best economics and reliability for both the turbo-generators and T-G plant would occur with the minimum number of units. With three primary and three secondary loops, unit pump capacities would have to be over 280,000 and 220,000 gpm respectively. Also, the intermediate heat exchangers and steam generators would each require about 100,000 and 150,000 square feet of effective heat transfer surface respectively. To put these capacities in

Figure 4. SYSTEMS TEMPERATURE DISTRIBUTION

perspective with respect to present planned or anticipated AEC studies and programs, consider the B&W Steam Generator design⁽²⁾ which has an effective heat transfer surface area of about 35,000 square feet. In a Westinghouse sodium pump study⁽³⁾ performed for the AEC, flows of around 120,000 gpm in a 3 loop - 1000 MWe plant are predicted. This leads to the reasonable selection of six as the number of primary and secondary loops with two steam generators paired to each of three turbo-generators. A simplified flow diagram for the plant is presented in Figure 5.

ARGONNE NATIONAL LABORATORY 10,000 MWT SODIUM COOLED FAST BREEDER REACTOR

FIGURE 5. **SIMPLIFIED FLOW DIAGRAM**

5. PLANT LAYOUT AND PIPING ARRANGEMENT

The reactor core requirements and the refueling concept govern the general arrangement of equipment in the reactor building. This arrangement dictates to a large degree the layout of the entire plant. The plan and elevation of the plant conceptual design are presented in Figures 6 and 7 respectively.

The starting point for the secondary sodium system and turbine building layout was the 240 foot diameter spherical reactor building with six primary sodium loops more or less symmetrically spaced around the center.

One feasible method of arranging the secondary plant is to group the six steam generators and secondary pumps, with connecting piping and valves, in one building. The advantages of this method are:

1. Secondary plant building costs are minimized.
2. Steam and feedwater pipe runs to the turbine plant are reduced.
3. Duplication of common facilities, such as cranes, is avoided.

Another arrangement approach and the one selected for this study, was to minimize the secondary sodium pipe runs. A thorough technical and economic analysis is required to positively identify the superior secondary plant configuration. This is beyond the scope of the present study. Some of the principal reasons for selecting the latter arrangement are:

1. Large diameter (42 inch) sodium pipe is expensive.
2. Extra pipe length increases the extent of trace heating, insulation and thermal stress requirements.
3. Extra sodium hold-up requires additional storage capacity, which must also be trace heated.
4. Longer sodium piping might increase the probability of a pipe rupture.

Figure 6. Plant Conceptual Design Plan

By pairing the steam generators and secondary sodium pumps the number of steam generator buildings is three. In this way a single sodium storage tank and other auxiliaries are used for two secondary loops, resulting in some saving. Each of the three steam generator buildings is approximately 62 feet by 100 feet. The main auxiliary equipment in each building consists of a sodium storage tank, cold traps and a regenerative heat exchanger. The pairing of the steam generators into three separate buildings does not increase the number of auxiliary equipment components.

Since one large building costs less than three small buildings of the same floor area, it was decided to house the three identical turbine generator units in a single large turbine hall. Moreover turbine plant maintenance is thereby facilitated and related equipment duplication is avoided. The turbine generator building is approximately 400 feet long by 280 feet wide and is symmetrically located adjacent to one steam generator building. Three turbine generators are spaced on 120 feet centers and are each flanked by four live-steam reheaters below the operating floor.

Piping Arrangement and Equipment Support

The intermediate heat exchanger and primary sodium pump are rigidly mounted, and the primary piping loops have sufficient bends to safely accommodate expansion stresses. In each secondary system loop both the steam generator and sodium pump are hung by four tie-bars which support the weight, but allow lateral motion due to the expansion of the secondary piping when heated to operating temperature. This method reduces the expansion bending stresses in the pipes, permitting tightly spaced equipment layouts with more direct piping runs.

Stainless steel (SA-213 TP-304) was selected as the piping material due to its compatibility with sodium, ease of fabrication, and comparatively low cost. The piping wall thickness is minimal, so this alloy has an economic advantage over stronger but more expensive alloys. Type 304

stainless steel is compatible with, and may be welded to, type 316 stainless steel and Incoloy 800 (the materials specified for the IHX and steam generator). Moreover, no carbon mass transfer is expected at the operating temperatures.

An approximate strain energy analysis of the secondary piping was performed by the elastic center method, with simplifying but conservative assumptions to reduce the amount of work. Material properties were taken from Section VIII of the ASME Code for unfired pressure vessels. The piping was designed for internal pressure and thermal expansion stresses in accordance with ASA B31.1, Code for Pressure Piping. Some significant piping parameters are presented in Table 1.

Table 1. Secondary Sodium Piping Parameters

	Hot Leg	Cold Leg
	Twin 30" O.D.	42" O.D.
Maximum operating pressure, psia	100	110
Maximum operating temperature, °F	1000	620
Design pressure, psi	200	200
Design temperature	1025	700
Material	SA-213 TP-304	SA-213 TP-304
Allowable hoop stress, S, psi	8,650	10,800
Wall thickness, in., straight	.40	.50
elbow	.50	.60
Trace heating method	electric	electric

The piping is electrically trace heated to prevent sodium solidification. No valves are required in the secondary system. However, a sodium by-pass line around the steam generator may be required to limit terminal temperature difference. Part and full load temperature control is maintained with the variable speed secondary pump motor.

6. SECONDARY SODIUM SYSTEM DESCRIPTION

The function of the secondary system is to transfer heat from the primary sodium system to the steam system. A system schematic flow diagram is presented in Figure 5. The secondary system is composed of six identical loops. Each loop consists of a single steam generator, a single sodium circulating pump, an intermediate heat exchanger, connecting piping, and operational control instrumentation. The intermediate heat exchangers and a portion of the systems piping are located in the reactor building. The pumps, steam generators, and the balance of the piping are located in the steam generator buildings.

In each loop sodium coolant flows through the tube side of the intermediate heat exchanger, leaving through two nozzles at the top of the unit. The two pipes pass through penetrations in the reactor building which are sealed with expansion joints. In the steam generator building the coolant enters the steam generator through two nozzles near the top of the shell. After heat has been transferred to the power generation system, the coolant leaves the steam generator through a single nozzle at the bottom of the shell, and is pumped back to the intermediate heat exchanger. The flow passes through a single pipe, which again penetrates the reactor building through expansion joints, and enters the intermediate heat exchanger (through a nozzle at the top) where the cycle is then repeated. Bypass lines with control valves are provided around the steam generator to minimize variations of terminal temperature difference. Table 2 presents the secondary system design data.

One of the prime purposes of a secondary sodium heat transfer system is to facilitate the containment of radioactive primary sodium completely in the reactor building, while keeping all of the water from the power generating system outside of the reactor building. Therefore, as described previously, the nonradioactive secondary sodium system transmits the heat from the primary system to the power generation system. The non-radioactive secondary sodium system is monitored constantly to detect any leaks that would transmit radioactivity outside of the reactor building.

Table 2. Principal Secondary Sodium System Characteristics

Item	Primary	Secondary	Water / Steam
No. of loops	6	6	6
Heat load, MWt	1667	1667	1667
10^9 Btu/hr	5.69	5.69	5.69
Flow, 10^6 lb/hr	57.2	49.7	6.13
10^3 gpm	143	113	
Maximum bulk temperature, °F	1050	1000	900
Minimum bulk temperature, °F	720	620	480
System pressure drop, psi	80	30	300
Maximum operating pressure, psia	100	115	2700
Piping size, in.	48	42 & 30	6 & 10
Materials	304 SS	304 SS	316 SS Shell
	316 SS	316 SS	Incoloy 800 Tubes
Heat Exchanger Area, ft ²	54,000	75,500	
Pump Power, shp nominal	10,000	3200	
MWe input	6.1	2.0	

7. INTERMEDIATE SODIUM HEAT EXCHANGER CONCEPTUAL DESIGN

The intermediate heat exchangers (IHX) are counterflow, shell and tube type units with primary sodium on the shell side and secondary sodium in the tubes. The parameters are summarized in Table 3 and the conceptual design is shown in Figure 8. Each of the six units (one per loop) is rated at 1667 MWt.

Secondary sodium enters the 42" nozzle at the top-center of the unit, flows through the downcomer to the lower tube sheet, flows up through the tubes and leaves through the two 30" outlet lines at the top of the unit. The heat transfer coefficient on the inside of the tubes was calculated by using the equation recommended in WCAP-4402⁽⁴⁾. The heat transfer coefficient for parallel flow along the outside of tubes on a triangular pitch was also based on an equation recommended in the same report. This coefficient is conservative since some cross-flow, caused by the baffles, will result in a higher coefficient.

Primary sodium enters near the top of the shell through two 36" nozzles. Baffles distribute the flow circumferentially and direct it upward to the top of the shell region. Sodium then flows downward; being directed back and forth across the tubes by staggered doughnut baffles. At the bottom of the shell side, the sodium passes through a perforated wall to prevent channeling, and exits through two 36" nozzles.

To reduce the magnitude of the thermal transients impressed on the structural members, thermal baffles are placed next to the shell and tube-sheets. This technique will damp out the rate of temperature change in these members to the point where their structural integrity can be maintained. In addition, there is a gas gap for thermal insulation between the secondary sodium central downcomer pipe and the rest of the unit. There is no cover gas space at the top of the IHX. The expansion of the primary sodium on the shell side of the IHX will be accommodated in the

Table 3. Intermediate Sodium Heat Exchanger Parameters

General

No. of units	6
Unit type	Counterflow, shell and tube
Unit rating, MWt	1667
10^6 Btu/hr	5690
Unit weight, 10^3 lb	400
Over-all length, ft	42
Over-all diameter, ft	14
Tube bundle removable from above	yes

Shell Side

Fluid	Primary radioactive sodium
Flow rate, 10^6 lb/hr	57.2
Inlet temperature, °F	1050
Outlet temperature, °F	620
Design temperature, °F	1075
Operating pressure, psia	87
Design pressure, psi	200
Flow pressure drop, psi	12.5
Wall thickness, in.	1.6
Inlet, no./dia. in.	2/36
Outlet, no./dia. in.	2/36
Material	316 SS

Tube Side

Fluid	Sodium
Flow rate, 10^6 lb/hr	49.7
Inlet temperature, °F	620
Outlet temperature, °F	1000
Design temperature, °F	1075
Operating pressure, psia	115
Design pressure, psi	200
Flow pressure drop, psi	10
No. of tubes	9400
Outside diameter, in.	.75
Wall thickness, in.	.035
Effective length, ft.	29.2
Triangular pitch, in.	1.25
Inlet, no./dia. in.	1/42
Outlet, no./dia. in.	2/30
Material	316 SS

Thermal Data

Effective tube outside surface, ft^2	54,000
Over-all effective heat transfer coefficient, Btu/hr ft^2 °F	1460
Log mean temperature difference, °F	72.1

DEPT	WESTINGHOUSE ELECTRIC CORPORATION
CHGR	ATOMIC POWER DIV. PITTSBURGH PA. U.S.A.
DES. ENG.	VERTICAL SODIUM HEAT EXCHANGER
REV. ENG.	Conceptual Des. #1
MTLS. ENG.	
APP.	SCALE
DATE	DO NOT SCALE
	SUB 1.2

318803-D

Figure 8. Intermediate Sodium Heat Exchanger Conceptual Design

Reactor Overflow Tank. Any gas entrained in the primary sodium and carried to the IHX will be vented to the reactor cover gas system.

All parts of the IHX are to be fabricated of 316 stainless steel. 316 stainless steel was selected because it is suitable for sodium service, and more economical than 304 SS due to a high-temperature strength advantage. The top head is flanged and bolted to the rest of the unit. The tubes are rolled and welded to the tube sheets. If the upper head were pulled, the tube bundle would go along with it, leaving the lower shell and lower head.

Although quality materials and manufacturing techniques will be used throughout, the possibility of a leak must be recognized and its detection and the resulting procedures must be planned. If a tube should rupture, the secondary sodium will leak into the primary system because of the pressure differential. This will be indicated by a volume decrease in the secondary system and a volume increase in the primary system. Both the secondary and primary sodium sides must be drained or pumped out to plug a leaking tube. The outstanding problem is the radioactivity level due to sodium and fission products. The whole bundle would be replaced if repair were infeasible. The units are designed so that the tube bundles may be removed without removing any primary sodium or piping.

The size of this unit is such that it can be transported intact by rail. This reduces field installation to seven large pipe welds per unit and the associated instrumentation hook up.

8. SODIUM HEATED STEAM GENERATOR CONCEPTUAL DESIGN

The proposed steam generator is a once-through, vertical, shell and tube conceptual design, illustrated in Figure 9. The design and thermal data are presented in Tables 4 and 5 respectively. Six units provide a total heat exchanger capability of 10,000 MWt. Although this is more than double the thermal capacity of presently proposed sodium steam generators, the design is a reasonable extrapolation of present day industry manufacturing capabilities, by virtue of the compact, functional design.

The downward sodium shell side flow permits stable operation, without any tendency to stratify. Water/steam flows upward through serpentine tubes in a multi-pass cross-flow arrangement, thereby achieving near optimum counterflow. The once-through heat exchanger concept has been selected for its simplicity of construction and operation, low cost, compactness, adaptability to possible supercritical pressure steam conditions, and very low water hold-up. A low water hold-up permits rapid emptying in the event of a leak. High purity feedwater treatment and control systems are already proven for once-through boiler designs.

The steam generator shell, tube sheet and internals will be constructed of type 316 stainless steel which is well known for its good strength properties and its suitability for service in liquid alkali metals. Type 316 stainless steel is structurally superior to 304 stainless steel due to its greater high temperature strength resulting in improved economics. Moreover, the thinner sections required by the use of 316 stainless steel reduce the thermal stress induced by transient operating conditions.

The tubes will be fabricated of Incoloy 800, an austenitic alloy comparable in strength to type 316 stainless steel, and possessing good resistance to mass transfer and chloride stress corrosion in water/steam. The use of a tube material compatible with both sodium and water systems eliminates the very difficult manufacturing problems and major expense associated with bi-metallic or double wall tubes.

Table 4. Sodium Heated Steam Generator Parameters

General

No. of units	6
Unit type	Once-through, counterflow, shell and tube
Unit rating, MWt	1667
10^6 Btu/hr	5690
Unit weight, 10^3 lb	465
Over-all length, ft	52
Outside diameter, ft	14.2

Shell Side

Fluid	Sodium
Flow rate, 10^6 lb/hr	49.7
Inlet temperature, °F	1000
Outlet temperature, °F	720
Design temperature, °F	1025
Operating pressure, psia	91
Design pressure, psi	200
Flow pressure drop, psi	10
Wall thickness, in.	1.6
Inlet, no./dia. in.	2/30
Outlet, no./dia. in.	1/42
Material	316 SS

Tube Side

Fluid	Water/steam
Flow rate, 10^6 lb/hr	6.13
Inlet temperature, °F	480
Outlet temperature, °F	900
Design temperature, °F	1025
Operating pressure, psia	2675
Design pressure, psi	3000
Flow pressure drop, psi	225
No. of tubes	4800
Pattern	Serpentine
Outside diameter, in.	.500
Wall thickness, in.	.065
Effective length, ft.	120
Square pitch, in.	.875
Inlet no./dia. in.	6/6
Outlet no./dia. in.	6/10
Material	Incoloy 800

Tube Sheets

Water side thickness, in.	8-10
Steam side thickness, in.	10-12
Triangular tube pitch, in.	.75
Material	316 SS

Table 5. Sodium Heated Steam Generator Thermal Data

Thermal Data	Subcooled	0-40% Quality	40-60% Quality	60-100% Quality	Superheat	Total per Generator
Heat transferred, 10^9 Btu/hr	1.72	.834	.417	.834	1.87	5.675
Effective outside surface area, ft^2	23,700	12,700	5,400	9,100	24,600	75,500
Overall heat trans- fer coefficient Btu/hr ft^2 °F	821	924	683	609	531	

Since heat transfer rates are relatively high on both the sodium and steam sides of the tubes, the tube wall conduction resistance is a major factor in determining the amount of transfer surface required. By using small diameter tubes (1/2"), the wall thickness required to contain the pressure is also relatively small (.065" min.). This helps to minimize the required surface area and results in a small bundle volume. The relatively small tube also limits the rate at which water could leak into the sodium, should a tube break occur. The proposed conceptual design provides for complete, rapid drainage of water and, if necessary, of sodium.

The proposed arrangement allows the tubes to be spaced closely together, yet provides the relatively large sodium flow areas required for a moderate sodium pressure drop. The close spacing of the tubes results in a compact bundle, which in turn results in the small overall size of the unit and correspondingly thinner shell walls. This feature, in turn, enhances the generator's ability to withstand thermal transients.

A cross-section of the generator is depicted in Figure 9. There is one basic tube bank module size. Six banks are nested together to fit compactly within a 14 foot diameter circle. The tubes are supported by notched plates attached to cross rods traversing the tube banks. The cross rods, in turn, are supported by and tie together, the different support plates. The support plates carry the weight to the 14 foot diameter wrapper which, in turn, is supported from the shell.

The main sodium flow is admitted at the top through two pipes which penetrate the shell and lead to tee sections. The tees route the sodium flow to four downcomers which terminate in perforated caps in distribution boxes located just below the sodium level. The purpose of the perforations and distribution boxes is to prevent the

incoming sodium from impinging directly on the tubes which could cause severe vibration problems. The vertical baffles around each of the six tube bundles are designed to prevent a sodium-water reaction from progressing to adjacent bundles. These baffles are also used as structural containment and support for the tubes in each bundle.

The sodium steam generator presented in this report was conceived to satisfy the dual requirements of low cost combined with high reliability. To achieve these seemingly competing objectives, the design incorporates the potential for correct engineering and quality manufacture, combined with proper selection of materials.

Detailed attention to mechanical design, in particular stress analysis, will assure that the unit possesses the potential for reliable long term operation. On the other hand, correct thermal analysis will assure a compact unit, contributing to low cost. Recognizing the importance of quality manufacture, the design must be simple so that previous manufacturing experience can be applied. Finally, the materials chosen for this unit have the potential for long service in both sodium and water.

9. PRIMARY AND SECONDARY PUMP CONCEPTUAL DESIGNS

The results of the Westinghouse Sodium Pump Study which was performed for the U. S. Atomic Energy Commission⁽³⁾, and reported in Westinghouse report WCAP 2347, showed the mechanical, shaft sealed pump design to be superior to the totally enclosed pump design on the basis of reliability, cost, and systems considerations. Both designs were rated equal from the standpoint of design predictability. The major reason for this three-point advantage of the shaft sealed unit over the totally enclosed unit is that the shaft seal completely divorces the drive motor from the sodium system. With the totally enclosed design, the drive motor and its associated auxiliaries (bearing lubrication system and winding cooling system) are incorporated within an enclosure which is directly linked with the sodium system.

Therefore the pump concepts selected for this design study are of the shaft sealed, mechanical, vertical shaft type, with variable speed electric motor drives. A conventional thrust and radial bearing is located at the upper end of the pump shaft above the floor (shield) level. A shaft seal is located just below the thrust bearing. The shaft extends down through the gas cover and the free surface of sodium. A sodium lubricated radial bearing is employed near the impeller end of the shaft. A static seal is provided between the inside diameter of the pump tank and the lower radial bearing support to reduce or prevent leakage from the discharge side of the pump into the pump tank. Radial baffling in the pump tank is required to prevent vortexing around the shaft. A labyrinth or vertical baffle is used above the free surface to limit passage of sodium vapors, and to limit convective heat transfer in the cover gas around the shaft. Overflow and equalizing lines to the reactor vessel, or other free surfaced vessels, are provided to maintain a stable liquid level in the pump tank.

The pump end is a single suction type, in which the sodium is drawn into the bottom of the impeller and discharged through a diffuser into the pump casing. The pump internals (shaft, impeller, bearing support, bearing, and baffling) can be withdrawn vertically from the pump tank without requiring personnel to work below floor level. Thermal insulation and heaters are indicated around the pump tank and casing, and radiation shielding is shown at the top of the pump tank. The pumps were designed in accordance with Section VIII of the ASME Code for Unfired Pressure Vessels.

The design specifications for the primary and secondary sodium pumps are presented in Table 6. These specifications are based on the relevant systems functional requirements. The primary and secondary pump conceptual designs are presented in Figures 10 and 11 respectively. It should be emphasized that these designs are preliminary and do not have the degree of refinement to be found in pumps currently being built.

The designs are different to conform to the respective system functional requirements as described in this section. The primary pump price is approximately double that of the secondary pump.

Primary Sodium Pump

As shown in Figure 10, each primary pump unit consists of a volute-type centrifugal pump, driven by a 10,000 SHP, 450 rpm, wound rotor, induction motor. The pump impeller, diffuser, shaft and bearing assembly are designed for withdrawal from the pump tank. The sodium level in the pump tank is maintained by providing an overflow line to the reactor. The overflow rate is determined by the amount of leakage around the lower static seal and through the lower radial bearing. Argon cover gas is used to balance gas pressure between the reactor and the pump tank. Radial baffling is provided in the

Table 6. Sodium Pump Functional Specifications

Characteristic	Primary Na Pumps	Secondary Na Pumps
No. pumps	6	6
Fluid pumped	Radio active sodium	Sodium
Flow per pump, gpm	143,000	113,000
Inlet temperature, °F	1050	620
NPSH, ft.	50	200
Developed head, ft.	289	105
Pump speed ratio norm/min	2:1	2:1
Design pressure, psi	200	200
Design temperature, °F	1175	650
Cover gas	Argon	Argon
Shaft seal gas pressure, psi	0-1 psi	0-100 psi
Shaft length, floor level to impeller, ft.	47	30
Shielding required, ft.	5	0
Suction diameter, in. I.D.	47	41
No. required	6	6
Motor shaft horsepower	10,000	3200
Motor speed (normal) rpm	450	600
Motor efficiency at rated hp	96	95.5
Motor weight, lb	120,000	35,000
Pump design flow, gpm	143,000	113,000
Pump design head, ft	289	105
Pump estimated efficiency, %	85	83
Sodium specific gravity	.800	.875
Pump weight, lbs	346,050	113,300
Shaft seal design pressure, psi	10 psi	100 psi
Total unit weight, lbs	446,000	148,300
Suction diameter, in. I.D.	47	41
Material type, except bearings & seals	304 SS	304 SS

BILL OF MATERIAL		
ITEM	DESCRIPTION	REMARKS
1	CASING	SST CASTING 14,925 LBS
2	DIFFUSER	" 11,255 LBS
3	IMPELLER	" 1,890 LBS
4	CASING ADAPTOR	" 2,195 LBS
5	RADIAL BEARING	SST FORG 1,410 LBS
6	SHAFT (CENTER)	SST PIPE 8,200 LBS
7	LABYRINTH SEAL	SST FORG 235 LBS
8	JOURNAL	CARBIDE OR STELLITE 365 LBS
9	BRG INSERT	" 20 LBS
10	DIFFUSER NOZZLE	SST CASTING 8,500 LBS
11	SUPPORT SLEEVE	SST PLATE 9,140 LBS
12	PUMP TANK	SST PLATE 18,300 LBS
13	IMPELLER RETAINER	SST FORG 450 LBS
14	LABYRINTH SUPPORT	SST PIPE 460 LBS
15	LABYRINTH RING	SST PLATE 90 LBS
16	OUTLET NOZZLE	SST CASTING 2,800 LBS
17	HEAT SHIELD	SST SHEET 1140 LBS
18	TANK FLANGE	SST FORG 520 LBS
19	SUPPORT SKV FLG	SST FORG 5,140 LBS
20	THRUST RUN HSG	C'STL FORG 3,830 LBS
21	UPR RADIAL BRG	C'STL WITH BABBITT LINING 7,200 LBS
22	THRUST RUNNER	SST FORG 1690 LBS
23	UPR RADIAL BRG	C'STL WITH BABBITT LINING 900 LBS
24	SHAFT (LOWER)	SST " 1,770 LBS
25	SHAFT (UPPER)	" " 1,290 LBS
26	THRUST SHOE	BABBITT 600 LBS
27	MAIN LINK	SST FORG 600 LBS
28	SECONDARY LINK	" " 600 LBS
29	COOLING COILS-OIL	SST TUBING 500 LBS
30	#1 SEAL RUNNER	SST FORG 12 LBS
31	#2 SEAL RUNNER	" " 12 LBS
32	#3 SEAL RUNNER	" " 12 LBS
33	#1 SEAL	" " 4 LBS
34	#2 SEAL	" " 4 LBS
35	#3 SEAL	" " 4 LBS
36	SEAL HOUSING	SST FORG 130 LBS
37	SEAL HOUSING	SST FORG 60 LBS
38	#1 SEAL SUPPORT	SST PLATE 40 LBS
39	#2 SEAL SUPPORT	SST PLATE 12 LBS
40	#3 SEAL SUPPORT	SST PLATE 16 LBS
41	SEAL ASSY SUPPORT	SST PLATE 870 LBS
42	LWR SLEEVE	SST PIPE 1 LB
43	CENTER SLEEVE	" " 7 LBS
44	UPR SLEEVE	" " 7 LBS
45	LOCKNUT	SKE 6 LBS
46	LOCKNUT	SKE 25 LBS
47	COUPLING	C'STL CAST 445 LBS
48	MOTOR SUPPORT	CARBON STL 5,100 LBS
49	LABYRINTH SEAL	SST 3 LBS
50	MOTOR	35,000 LBS
51	RADIAL BAFFLES	SST SH 185 LBS
52	VERTICAL BAFFLES	" " 290 LBS
TOTAL WEIGHT (APPROX)		148,300 LBS.

Figure 11. Secondary Sodium Pump Conceptual Design

vicinity of the shaft at the sodium surface. Circumferential baffles are included in the gas/vapor portion of the pump tank to limit splashing and travel of sodium and sodium vapor. Shielding is provided by filling two fabricated tank areas with concrete and/or other shielding materials to form a plug at the floor level. One step is provided at the I.D. and O.D. of the plug to prevent radiation streaming. The tubular shaft is sized for a first lateral critical speed 1.2 times the maximum running rpm.

The lower radial bearing is a sodium-lubricated hydrostatic bearing. The selection of bearing type, and actual bearing design would be based on a development and test program. The upper radial and thrust bearing is a conventional oil-lubricated bearing located above the multiple shaft seals in a normal environment.

The shaft seal shown consists of three separate bellows-loaded sealing surfaces. This system employs clean argon gas as barrier gas to prevent leakage of contaminated blanket gas. Two of the bellows seals form the barrier chamber, into which clean gas is introduced. In-leakage from this chamber enters the pump tank. Out-leakage is collected in a leak-off chamber created by the third bellows seal.

Although no check valve is shown in the design, a nominal 48 in. diameter integral, centerguided, check valve could be incorporated in the pump casing suction nozzle. The main function of such a valve would be to restrict backflow through the pump casing in the event of pump shutdown. The design consists of an auxiliary supported spring-loaded poppet valve. The valve remains slightly open to allow natural circulation when the motor is stopped. Upon attempted reversal of flow, the disc seats on the lower surface of the casing nozzle. By-pass slots may be provided on the casing to supply a small amount of reverse flow, if required.

Secondary Sodium Pump

As shown in Figure 11, the secondary pump consists of an axial flow pump, driven by a 3200 SHP, 600 rpm, wound rotor, induction motor. The pump impeller casing, shaft, and bearing assembly are designed for withdrawal from the pump tank. The sodium level in the pump tank is maintained by a feedline to the surge tank, and bleed from the pump discharge. The level is determined by the leakage rate through the upper casing to the shaft labyrinth seal and the leakage past the casing to the tank static seal. Radial baffling is provided in the vicinity of the shaft at the sodium surface. Circumferential baffles are shown in the gas/vapor portion of the pump tank to limit splashing and travel of sodium and sodium vapor. A series of thermal baffles are provided at the top of the pump tank to limit heat transfer into the shaft seal area. The tubular shaft is sized for a first lateral critical speed 1.2 times the maximum running rpm.

The lower radial bearing is shown as a sodium lubricated plain journal bearing. However, a pivoted pad bearing or a hydrostatic bearing may be selected pending the results of a development and test program. The upper radial and thrust bearing is a conventional oil lubricated bearing, since location above the multiple shaft seals is in a normal environment.

Pump Drives

To provide drives having continuously adjustable speed control, wound-rotor induction motors are presented herein for determining cost and space requirements. However, in the event of extension of this study, Westinghouse suggests a review of the type of drive, including the speed control system. The motors presented are based upon 3-phase, 60 cycle, 4000-volt supply, a speed range as great as 2.5 to 1, and no extra inertia requirement. Class B Thermalastic Epoxy insulation is used, for operation with a 70°C rise in an ambient temperature not exceeding 50°C. The bearings are oil lubricated, and the thrust

bearing is rated to carry the weight of the motor rotating parts. Pump thrust will be carried by the upper conventional Kingsbury thrust bearings. Cooling will be required for the motor thrust and upper guide bearings. If the motors finally adopted for the drive require carbon brushes, an enclosure with forced ventilation for collecting and filtering brush dust will be incorporated in each motor or each group of motors to suit the installation arrangement.

Instrumentation and protective circuit components for the motors can be provided as required to fit utility practice such as temperature detectors in windings, bearings, oil, and air; extra leads for differential protection, integral mounting of neutral current transformers; and oil level switches.

10. SECONDARY SODIUM AUXILIARY SYSTEMS

Sodium Service System

Sodium service facilities are provided for filling and draining the secondary sodium heat transfer system, and for purification of the sodium coolant as presented in Figure 12. Identical facilities are provided for each of the six individual loops that comprise the secondary sodium heat transfer system. The service facilities include means for receiving and storing new sodium coolant, and for purification of the sodium when transferring to the heat transfer systems from the storage facilities. The system is also capable of individually filling and draining the sodium coolant from each loop of the secondary sodium heat transfer system, and continuously purifying the sodium coolant during operation.

Sodium for the secondary heat transfer system is received by three 220,000 gallon storage and fill tanks. Transfer of sodium from the storage and fill tanks to the secondary system may be accomplished either by pumping with the 100 gpm electromagnetic pumps, or by gas pressure. During the filling operation, cover gas in the system is equalized through interconnecting gas equalization lines. Excess gas escapes to the vent system through vapor traps. The sodium is transferred to the system until the steam generators are filled to a predetermined level. Expansion of sodium during heating of the system is accommodated in the steam generators and the attached expansion tanks.

The three secondary system storage and fill tanks are located in unshielded areas of the three secondary heat transfer system buildings adjacent to the reactor building. Each tank handles the sodium from the two secondary loops located in its building. Sodium may be drained from each of the loops to their respective fill and

storage tanks by either gas pressure or service pumps. The secondary service system also contains three 600 gallon drain tanks located in their respective areas to permit final draining and/or isolation of limited quantities of sodium as might be required during maintenance.

Purification equipment in the sodium service system functions to remove impurities from the sodium. Circulating cold traps and plugging meter assemblies are provided. The cold traps remove sodium oxides and other impurities from the sodium. Before entering the cold trap the sodium is precooled in a regenerative heat exchanger. On entering the cold trap the sodium is further cooled. The sodium then enters a portion of the cold trap which is packed with a stainless steel wire mesh. There the velocity is decreased and the oxides and other impurities, that have precipitated out due to the decreased temperature, will collect.

The purified sodium then leaves the cold trap and flows back through the regenerative heat exchanger where it is reheated and returned to its source. To prevent solidification of sodium, the cold trap temperature is kept above 250°F except when it is shut down. The entire cold trap can be replaced when saturated with oxide. Each loop in the secondary heat transfer system is equipped with a cold trap. A standby cold trap is provided in parallel to each two operating cold traps. In this way a cold trap can be replaced without interruption of the cold trapping operation.

Plugging indicators are provided to determine the oxide content of the sodium. As the sodium enters the plugging indicator assembly it is cooled in a heat exchanger. As the sodium is cooled, the temperature is recorded to determine the point at which the oxides or other material begin to precipitate out and plug an orifice plate in the indicator. Oxide concentration is determined by comparing

the plugging temperature with a plot of the saturation temperature for sodium oxide in sodium. Normally a small flow of sodium is maintained through the plugging indicator when it is not being used for measurements. Three plugging indicators are used, one for each two secondary heat transfer loops.

The piping and valving for the purification facilities of the secondary sodium service system are arranged so that sodium from either the fill and storage tanks or the main systems can be purified. This enables purification of sodium prior to the initial filling of the systems, purification of makeup prior to its introduction to the heat transfer systems, purification of stored sodium, and purification of sodium in the main heat transfer systems. Cold trapping of a filled heat transfer system is done by tapping a small sodium stream from the discharge side of the circulation pumps, sending it through the cold traps, and returning it to the heat transfer system on the suction side of the pump.

The purification facilities of the secondary sodium service system are located in unshielded areas of the three secondary heat transfer system buildings adjacent to the reactor building. The equipment list is presented in Table 7.

Auxiliary Coolant System

An auxiliary Sodium-Potassium alloy (NaK) cooling system is provided for cooling duty in the secondary sodium service system as presented in Figure 13. The use of NaK for sodium cooling results in good heat transfer properties and at the same time eliminates the possibility of reaction between coolants which would be present if water was used.

Table 7. Sodium Service System Equipment List

- 1) Fill Tanks (3) 220,000 gal.
- 2) Drain Tanks (3) 80 ft³
- 3) Service E.M. Pumps (6) 100 gpm 100 ft. head
- 4) Cold Trap Regenerative Heat Exchangers (6) $Q = 1,360,000$ BTU/hr
- 5)   Tube - $T_{in} = 620^{\circ}\text{F}$ $T_{out} = 400^{\circ}\text{F}$
          Shell - $T_{in} = 250^{\circ}\text{F}$ $T_{out} = 470^{\circ}\text{F}$
- 5) Cold Traps (9) 225 gal. $Q = 955,000$ BTU/hr
           $T_{in} = 400^{\circ}\text{F}$ $T_{out} = 250^{\circ}\text{F}$
- 6) Plugging Meter Assembly (incl. flow control) (3) $Q = 52,600$ BTU/hr
           $T_{in} = 620^{\circ}\text{F}$ $T_{out} = 250^{\circ}\text{F}$
- 7) Expansion Tanks (6) 1,250 gal.
- 8) Separators (6)
- 9) Freeze Traps (21)
- 10) Vapor Traps (9)
- 11) Valves
- 12) Piping
- 13) I & C

Figure 13. Auxiliary Coolant Systems

E. D. SK. 313331-C

1 CHANGE		DPTL. CASSADY CHG. P. M. Cassady DES. ENG. P. M. Cassady MFG. ENG. P. M. Cassady HTLS. ENG. P. M. Cassady APP. P. M. Cassady DPTG. SUPV. P. M. Cassady	WESTINGHOUSE ELECTRIC CORPORATION ATOMIC POWER DIV., PITTSBURGH, PA., U.S.A. TITLE Na K COOLANT SYSTEM SCALE ED SK 313331-C DIMENSIONS IN INCHES DO NOT SCALE SUB 1

The primary function of the NaK auxiliary coolant system is for cold trap cooling. To cool the sodium entering the cold traps, NaK coolant flows through a jacket around the cold trap. The NaK coolant supplied to the cold traps is pumped by two 150 gpm electromagnetic (EM) type pumps which are connected in parallel. The total heat load of the cold traps is 5.73×10^6 BTU/hr. The heat picked up from the cold traps is rejected to the atmosphere in an air-cooled heat exchanger. An expansion tank is provided to accommodate coolant expansion during operation.

The NaK auxiliary coolant system is provided with service facilities and equipment. NaK coolant enters the system from a fill station, through a filter and then into a 1200 gallon supply and storage tank. NaK is transferred from this tank to the coolant system by gas pressure. A diffusion cold trap is supplied to keep the impurity level of the NaK low.

The primary sodium system has a NaK auxiliary coolant system associated with it, that is very similar to this system. These two systems could be combined into one NaK auxiliary system. The equipment list for the system is presented in Table 8.

Cover Gas System

The cover gas system provides a protective inert atmosphere for the sodium coolant. The inert cover gas selected for use in this reactor is argon. This system includes equipment for receiving, storing, purifying and distributing the cover gas.

In the secondary sodium system, the cover gas system maintains an inert gas blanket in all equipment and piping of the secondary heat transfer loops, and their associated service and auxiliary systems, where a free surface of sodium exists. The system is

Table 8. Auxiliary Coolant System Equipment List

- 1) Supply Tank 1200 gal.
- 2) Fill Station
- 3) Filter
- 4) EM Pumps (2) 150 gpm
- 5) Air Cooler Q = 5,730,000 BTU/hr
- 6) Expansion Tank 70 gal.
- 7) Diffusion Cold Trap
- 8) Vapor Trap
- 9) Valves
- 10) Piping
- 11) I & C

designed to maintain the constant gas pressures required in the secondary system and its associated auxiliaries. The inert gas is also utilized as the displacement gas during some of the sodium draining, filling, and transferring operations.

Since the primary sodium coolant also requires a system for supplying inert cover gas, it has been assumed that its receiving, storing, and purifying facilities would also serve for gas to be supplied to the secondary system. Therefore only distribution supply lines and flow regulating equipment has been included in the secondary auxiliary systems design. Instruments are provided in the cover gas supply lines to monitor the gas usage. In addition to supply lines, components are connected with equalization lines where necessary.

As in the cover gas supply system both primary and secondary sodium systems require gas venting and disposal equipment. It was, therefore, assumed again that the facilities supplied for the primary system would also serve for the secondary system. Because of this, only vent lines and flow regulating equipment have been included in the secondary systems design. All vents for gases that are in contact with sodium have vapor traps in them to remove sodium vapor prior to entering the gaseous vent and disposal system.

Shown in Table 9 is a summary of system gas volumes from the secondary heat transfer and auxiliary systems. From this list the amounts of inert cover gas needed for the systems, when being filled, when filled but non-operational, and when operational, can be determined.

Table 9. System Gas Volumes

1. Auxiliary system empty	91,130 ft ³
2. Auxiliary system full	8,370 ft ³
3. Auxiliary system during secondary system operation	64,380 ft ³
4. Loop system empty	78,130 ft ³
5. Loop system operating	16,450 ft ³
6. Total system operating	80,830 ft ³
7. NaK system empty	270 ft ³
8. NaK system operating	150 ft ³

Preheating System for Secondary Sodium

Prior to admitting sodium, all sodium systems are preheated to 400°F. This insures that the liquid sodium admitted to the systems will remain molten and circulate freely to all pipes, tanks and other related equipment. In addition, some equipment is continuously or intermittently heated during operation.

Electric resistance or induction heating is utilized for virtually all components and piping. Wherever practical, sodium piping is heated by electrical induction heating. In areas where induction heating is not practical, resistance heating units are employed. These units are either the tubular type or the clamp on strip type, depending upon location and configuration. Tubular heaters are employed for heating tanks. Other components are provided with resistance heaters as required for their proper functional operation. The electrical heating system is automatically controlled by means of scanning type recorder controllers located in the control room. Each controller will incorporate an over-temperature alarm connected to an annunciator.

The steam generator is heated internally with preheated pressurized water or steam. Shell heating is accomplished with electrical heaters.

Secondary Plant Control System

One possible secondary plant control philosophy is illustrated in the simplified control block diagram, Figure 14. The final secondary plant control system design would necessarily depend upon the design of the overall plant, nuclear, and primary plant control system, into which it would be tied.

Figure 14. SECONDARY PLANT CONTROL SYSTEM

The secondary plant control system consists of secondary loop pump control, steam generator, and steam reheater controls. The feedwater control system, as illustrated in Figure 14, depicts a once-through superheat steam generator and a separate live steam reheater. In addition, a side-stream differential temperature limiting flow circuit has been provided to limit the maximum allowable differential temperature between the steam generator outlet sodium and feedwater inlet temperatures. The proper temperature differential will be maintained by controlled sodium bypass flow around the steam generator.

The secondary loop pump speed is controlled on the basis of the secondary loop cold leg temperature. The cold leg temperature controller receives its set point from the steam plant load versus steam temperature and pressure programmer. The programmer provides reduced temperature set points for plant loads below 50% capacity.

The steam generator superheated steam outlet temperature is controlled from steam pressure and feedwater flow. The load versus steam temperature and pressure programmer senses steam temperature and plant load to calculate control set points for feedwater flow, steam pressure, and reheater temperature. By controlling feedwater flow, and steam pressure with respect to plant load, and secondary sodium flow and temperature, superheated steam temperature is controlled.

Steam pressure to the turbine is controlled to follow a plant load program below 50% plant capacity. Above 50% plant capacity, steam pressure is controlled at a constant value. The steam pressure controller receives a calculated set point from the load versus temperature and pressure programmer.

The steam power plant utilizes a reheat cycle turbine with a live steam heated reheater. Reheat steam temperature is controlled by throttling live steam flow from the steam generator to the reheater unit. The reheat temperature controller receives a programmed temperature set point from the load versus temperature and pressure programmer.

Feedwater control for the once-through superheat boiler is accomplished by flow control based on a calculated set point determined by the load versus temperature and pressure programmer.

11. OPERATION AND MAINTENANCE OF STEAM GENERATORS

Startup System

In order to bring the once-through type steam generating system used in this plant into service, an auxiliary startup system is required. The latter system is an integral portion of the turbine and feedwater plants; however, it is essential for startup with the once-through steam generator and a brief description is presented here.

The main function of the startup system is to protect the steam generating system and the turbine from abnormal temperatures and operating conditions. The basic system, as shown in Figure 15, is composed of:

- a) Turbine bypass lines to condenser, with valves.
- b) Flash tank.
- c) Flash tank drain lines to condenser and to feedwater train, with valves.
- d) Steam lines from flash tanks to condenser, feedwater train, and turbine gland seal system, with valves.
- e) Attemperator located in the turbine bypass line.
- f) Steam bypass and feed lines for reheaters.
- g) Electric motor driven startup feedwater pump.
- h) Balance of necessary valves, piping and controls to complete the system.

The method for bringing this system to power from a cold start involves the use of the preheating system for initial heat-up and then nuclear power. Prior to startup, sodium is circulated slowly at 400°F in the primary loop while the secondary loop is empty. The secondary loop is then heated by the preheating system. The steam generator is heated internally by pressurized water, while the shell is heated by electric heaters at a matched rate. When the

Figure 15. Startup System for Sodium Steam Generator

secondary system is heated to 400°F, the loop is filled with sodium of adequate purity and circulation is established at minimum flow. After increasing sodium circulation to about 15% full load for a loop, further heating is provided by the reactor. Feedwater flowing to the steam generator during this process is delivered by electrically driven startup pumps at pressure and approximately 15% full load. The water, which is gradually warmed by the steam generator, bypasses the turbine and is let down via a group of control valves to flash tanks. Steam separated in the flash tank is utilized in the initial heating of feedwater and in the provision of steam for the turbine gland seals. Excess steam and condensate are returned to the turbine condensers where the feedwater cycle begins again. The use of flash tanks and a startup turbine bypass flow path also serves to protect the turbine and steam equipment during periods when flashing water or wet steam are produced during the start from cold conditions. When proper conditions are reached, the turbine is first preheated, then the startup system is shut off, and finally the turbine is put on line.

Operation

During normal operation, the steam generators are under fully automatic control. The control system and its operation are discussed under Secondary Plant Control system.

The cover gas in the steam generator is continuously monitored for hydrogen concentration and pressure. A high concentration of hydrogen or a rapid increase in pressure would automatically trip out the feedwater pump and simultaneously open a fast acting blow-down valve to clear the generator of steam and water. The primary pump for the same loop would be tripped off. A detailed study of the secondary loop behavior is required to define the action to be taken. One course of action is to trip the secondary pump off

and dump the sodium. The alternate is to reduce the secondary pump speed to minimum and continue to operate the loop cleanup system. This latter course of action minimizes the effects of corrosion by dilution and removal of the Na_2O and NaOH .

The choice of a once-through steam generator places unique and demanding requirements upon the associated feedwater treatment system. The ability to obtain reliable and long life operation in such a steam generator is directly related to the operational success of the feedwater treatment cycle. In once-through steam generators there is a risk that solids entering the unit with feedwater will foul heat transfer surfaces or precipitate on turbine blades. For this reason, feedwater quality must be maintained at an exceptionally high level.

Repair of Steam Generators

If one or more tubes should leak they can be isolated from the rest of the tubes by plugging. Under optimum conditions, it might take two weeks to plug a few tubes. The actual steps would be as follows:

1. Isolate water and steam lines.
2. Drain water and sodium into respective tanks.
3. Cool down. Insulation removal or a gas heat exchanger would help.
4. Expose headers, one bank at a time.
5. Pressurize shell side and identify leaky tubes.
6. Plug failed tubes.
7. Inspect plug repair.
8. Reconnect lines.
9. Add water to tubes.
10. Cold hydrostatic test.
11. Hot hydrostatic test.
12. Add sodium.
13. Bring to operating conditions.
14. Check for leaks.

Location of small size leaks in the tubes of the large steam generator bundle can be very difficult. There are several possible tests that can be used to identify leaking tubes including hydrostatic testing, helium leak testing, bubble testing and weld inspection testing. In the hydrostatic test the tube side of the steam generator is pressurized at temperature and the tubes are inspected for leaking water. The steam generator shell is pressurized with helium in the helium leak test, and the tubes are individually checked for helium leakage. The bubble test uses hot water in the tubes of the steam generator and nitrogen under pressure in the shell. Tubes are checked for bubbles of nitrogen to locate leaks. Since, a great number of the small leaks in steam generators occur where the tubes are welded to the tube sheet, conventional weld inspection tests, such as zyglo etc., may be used for leak detection in this area. As was stated previously, small leaks can be very difficult to determine, and more than one or all of these tests may be necessary to locate any leaks.

In the unlikely event that a whole bundle requires replacement, a major operation is involved. The removal of a complete bundle under ideal conditions might take several months. During the detailed design of the unit, the sequence of operations to perform this task will be reviewed and appropriate provisions made to facilitate bundle removal. For the design concept presented in this report, bundle removal involves cutting the outer shell section, baffles, and water and steam headers and pulling the bundle out through the side. Although this may be too involved an operation to ever be carried out, advantages are gained in the areas of tube support and baffling with this design.

An alternate design was considered for the sodium connections, and the water/steam connections. If the steam lines were terminated in the top dome, and the water lines in the bottom dome, then it might be possible to disconnect the water headers, unbolt the top head, and pull the top head and all bundles from the shell. The sodium inlet lines would have to be split into four separate inlets and rerouted. There are some pro-

blems with tube support and baffling near the top header but the general concept shows promise.

During steam generator repair operations the unaffected loops will continue to operate. Turbines that have both steam generators operating will continue to operate at full load, while turbines that have one steam generator shut down and isolated will operate at a reduced load. This procedure will minimize the effect of steam generator repair on plant availability.

To minimize the effect of replacement of a whole bundle on the plant availability, another procedure may be followed. This procedure involves having a spare steam generator available at all times. When a steam generator requires bundle replacement or time consuming repairs, it is shut down and isolated. Following this it is removed from the system, and the spare steam generator is installed in its place. The plant can then be returned to normal full load operation, and the maintenance work on the steam generator, that was removed from service, can proceed simultaneously. This procedure allows maximum plant availability for the economic penalty involved in having a spare steam generator.

Sodium Water Reaction

Extreme care must be exercised in the detailed design and manufacture of the steam generator to assure integrity and reliability. Even though leakage of water or steam into the sodium is unlikely, such a situation could lead to corrosion or even violent chemical reaction, and the consequences of such a possibility must be considered and dealt with. The products of a sodium-water reaction (in excess sodium) at high temperature are mainly hydrogen and sodium oxide. If a small leak occurs the first indication is based on the increase of hydrogen in the cover gas over the sodium. A gas chromatograph, tuned to hydrogen, is normally used for this purpose. A small leak could also cause the formation of hydrides and oxides in the sodium. A plugging meter would detect small increases

of these impurities. However, the warning would not be prompt because the sodium flow cycle is usually a few minutes, and plugging runs are not normally made continuously. A meter for hydrogen in sodium, a meter for oxygen in sodium, and a resistivity meter for impurities in sodium have all been considered as in-line monitors. However, these are in the development stage and are not proven at this time.

A large water or steam leak within the steam generator would be detected by a sharp increase of the cover gas pressure, and probably the sodium level would rise. The steam generator shell is protected by an inert gas surge volume over the sodium along with a suitable rupture disc which will burst to relieve excess pressure. Located after the rupture disc is a separator, which is used, when the disc bursts, to retain the solid sodium-water reaction products and pass gas reaction products to the atmosphere. A rubber diaphragm is used on the separator exhaust to maintain a nitrogen atmosphere between it and the rupture disc.

The relief device for the preliminary steam generator design is simply shown as a rupture disc at the top of the shell. Progressive failures from tube to tube would be restricted to one of the six sections of the proposed generator because of the compartment walls. During the detailed design of this steam generator, the initiation, propagation, and effects of a large sodium-water reaction will be considered. The pressure relief system will be designed such that the largest credible reaction can be handled without failure of the shell. Steps will be taken to minimize the possibilities for propagation of the reaction through the rupture of adjacent tubes. Where required, experimental programs will be carried out to verify the results of a design analysis.

12. EQUIPMENT COST DATA

A fundamental factor in determining the cost of equipment is the level of manufacturing experience at the time. A review of various United States Atomic Energy Commission's public announcements indicates that a 300 to 350 MWe prototype plant should be in operation around 1972 or 1973. This could lead to the completion of a 1000 MWe commercial plant by about 1980. Probably several more plants of this nature would be built and operating before the design of the VLFBR plant was frozen. As a result of the research and development and operation of the 1000 MWe commercial plant, the design concepts of the major equipment and systems would be firmly established. Actual costs would be known for loops of approximately half the capacity of that required for the VLFBR. At that time accurate cost estimates could be made. The cost estimates prepared for this study are based upon the assumptions that one or more 1000 MWe plants have been successfully operated and that they have had equipment designs consistent with that of the proposed VLFBR equipment designs.

The costs presented here are engineering estimates based entirely on conceptual designs. All estimates are based on 1965 dollars at current material and labor rates. Major equipment costs were estimated by the Westinghouse Divisions who normally design, manufacture and sell a similar class of components.

The installation costs were estimated by the Nuclear Power Service Department of Westinghouse Atomic Power Division. This group is responsible for the inspection and acceptance of all commercial nuclear power plant work contracted by Westinghouse.

The cost of the following items are not included in the estimates:

1. Plant and system engineering.
2. Architect-engineering.
3. Building structures.

4. Equipment foundations.
5. Interest during construction.
6. Prime contractor's G&A, overhead, and profit.

Since the price estimates are based primarily on conceptual designs of equipment, they have an appreciable uncertainty. We have applied a 20% increase to equipment prices (exclusive of motors at 5%) and a 10% increase to installation costs to arrive at a high estimate price. The true uncertainty is different for different items, but no definitive data was developed in this study. Therefore, the 20%, 10%, and 5% margins have been chosen to give identification to the probable total uncertainty.

In addition to the general factors mentioned above, a special steam generator uncertainty allowance has been made which is discussed in that section below.

Intermediate Heat Exchanger and Sodium Steam Generator

The basis for the conceptual design of these units was provided by the Heat Transfer Apparatus Group of Westinghouse Steam Divisions. This group designs, manufactures and sells major heat transfer apparatus for nuclear as well as fossil-fired power plants. The price is estimated on a commercial basis and includes material, labor, tooling, detail engineering, inspection and engineering shop follow to construct the twelve units. Not included are optimization studies, performance testing, or research and development work.

The price given for the steam generators presumes that the important features of the design described in Section 13 will be verified. If, for example, the tubing material were not as satisfactory as anticipated, it might be necessary to fall back upon the use of two different tube materials. This probably would necessitate doubling the number of tube sheets and headers. If the lower tube sheets cannot be submerged in sodium, then a significant fraction of additional tube length will be added to permit

the tube-sheets to be located in the cover gas space, and special provisions for draining the tubes may be required. If these and/or other detail of design and fabrication which make drastic changes in the concept were to become requirements, the price of the units would increase significantly. To cover these possibilities, which cannot be defined quantitatively from the present state of technology, a special steam generator allowance has been made which amounts to 50% of the high estimate.

The installation costs include material, labor at \$7.00/hr., support structure and insulation.

Primary and Secondary Sodium Pumps and Center-Guided Check Valve

The conceptual design of these units was performed by Westinghouse's Atomic Equipment Division (WAED). This group builds pumps for all Westinghouse commercial nuclear power plants and for the U.S. Naval Reactor Program. WAED has designed and built special-purpose sodium pumps. The price is estimated on a commercial basis, and includes material, labor, tooling, detail engineering, inspection, and engineering shop follow to construct the twelve units. Not included are optimization studies, performance testing or research and development work. The installation costs include material, labor at \$7.00/hr., support structures, and insulation.

Secondary Sodium Piping

This system was designed and cost estimated by the Advanced Systems Section of WAPD. Straight pipe was estimated at \$1.25/lb and elbows at \$2.00/lb. Shop welding was estimated to be an additional 15% of the cost.

Installation costs include material, labor at \$7.00/hr., pipe hangers and insulation. The costs of reactor building penetrations and piping expansions bellows are not included. Heat tracing is included in the auxiliary systems cost.

Auxiliary Systems

These systems were designed and the cost estimated by the Advanced Systems Section of WAPD on the basis of past cost data for similar equipment. The engineers responsible for this had worked with United Engineers and Constructors on the conceptual design and cost of a similar plant of 200 MWe capacity.

Cost Summary

Based upon the above data, costs to the utility of the installed equipment are presented in Table 10. The results show that the estimated installed cost to a utility of the primary sodium pumps, secondary sodium system including pumps, IHX and SG and secondary sodium auxiliary systems is in the range of 13.00 to 15.40 \$/Kwe, with an extreme of 18.80 \$/Kwe. Excluded from the above are system and plant engineering, buildings, foundations, interest during construction, and prime contractor G&A, overhead, and profit.

TABLE 10

COST SUMMARY

Item	Cost, \$1000					
	Estimate			High Estimate		
	Equipment	Installation	Total	Equipment	Installation	Total
1. Intermediate Heat Exchangers	10,800	230	11,030	12,960	250	13,210
2. Sodium Heated Steam Generators*	22,000	250	22,250	26,400	280	26,680
3. Primary Sodium Pumps	5,430	80	5,510	6,520	90	6,610
4. Primary Sodium Pump Drive Motors & Liquid Rheostats	2,880	20	2,900	3,020	20	3,040
5. Primary Sodium Pump Centerguided Check Valves	300	---	300	360	---	360
6. Secondary Sodium Pumps	3,260	60	3,320	3,910	70	3,980
7. Secondary Sodium Pump Drive Motors & Liquid Rheostats	1,030	10	1,040	1,080	10	1,090
8. Secondary Sodium Piping	600	200	800	720	220	940
9. Secondary Sodium Auxiliary Equipment	2,700	760	3,460	3,240	840	4,080
TOTAL COST, \$1000	49,000	1,610	50,610	58,210	1,780	59,990
*Special steam generator contingency				13,200	---	13,200
Extreme Cost, \$1000				71,410	1,780	73,190
Total cost, \$/kwe	13.00					
Total extreme cost, \$/kwe						

13. RESEARCH AND DEVELOPMENT REQUIREMENTS

Introduction

Although the total development program for sodium technology, components and systems is clearly one of considerable difficulty and expense, the total program discussion is quite beyond the scope of this report. This design report assumes the successful completion of the development and the construction and operation of several sodium cooled breeders in size ranges up to 1000 MWe. Of principal interest in this section is the incremental development required to extend the technology from 1000 MWe to 4000 MWe; some tasks in the existing AEC program are mentioned to emphasize possible revisions for meeting the VLFBR design requirements.

Summary of Requirements for the VLFBR Secondary System

In the area of the secondary system, work is presently under way in the development of steam generators and in the investigation of the associated sodium technology and over the indicated period much additional work will be required. However, in reviewing the performance requirements and design features outlined in this report for the secondary system components, it is apparent that, presuming satisfactory completion of a program to develop a 1000 MWe FBR, further development to design, construct and operate the 10,000 MWt plant will be the ordinary manufacturing development necessary for limited scale-up of equipment size. Extrapolations of proven technology by less than a capacity factor of three would be required. This is well within the capability of the manufacturing industry, as demonstrated by the extrapolation of current water reactor technology to the design of plants under construction. The range of extrapolation for important performance characteristics is illustrated in Table 11.

Present design is illustrated by reference to the postulated performance for the Enrico Fermi plant. Although the thermal conditions will not be realized due to subsequent design changes, this example is somewhat repre-

Table 11. Performance Characteristics, Present and Future,
System Components

	<u>Present*</u> <u>Design</u>	<u>Planned**</u> <u>Development</u>	<u>10,000 MWt***</u> <u>Conditions</u>	
<u>Steam Generator</u>				
Heat duty, MWt	143 (nominal)	772	1667	
Steam press., psi	900	2450	2450	
Steam T _{max} , °F	780	1050	900	
Sodium T _{max} , °F	820	1140	1000	
<u>IHX</u>				
Heat duty, MWt	143 (nominal)	833	1667	
T _{max} , °F	900	900-1200	1050	
<u>Pumps</u>				
			<u>pri.</u>	<u>sec.</u>
Flow, gpm	10,000	60,000-120,000	143,000	113,000
Head, ft	350	350	289	105
T _{max}	600	900-1200	1050	620

*Design performance of the Enrico Fermi Plant as reported in APDA-124.

**Steam generator from BW 67-2; IHX estimated; Pumps from recent AEC-RFP.

***As described in this document.

sentative of current state-of-the-art. The features of the AEC program in component development are illustrated by the B&W steam generator development program and by the recent AEC requests for proposals for a pump design study program, and a bearing and seal development program. Schedule estimates for these programs indicate that these size components could be available as early as the first half of the 1970's.

The significant design parameters for the VLFBR are tabulated in the last column of the table. For the heat transfer apparatus, approximately a factor of two increase in heat duty is required beyond the development planned for the 1000 MWe plant. This is somewhat balanced by the lower temperature requirements for the larger unit. The pump flow requirements are near or slightly above the goal in the present AEC program. Again, however, this slight extrapolation in flow is balanced by the much lower head requirement.

The four major areas of the secondary system and the development tasks required for large sodium reactors are discussed below. In Appendix D, the present AEC program as it pertains to development of secondary system components for large sodium reactors is summarized and the details of the required development for large sodium components are presented.

Steam Generator

Although the present active AEC program is directed toward the fabrication and testing of three nominally prototype units in the SCTI, a review of these three design indicates that only one (B&W) holds promise of application for large installations. The complexity of this latter design tends to yield a costly component. The design described for the VLFBR is significantly simpler, hence will be appreciably less expensive to fabricate and should simultaneously exhibit greater reliability. Further, it is deemed to be very prudent that development of a key component such as the steam generator, be pursued on parallel paths, each of which holds promise for ultimate success in either the LFBR or VLFBR plant. It is thus recommended

that a program be initiated and pursued to successful completion to provide the necessary design data for the confident specification of the steam generator outlined in this study. This program would include tasks in (a) Materials Development, (b) Fabrication Development, (c) Design Development, (d) Model Testing, (e) Evaluation of the Sodium-Water Reaction, and (f) Testing of a 30 MWt Prototype.

Intermediate Heat Exchanger (IHX)

Performance of the IHX in several installations has been quite satisfactory. As a result, there does not appear to be a specific AEC program for development in this area. Because of the lack of a large pressure differential across the tubes, the lack of phase change in either fluid, and relaxed materials requirements since sodium is on both sides of the tubes, an approach embodying design review and operational surveillance is recommended. The design of these large units is within the present capabilities of heat transfer engineers. Flow induced vibration in the tubes is a problem which should be investigated for each specific design. At Hallam, initial operation indicated the presence of flow-induced vibrations which were successfully eliminated by the installation of suitable baffling. Further, the evolutionary approach allows for design evaluation at several stages prior to specifying the IHX for the VLFBR.

Pumps

Pump performance to date has been essentially up to expectation with the malfunctions being correctable without total pump replacement. This appears to offer a sound base from which to proceed to the development of larger pumps for future requirements. The AEC is presently initiating a program of pump development which is directed toward design, development, and proof testing of pumps in the 50,000-120,000 gpm flow range. Major features of this program appear to be (a) Large Sodium Pump Design, (b) Bearing and Seal Test Program, and (c) Sodium Pump Test Facility. Although the subsequent tasks in this program are not known, in order to insure an early success in this program, it is recommended that detailed analysis and

possibly some developmental testing be conducted in (a) pump hydraulics, (b) thermal studies, (c) dynamic vibrations analysis, (d) fluid stability studies, (e) mechanical design, (f) materials, (g) electrical design, and (h) instrumentation and control. As noted in the table, successful completion of the presently indicated AEC program with respect to head and flow will effectively encompass the requirements of the VLFBR.

Sodium Technology

In general support of developments in these three component areas (as well as, of course, the entire sodium reactor program) the AEC is conducting a program on what is classified here as Sodium Technology. Topics covered include corrosion, instrumentation, chemical analysis, and purification. The scope of the effort in this area appears to be quite extensive in both depth and breadth. Thus it is assumed that the key development problems will be solved for the LFBR and, hence, for the VLFBR. In any event, there are no unique problems for the VLFBR in this category.

BIBLIOGRAPHY

1. United Engineers and Constructors, Inc., "Engineering Study for Large Steam Electric Generating Units Applied to Argonne Fast Breeder Reactor Studies", November 1964, Vols. 1, 2 & 3. Argonne National Laboratory Contract No. 31-109-38-1717.
2. Babcock & Wilcox Co. Boiler Division, "Preliminary Design Report, Full Size Steam Generator", BW 67-2, July 1, 1964, AEC Contract No. AT(11-1)-1280. With the Chicago Operations Office of the United States Atomic Energy Commission
3. C. C. Randall, et al., "Sodium Pump Development and Pump Test Facility Design", WCAP-2347, August 1963. AEC Contract AT(30-1)-3123. With the New York Operations Office of the United States Atomic Energy Commission.
4. L. E. Efferding and A. A. Bishop, "Review of Liquid Metal Heat Transfer and Pressure Drop", WCAP-4402, October 1963. AEC Contract AT(30-1)-3251. With the New York Operations Office of the United States Atomic Energy Commission.

APPENDIX A

PRELIMINARY ANALYSES DETAILS

Cycle and Steam Conditions Selection

In a plant of the size and type considered here, it is not practicable to optimize cycle and steam conditions at this preliminary stage of development, with a high degree of certainty. Justification for the use of reheat and high throttle steam temperature and pressure should be based primarily on economic gains. Technical considerations, although important, are also reflected by their effect on costs.

In this study, several reasonable alternatives were selected and the relative effect on power cost was estimated. Then, having considered the results in the light of potential reliability effects, an engineering judgment of the preferred cycle was made. The proposed level of effort for the study did not permit, nor would the accuracy of the available cost data justify, a complete optimization study at this time.

The selection of plant cycle and steam conditions was first performed in several separate steps as follows:

1. Decision on whether sodium reheat should be used.
2. Selection of throttle steam pressure.
3. Selection of throttle steam temperature.

Then, based upon a United Engineers and Constructors study of turbine plants for Argonne National Laboratory⁽¹⁾, the economics of steam conditions and cycle alternatives were further estimated. Lastly, the plant heat cycle type was chosen on the basis of the previously selected throttle steam conditions.

Sodium Reheat

The first part of the economic analysis was based upon a USAEC sponsored Westinghouse study of an entirely different type of reactor plant⁽²⁾.

However, two 1000 MWe modern turbine plants were studied with external reheat (in-core) and condensing steam reheat. The relevant plant characteristics are given in Table 1.

Table 1. Turbine Generator Plant Parameters

Item	Sodium Reheat	Condensing Steam Reheat
Throttle steam conditions, psi/°F/°F	3500/1050/1000	3500/1050/CSRH
Net output, MWe	1027	1000
Net heat rate, Btu/kwh	7910	8123
T-G plant capital cost, excluding RH 10^6 \$	45.2	44.7
T-G plant capital cost, \$/kwe	44.00	44.70
Reheater cost, \$/kwe	r	2.30
Steam generator cost, \$/kwe	s	1.08 s

The reactor plants are assumed to be identical for purposes of this analysis. The factors affecting unit power costs are reactor plant, reheater, steam generator, turbine plant costs, and plant heat rate. The affect of these is shown in Table 2, using 7% annual charges and 80% plant factor.

Table 2. Differential Power Cost Comparisons, Sodium Reheat and Condensing Steam Reheat

	Sodium RH	Condensing Steam RH
<u>Capital</u> (7% a.c., & 80% p.f.)		
Reactor plant	.630	.646
Turbine plant	.440	.447
Reheater	.01 r	.023
Steam generator	.01 s	.0114 s
<u>Fuel</u>	<u>.250</u>	<u>.257</u>
Total differential	$1.320 + .01 r + s$	$1.373 + .0114 s$
Relative differential	$.01 r - .0014 s - .053$	0

Figure 1 shows the effect of steam generator and reheater cost on differential power cost. It may be seen that, if the sodium reheater costs \$6/kwe, the apparent economic gain in sodium reheat ranges from .000 to .013 mill/kwh with steam generator prices varying from \$5/kwe to \$15/kwe. The B&W design⁽³⁾ of reheater cost \$4.60/kwe for the equipment alone, however, the reheater transferred only 12% of the plant heat output compared to 20% in the cycle considered here. The apparent economic disadvantage of condensing steam reheat is slight. However, technically, the simplification and improved reliability due to elimination of the sodium reheater is appreciable. Based upon the above it is reasonable to eliminate sodium reheat.

Throttle Steam Pressure

Investigation of plant heat rates with different turbine throttle valve pressures indicated that an improvement of about 250 BTU/kwh could be expected by using 2400 psia throttle steam rather than 1800 psia steam. A further improvement of around 200 Btu/kwh was found if the throttle pressure were raised to 3500 psia.

In comparing several plants in which only the steam throttle pressure changes, the reactor plant and secondary sodium plants would be identical, except for the steam generator. The over-all heat transfer coefficients in four steam generator regions (subcooled, saturated boiling, film boiling and superheat) was analyzed for 2500 psia and 1900 psia average water/steam pressure. The results showed a 5% smaller heat transfer surface required for the higher pressure. This would probably be offset in part by the reduced cost of the lower pressure unit due to the thinner tube wall required. As far as steam generators alone are concerned, there is no discernible cost advantage in going from 2400 psia to 1800 psia throttle steam. It is rather difficult to say whether a 3500 psia steam generator would cost more or less than a 2400 psia unit. For the time being, it will be assumed that they are the same price.

Figure 1. DIFFERENTIAL POWER COST, SODIUM REHEAT STEAM CYCLE
(REF. CONDENSING-STEAM REHEAT CYCLE)

United Engineers and Constructors, Inc. performed a design and cost study of several nominal 500 MWe and 1000 MWe turbine generator plants⁽¹⁾. The output to cost comparison gave a size exponent which varied between 0.80 and 0.90. A larger size exponent was found for the 1800 psia plant. This is partly due to the fact that two separate 500 MWe turbines were used in the 1800 psia, 1000 MWe design, thereby making this plant relatively more expensive. A single turbine design for this plant is now considered feasible. Therefore, it is expected that the 1800 psia plant might not have as great a differential power cost as predicted here.

To establish the effect of pressure only on cost, the United Engineers estimate for the 1800 psia case was revised. In the previous study, the 1800 psia turbine had throttle and reheat temperature of 900°F, while the 2400 and 3500 psia cases had temperatures of 1000°F. The output of an 1800A/1000F/1000F T-G unit was estimated, and the unit cost calculated.

It is now possible to compare the differential power cost of three plants with 1800, 2400, and 3500 psi steam, assuming 7% annual charges and 80% plant factor. These differentials are presented in Table 3. It is seen that 1800 psia throttle steam results in a power cost penalty of .102 mill/kwh, while 3500 psia steam gives a cost advantage of .009 mill. It was decided to set the throttle pressure at 2400 psia thereby obtaining the most significant saving. This is consistent with the present AEC program in which 2400 psia steam is used as the reference pressure.

Table 3. Differential Power Cost for Several
Turbine Throttle Pressures

Differential Power Cost Item	Turbine 1800	Throttle. 2400	Pressure, psia 3500
Primary & secondary plant capitalization (7% A.C., 80% P.F.)	+0.030	0	-.014
Turbine generator plant capitalization	+0.058	0	+0.011
Fuel	.014	0	-.006
Total differential power cost, mill/kwh	.102	0	-.009

Throttle Steam Temperature

Based upon data previously available, it was estimated that a decrease in steam temperature of 100°F would increase the heat rate by 160 Btu/kwh. Calculations were performed relating the intermediate heat exchanger and steam generator surface areas to throttle steam temperature. It was found that an additional 75,000 square feet, or 10% additional heat transfer surface was required for 900°F steam temperature and 20% extra surface for 1000°F steam. This is equivalent to a plant capital cost increase of approximately \$1.00/kw and \$2/kw respectively.

Estimated differential power costs, based upon 7% annual charges and an 80% plant factor, are presented in Table 4, for 800°F, 900°F and 1000°F throttle steam. An estimated .016 mill/kwh power cost saving is achieved in increasing steam temperature by 100°F from 800°F to 900°F.

Table 4. Differential Power Cost for Three Turbine
Steam Throttle Temperatures

Differential Power Cost Item	Turbine Throttle Temp., °F		
	800	900	1000
Primary and secondary plant capitalization (7% A.C., 80% P.F.)	+.014	0	-.009
Secondary plant capitalization due to increased heat transfer surface	-.010	0	+.020
Turbine generator plant capitalization	+.007	0	-.010
Fuel	+.005	0	-.004
Total differential power cost, mill/kwh	.016	0	-.003

Therefore, a 900°F steam temperature was selected as the preferred technical and economic condition. A more detailed analysis could show a more precisely defined minimum, possibly falling between 850°F and 950°F. Since

the variation in power costs is in the thousandths of mills/kwh, such sophistication cannot be justified until equipment design and costs are more firmly established.

Further Cycle Investigation

An additional analysis was made to compare widely different cycle conditions by using turbine plant cost data in the United Engineers Study⁽¹⁾. Table 5 presents the data selected from the above study as well as estimated changes which were made to the heat rate, plant output, and cost for cycle changes. Cycles with live steam reheat replacing sodium reheat were considered; also, cases with 900°F throttle temperature are given.

The unit capital cost for all the above turbine plant cycles was computed by taking into account the size-price exponent computed from the U-E study for nominal 500 MWe and 1000 MWe T-G plant.

The sodium reheater cost was based upon the value derived by B&W⁽³⁾ of $\$4.6 \times 10^6$ for three 29,640 ft² surface units. No cost reduction was taken for size as it was assumed the cost of buildings installation, piping, etc. would cover the saving. There is a steam generator saving in a sodium reheat plant due to the fraction of energy absorbed by the reheater. The steam generator and intermediate heat exchanger price increase when 1000°F steam is produced, due to the increased heat transfer surface required by virtue of the reduced temperature differential. Also, the overall heat transfer coefficients should be reduced because a thicker tube wall is required. Wall thickness increases result from higher temperatures and pressures, however this effect was not taken into account in estimating the steam generator and intermediate heat exchanger price increase shown.

Finally, power costs are shown in Table 5 for the capital items discussed and with a fuel cost of .250 mill/kwh for a net heat rate of 8030 Btu/kwh. For all these plants, the reactor and secondary system are the same, except

Table 5 Comparison of Capital Items and Differential Power Cost for Several Cycles

Throttle Steam, psia Throttle Temp., °F	1800			2400			3500		
	1000/1000	900/900	900/LS	1000/1000	1000/LS	900/LS	1000/1000	1000/LS	900/LS
Net output, MWe		1029.5		1027.2			1028		
Net heat rate, Btu/kwh		8570		8100			7950		
W diff. on U-E heat rate	+170	+170	+170	+130	+130	+130	+80	+80	+80
Diff. due to RH removal			+220		+250	+250		+210	+210
Diff. due to steam temp.	-80					+150			+150
Corrected net heat rate, B/kwh	8660	8740	8960	8230	8480	8630	8030	8240	8390
Thermal rating, MWt	2590	2590	2590	2439	2439	2439	2397	2397	2397
Net output	1020	950	926	1010	980	964	1020	992	976
T-G plant cost, 10 ⁶ \$		49.80		46.20			47.55		
Correction for T-G output	-.10	-.97	-1.26	-.21	-.58	-.70	-.10	-.41	-.65
Increased equipment cost	--	--	+.91	--	+.93	+1.46	--	+1.32	+1.99
Est. T-G plant cost, 10 ⁶	49.70	48.87	49.45	45.99	46.55	46.96	47.45	48.46	48.89
Thermal rating, MWt	10,000								10,000
Net output, MWe	3940	3670	3580	4150	4020	3960	4,250	4140	4070
Price size equipment	.89	.89	.89	.82	.82	.82	.83	.83	.83
T-G plant cost, 10 ⁶ \$	162.0	162.1	164.5	146.8	148.0	148.2	154.8	158.3	159.8
Reheater est. cost, 10 ⁶ \$	19.5	17.5	6.0	19.5	6.0	6.0	21.5	6.0	6.0
Steam gen. saving, 10 ⁶ \$	-2.3	-2.3	--	-2.8	--	--	-2.8	--	--
Steam gen. & IHX increase, 10 ⁶ \$	8.3	--	--	8.3	8.3	--	8.3	8.3	--
Total affected cost, 10 ⁶ \$	187.5	177.3	170.5	171.8	162.3	154.2	181.8	172.6	165.8
Cost, \$/Kwe net	47.50	48.40	47.60	41.40	40.00	39.00	42.80	41.80	40.80
Capital (7% a.c. 80% p.f.) above items, mill, kwh	.475	.484	.476	.414	.404	.390	.428	.418	.408
Capital	.830	.891	.914	.789	.813	.825	.770	.790	.804
Fuel Cost	.270	.290	.297	.256	.264	.268	.250	.257	.261
Estimated Power Cost, mill/kwh	1.575	1.665	1.687	1.459	1.481	1.483	1.448	1.465	1.473
Relative diff. power cost, mill/kwh	.092	.182	.204	-.024	-.002	.000	-.035	-.018	-.010

Figure 2. ESTIMATED DIFFERENTIAL POWER COST VARIATION WITH
SELECTED STEAM CYCLE CONDITIONS

* L S SIGNIFIES LIVE STEAM REHEAT TURBINE CYCLE

for the items noted. However, the power output is different, therefore, capital cost per kilowatt must be considered for this portion. A value of \$63/kw was assumed for the reactor plant, and \$14/kw for the secondary plant (not previously included). The resulting estimated differential power costs are shown in Table 5. These differential costs are plotted on a pressure base as shown in Figure 2 for the three cycle conditions of 900°F throttle steam with live steam reheat (900/LS), 1000°F throttle steam with live steam reheat (1000/LS), and 1000°F throttle steam with 1000°F reheat steam (1000/1000).

Preferred Turbine Cycle and Steam Conditions

The results of the foregoing analyses are graphically summarized in Figure 2. Between 0.1 and 0.2 mill/kwh in power costs is gained by increasing turbine throttle pressure from 1800 to 2400 psia. An estimated gain of between 0.01 and 0.02 mill/kwh might be achieved by raising the pressure from 2400 to 3500 psia. Therefore, the selection of 2400 psia as the throttle steam temperature is entirely reasonable, since no great economic improvement is found here and subsequent detailed design calculations and cost could easily reverse the trend.

A similar argument applies to the selection of 900°F as the throttle steam temperature. Here, the presently estimated gain in raising the temperature from 900°F to 1000°F is only from .003 to .010 mill/kwh.

In rejecting sodium reheat for the plant cycle, the estimated maximum saving lost is between .015 to .020 mill/kwh. It was felt that this small saving might not be achievable in the final design for several reasons, as follows:

1. The above calculations are based on a considerably lower price for steam generators than B&W is currently predicting⁽³⁾.
2. The estimated differential heat rate was on the high side.

3. The reactor plant cost was assumed to be \$63/kw, which is probably high.
4. The steam to steam, live steam reheater was estimated to cost \$1.50/kwe. This is high when the heated steam is practically dry and therefore no integral moisture separation equipment is required.
5. The cost of the additional startup system equipment was neglected.
6. The additional maintenance cost and potential plant reliability reduction, due to the existence of sodium reheaters, has not been quantitatively evaluated.
7. If, at a more detailed stage of design, the overall plant systems indicate a reduced heat rate would improve economics, then this may be achieved by using a greater exhaust turbine annulus area.

The above reasons tend to justify the selection of 2400 psia, 900°F throttle steam. The basis for live steam reheat selection is discussed in the following paragraphs.

Three different turbine cycles based on 2400 psia/900°F throttle steam, without sodium reheat, were considered, and heat balances were performed as a basis for selecting the preferred cycle. In all cases, seven stages of regenerative feedwater heating were employed, resulting in approximately 480°F final feedwater temperature. The computed heat rates include generator losses and boiler feedpump power. The steam expansion lines for the three cycles are presented in Figure 3.

The three cycles are described below:

1. Condensing steam reheat. Exhaust steam, from the high pressure turbine, heats exhaust steam, from the intermediate pressure turbine, in external steam-to-steam

heat exchanger and moisture separation units. The heat rate is 8654 Btu/kwh. This is the highest heat rate of the three cycles considered. Moreover, the terminal temperature difference in the reheater is small, resulting in a large heat transfer surface. Therefore, this cycle was rejected.

2. Moisture separation only. Although there is some internal steam separation, external steam separation between the intermediate pressure and low pressure cylinder is required. Otherwise, the maximum moisture would be above 13%, and excessive blade erosion would occur. This cycle has an estimated heat rate of 8624 Btu/kwh and is close to the lowest of the three. However, this cycle has a major drawback, since the low pressure end steam expands from 75 psia to 1-1/2 in. Hg. Standard design, low pressure, turbine cylinders expand steam from between 150-200 psi to 1-1/2 in. Hg absolute. Thus, removal of several sets of blading would be required, thereby drastically changing the standard low pressure turbine cylinder design. For the purposes of this study, this reason is sufficient to reject this cycle.
3. Live steam reheat. Throttle steam is used to reheat exhaust steam from the intermediate pressure cylinder. A simplified heat balance diagram is presented in Figure 4. The resulting heat rate is 8615 Btu/kwh, the lowest of the three cycles. No moisture separation is required, and, because of the comparatively large steam-to-steam reheater temperature difference, the required heat transfer area is a minimum. This is the preferred steam cycle.

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Figure 4. VLFBR SIMPLIFIED HEAT BALANCE

Three independent tandem compound quadruple flow turbine generators are required. Each turbine-generator unit accepts steam in the high pressure cylinder at 2400 psia/900°F where it expands to 570 psia and 570°F. Expansion in the intermediate pressure cylinder is down to 200 psia and 380°F. This steam is then reheated with live steam to 660°F before the steam enters the quadruple flow low pressure ends, where expansion is down to 1-1/2 in. Hg absolute. Each of the three identical turbine-generator assemblies has an overall length of 211 ft. and a gross output of 1320 MWe. A preliminary turbine-generator outline is presented in Figure 5.

Secondary Sodium Loop

Having selected steam and feedwater conditions for the turbine plant, the secondary sodium system temperatures can be more exactly established.

As the first step, an approximate expression for the sum of the intermediate heat exchanger area and the steam generator area was constructed, using average temperature differences and average heat transfer coefficients. Experience has shown this to be a useful approximation for typical designs. Taking the first derivative with respect to the average intermediate temperature of the total heat transfer surface and equating it to zero, yields an equation defining a unique average intermediate temperature. This value is a first approximation to the average intermediate sodium temperature which results in a minimum total heat transfer surface. The value obtained for the reference conditions is 810°F. Design studies in depth could further refine this value by utilizing more exact heat transfer relationships and by assigning weighting factors to the two kinds of heat transfer surface to reflect their relative costs.

To determine terminal temperatures, several sets of terminal secondary sodium temperatures were assumed, and the resulting heat transfer surface areas were computed. The effect of pumping power and pump cost was approximately evaluated against an estimated cost of heat transfer area. The cost numbers used were approximate, and served primarily to establish that the

TURBINE	
KW	1,320,000
TYPE	TCMF
LAST ROW BLADE LENGTH	52"
STEAM CONDITIONS:	
INITIAL PRESSURE, PSIA	2,400
INITIAL TEMP., FTT	900
REHEAT TEMP., FTT	-
EXHAUST PRESSURE, IN. HG. A.	1.5

GENERATOR	
KVA	1,600,000
POWER FACTOR	0.90
KW	1,320,000
S.C.R.	0.50
GAS PRESSURE, PSIG	75
RPM	1,800

* DIMENSIONS ARE APPROXIMATE

Figure 5. WESTINGHOUSE TURBINE-GENERATOR UNIT PRELIMINARY OUTLINE *

cost versus temperature curve was fairly flat in the vicinity of the minimum. Therefore, temperatures were chosen which made the maximum tube wall temperatures (hence, tube thermal stresses) approximately equal, when allowance was made for film drops and fouling of the water-steam side of the steam generator.

The final temperatures for the intermediate sodium loop are 620°F in the cold leg, and 1000°F in the hot leg. The flow rate is then 298×10^6 lb/hr or 678,000 gpm. Table 6 contains the final system temperatures and flow rates. The temperature profiles through the heat exchangers are plotted in Figure 6.

Table 6. Principal Systems Characteristics

Item	Primary	Secondary	Water/Steam
No. of loops	6	6	6
Heat load, MWt	1667	1667	1667
10^9 Btu/hr	5.69	5.69	5.69
Flow, 10^6 lb/hr	57.2	49.7	6.13
10^3 gpm	143	113	
Maximum bulk temperature, °F	1050	1000	900
Minimum bulk temperature, °F	720	620	480
System pressure drop, psi	90	27	200
Maximum operating pressure, psia	110	110	2600
Piping size, in.	48	42 & 30	
Materials	304 SS	304 SS	316 SS
	316 SS	316 SS	Incoloy 800

Figure 6. SYSTEMS TEMPERATURE DISTRIBUTION

Preferred Number of Loops

In a plant of such large capacity, the number of main loops used has a strong bearing on the economic and technical desirability of the plant. The principal means of achieving economic advantage is through the use of few, large size, reliable components, rather than multiple duplication of currently available small components. In this way, plant reliability may be maintained at a maximum. The component size must not, however, be increased to the point where its cost per unit of capacity does not reduce.

With flow and heat removal of the magnitude specified above, the use of between three and eight loops is the extreme practical. Three, single shaft 1800 rpm turbines-generators of between 1300 and 1400 MWe output are considered feasible by the Westinghouse Steam and Large Rotating Apparatus Divisions.

Hence, from three to eight single shaft machines could be used, but the best economics and reliability for both the turbo-generators and T-G plant would occur with the minimum number of units. With three primary and three secondary loops, unit pump capacities would have to be over 280,000 and 220,000 gpm respectively. Also, the intermediate heat exchangers and steam generators would each require about 100,000 and 150,000 square feet of effective heat transfer surface respectively. To put these capacities in perspective with respect to present planned or anticipated AEC studies and programs, consider the B&W Steam Generator design⁽³⁾ which has an effective heat transfer surface area of about 35,000 square feet. In a Westinghouse sodium pump study⁽⁴⁾ performed for the AEC, flows of around 120,000 gpm in a 3 loop - 1000 MWe plant are predicted.

The above considerations lead to the selection of six as the number of primary and secondary loops, with the steam generators paired to each of three turbo-generators. The main components have the following capacities:

Primary pumps, flow, gpm each	143,000
Secondary pumps, flow, gpm each	113,000
Intermediate heat exchanger, output, MWt	1667
area, ft ²	54,000
Steam generator, output, MWt	1667
area, ft ²	75,500
steam flow, 10 ⁶ lb/hr	6.13

Flow Diagram

A simplified flow diagram of the main systems from reactor to steam generator is presented in Figure 7.

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BIBLIOGRAPHY - APPENDIX A

1. United Engineers and Constructors Inc., "Engineering Study for Large Steam Electric Generating Units Applied to Argonne Fast Breeder Reactor Studies", November 1964, Vols. 1, 2 & 3. Argonne National Laboratory Contract No. 31-109-38-1717.
2. I. M. Keyfitz, et al., "1000 MWe Supercritical Pressure Nuclear Power Plant Design Study", WCAP-2240, and "Detailed Cost Analysis", WCAP-2294, January 1964. AEC Contract AT(30-1)-2948. With the New York Operations Office of the United States Atomic Energy Commission.
3. Babcock & Wilcox Co. Boiler Division, "Preliminary Design Report, Full Size Steam Generator", BW 67-2, July 1, 1964, AEC Contract No. AT(11-1)-1280. With the Chicago Operations Office of the United States Atomic Energy Commission.
4. C. C. Randall, et al., "Sodium Pump Development and Pump Test Facility Design", WCAP-2347, August 1963. AEC Contract AT(30-1)-3123. With the New York Operations Office of the United States Atomic Energy Commission.

APPENDIX B

EVOLUTION OF STEAM GENERATOR DESIGN

This sodium steam generator remains the most crucial single problem of sodium cooled reactor plant designs. A careful evaluation of past successes and failures has been performed in arriving at the conceptual design features of the steam generators for this large future plant.

Previous Development

Starting in 1947 with the Genie-Alpha program⁽³⁾, the design concepts, which could be loosely classified as Phase I designs, were in many cases demonstration units built for development purposes with only secondary consideration given to the economics of such components. The initial design concepts, without the benefit of an existing technology, tended to borrow heavily from conventional boiler and heat exchanger practice but with elaborate precautions taken to guard against the proposed catastrophic effects of a liquid metal-water reaction. Such precautions usually took the form of double tubes with a comparatively inert third fluid, and/or a monitored annulus, between the liquid metal and the water, resulting in double tube sheets and a whole spectrum of design devices to accomodate differential axial thermal expansion. The major development has centered on sodium as the main heating fluid, but work has been carried out with sodium-potassium mixtures, potassium, bismuth (in Liquid Metal Fuel Reactor - LMFRE - program) and lithium. Mercury, NaK, helium and even air have been used in the concentric annulus as the buffer or monitoring fluid. The double tube design was also considered a method of attaining material compatibility with the liquid metal, water and steam environments and demonstrated an ultra-conservative approach to the problems of mass transfer and chloride and caustic stress corrosion.

However, in addition to the severe cost and heat transfer penalties, such elaborations as double tube designs tended to be largely self-defeating. The resulting mechanical complexity invalidated much of the thermal and stress analyses, made fabrication difficult, quality control a challenge and possible repair an exercise in imagination.

Borrowing from conventional boiler practice, earlier designs tended towards the concept of a recirculating evaporator section with a steam separation volume or drum before proceeding to the superheater. Such generators have been built with water on the tube side and the shell side.

The programs which have been undertaken have served to highlight the pertinent characteristics of liquid metal to water heat exchangers and, as may now be claimed, have evolved the basic concepts and criteria of a technology.

Because of early unsatisfactory experience with ferritic materials in high temperature sodium, the austenitic materials were selected for the construction of the earlier units. Operation of test units in the SIR program re-discovered the known problems associated with high thermal stresses and stress corrosion cracking of the austenitic material due to chlorides on the water side.

For the SRE tests conducted in 1957 at Santa Susana, California, a once-through horizontal U-type unit was employed using double tubes with mercury as the monitoring fluid and generating 20 MWt. The generator was of all stainless steel construction and, because of the previous cracking experienced in the SIR program, chloride stress corrosion was avoided by taking extreme care with the water chemistry. To reduce sodium pumping power, no shell side baffling was installed. High sodium conductivity was expected to insure uniform temperature profiles across the 24 inch I.D. shell. This later proved to be an unfortunate assumption.

Operation revealed a large temperature unbalance with higher temperature sodium flowing along the shell top for its entire length. This helped cause and, in turn, was aggravated by water flow and steam temperature unbalances. Water flow unbalance was largely eliminated by the installation of orifices in tube inlets, greatly reducing the sodium side stratification in this design^(3,4).

For the once-through EBR-II steam generator, a straight ferritic double tube design was used with the spaces between the water and sodium tubes and tube sheets open to the atmosphere. For accommodating differential thermal expansion in this design, the unique approach of cold springing all the tubes during fabrication was employed⁽¹⁾. The primary difficulties so far associated with this design have been due to the difficulties associated with welding the original thin walled tubing of the superheater. The superheaters were, in effect, identical to the evaporator units with the tube ends orificed to a 1/8 inch annulus.

The most extensive operating experience on plant size units has been acquired at the Hallam plant. Hallam steam generators⁽⁵⁾ are the natural recirculation type employing re-entrant double walled tubes (bayonet) with sodium in the tubes and steam and water on the shell side. Helium gas is used to monitor the space between the walls of the duplex tubes and between the water and sodium tube sheets. The only difficulty so far experienced with these units has been due to water carryover from the evaporator to the superheater because of variations of water level in the evaporator with load. In order to maintain the water level low enough to prevent carryover, yet high enough to assure covering the upper tubes of the evaporator, it has been necessary to control the water level to within ± 1 inch^(1,6).

The three Fermi units represent the first attempt to design and build once-through forced circulation, single walled steam generators. Ferritic material is employed for all tubing and special characteristics of the design include involute serpentine multiple return bends to accommodate axial differential thermal expansion between the shell and the tubes, both tube sheets located in the gas space and a large (150 ft³) gas volume and rupture disc relief system. Test operation resulted in re-tubing of the No. 2 unit.

The initial leaking of the No. 2 unit was again due to stress corrosion cracking at the tube bends, attributed to residual (sodium hydroxide and sodium nitrate) cleaning solution left in the tube bends. After approximately two weeks of isothermal operation, the first unit experienced a sodium water reaction believed to be caused by vibrational erosion damage of the tubes near the sodium inlet connection. In addition to the vibrational erosion damage, a number of tubes exhibited pressure rupture in the vicinity of the sodium water reaction due to a local thinning of the tube walls caused by rapid caustic corrosion. In subsequent tests, it was not possible to duplicate the rates of corrosion which must have occurred in these tube walls during the water leak into the sodium. The problems associated with the Fermi generators have been avoidable design and operating errors and should not be interpreted as an inherent defect in the once-through, single-walled concept.

Other significant work in the development of steam generators has included APDA work in 1956-57 with a 1 MW oil fired NaK facility on the B&W once-through single wall, horizontal "U" shell model and a vertical Alco bayonet tube recirculating unit. Also, the continuing APDA work first on the NaK-water reaction, and later on the sodium-water reaction, was a necessary preliminary step to constructing the single-walled Fermi units.

The development work done during the period 1947-1963 has evolved a general philosophy of steam generator design which is reflected in the current prototypes to be tested in the SCTI loop under AEC contract. As early as 1954, an APDA study showed the superior economic potential of the single-wall tube, once-through forced circulation design. With more information and confidence about the behavior of materials in the sodium, water and steam environments, the double-tube monitored annulus concept has been abandoned. The once-through concept removes the requirement for a steam separation volume and has resulted in the logical step of confining the high pressure water within the small diameter tubes with the low pressure liquid metal coolant on the shell-side. The dangers of stress corrosion cracking has tended to eliminate austenitic stainless steel from the evaporator section of the generator and pointed up the need for strict control of water chemistry. The information and confidence in material properties had led to sodium, with its lower cost and superior heat transport characteristics, replacing NaK as the preferred heat transfer fluid. The dangers of sodium stratification in horizontal and unbaffled sections, particularly at low flow rates, was most effectively demonstrated in the SRE testing as was the severity of thermal transients experienced in a liquid metal environment. This has resulted in a well baffled, usually vertical, sodium flow, to eliminate stratification with minimized section thicknesses, thermal shields, and, in certain designs, locating all tube sheets in the gas space to guard against thermal transients.

The basic concepts common to all three current designs scheduled for testing in the SCTI loop can be briefly summarized:

1. Sodium as the preferred heat transfer fluid
2. Once-through, forced circulation
3. Sodium on shell side, water on tube side
4. Single-wall tubing
5. Elimination of austenitic stainless steel from the evaporator of the generator.

The earlier costs of plant size, double tube, natural circulation steam generators has been estimated at \$20/kwe to \$30/kwe as compared to a quoted installed cost for the single-wall, once-through forced circulation Fermi units of \$10/kwe⁽¹⁾. However, the costs of about \$17/kwe for the 1000 MWe Babcock and Wilcox units⁽⁷⁾ to estimated costs of \$8/kwe⁽⁸⁾ for the Westinghouse 1000 Mwt Steam Generator design proposed to the AEC in November, 1962.

The design date of the domestic reactor sodium-steam generators prior to 1963 are given in Table 1.

Table 1

Steam Generator Design Characteristics - Reactor Units

Plant Location Unit	Hallam Nebraska		EBR-II Idaho		Fermi Michigan	SPE-PEP California	
	Evaporator	Superheater	Evaporator	Superheater	"Once-Through"	"Once-Through"	
Full load heat transfer per unit, MW	69	16	5.7	4.2	143	30	
Number of units	3	3	8	4	3	1	
Steam pressure, psig	900	895	1310	1300	900	750	
Shell side fluid	water	steam	sodium	sodium	sodium	sodium	
Flow rate, lbs/hr	2.5×10^5	2.5×10^5	3.12×10^5	6.24×10^5	5.30×10^6	$.72 \times 10^6$	
Temp "In", °F	304	530	794	866	820	1140	
Temp "Out", °F	530	875	588	794	520	670	
Tube side fluid	sodium	sodium	water	steam	water & steam	water & steam	
Flow rate, lbs/hr	2.8×10^6	2.8×10^6	0.31×10^5	0.62×10^5	4.76×10^5	$.88 \times 10^5$	
Temp "In", °F	830	895	550	580	380	400	
Temp "Out", °F	555	830	580	840	780	1100	
Heat transfer area ft ²	3680	2150	620	620	10800	2790	
Number of tubes	680	560	73	73	1200	199	
Outer tube O.D., ins	1.52	1.52	1.44	1.44	0.63	.69(str) .88 (bend)	
Wall thickness, ins	.072	.072	.094	.094-	.042	.054 .069	
Inner tube O.D., ins	1.38	1.38	1.25	1.25	--	.50	
Wall thickness, ins	.085	.085	.092	.092	(Single walled)	.050	
Material: Water side	A-212 Gr B	2-1/4 Cr-1 Mo	2-1/4 Cr-1 Mo	2-1/4 Cr-1 Mo	2-1/4 Cr-1 Mo	304 SS	
Na side	2-1/4 Cr-1 Mo	SCr-1/2 Mo	2-1/4 Cr-1 Mo	2-1/4 Cr-1 Mo	2-1/4 Cr-1 Mo	304 SS	
Core tube	304 SS	304 SS	--	--	--	--	
Double-walled tube	helium	helium	air	air	none	mercury	
Interspace fluid							
Manufacturer	Griscom-Russell		ANL	ANL	Griscom-Russell	B&W	

Present Design Status

The three 30 MWt prototype designs scheduled to be tested in the SCTI loop incorporate the basic concepts previously discussed. However, in the choice of materials and in mechanical arrangement and detail, the designs differ significantly. Also, the arbitrary requirement of meeting more modern fossil fuel steam conditions, in the range 2400 psi and 1050°F, dictate the choice of a high alloy or austenitic stainless steel in the superheater region of the generator.

The designs, in order of testing, were submitted by Alco, Atomics International and Babcock and Wilcox, respectively. The only true prototype of a large generator is the Babcock and Wilcox unit, representing the successful submission of a 1000 MWt AEC solicited design proposal in 1962 in competition with about six other companies. The Atomics International concept is the unique approach of the small modular units (an evaporator and superheater series connected) of about 20 MWt. However, the motivation for selecting the A.I. units for testing is not known and, although the modular concept is attractive for certain ratings, it is not known if it is proposed by A.I. in the 1962 competition to develop a large steam generator. The Alco unit represents the prototype of a 70 MWt generator design somewhat earlier under a separate AEC contract - generator final design report September, 1960⁽⁹⁾ and prototype final design report January, 1962⁽¹⁰⁾. The Alco approach is interesting in that the prototype differs radically in concept from the larger unit it was supposed to represent and reflects a significant updating in design thinking, more in line with present trends, between the time of the larger unit final design report and the prototype final design report.

These designs are discussed individually in more detail to highlight significant characteristics.

Alco Sodium-Stem Generator - AEC Contract No. At(11-1)-666

The original Alco unit, designed in 1960, consisted of separate evaporator and superheater sections arranged vertically and separated by a spherical water inlet - steam separation drum. The ferritic evaporator section was a recirculating, natural circulation unit with double (bayonet) tubes. Dry saturated steam left the central drum and entered the stainless steel straight tube vertical superheater. In this design, all stainless steel surfaces exposed to steam were clad with Inconel, in the case of the tubes, or Kanigen (nickel) plated.

In designing the prototype, the natural recirculation concept and the entire evaporator section were abandoned, and the once-through prototype design was largely based on the original superheater^(11, 12). The unit is of entirely stainless steel construction, largely type 316, and the original Alco preoccupation with the possibilities of stress corrosion cracking remain such that all surfaces in contact with both water and superheated steam are overlaid - Inconel overlay replacing the Kanigen plating of the original design.

The prototype is a geometrically simple, vertical cylindrical unit of essentially straight tubing, with sine wave curves to accommodate differential thermal expansion. The water tube sheet is located in the sodium at the bottom end of the unit with water upflow to the steam tube sheet located in the inert gas space above the sodium. The sodium flow is vertical, downwards, which with the closely-spaced disc and doughnut baffles, should provide a high degree of cross-flow. Annular cylindrical baffles are provided at the sodium inlet and outlet connections to distribute the flow and prevent direct impingement and hence possible vibration of the tubes due to the incoming or outgoing sodium flow. The main shell is fitted with a light, 1/8 inch thick, thermal shield and the water tube sheet is extensively shielded against sodium transients. All internal baffles, thermal shields and structural components are

type 304 stainless steel. All pressure containing parts are type 316 stainless steel. In order to guard against possible stress corrosion cracking, a high nickel alloy was specified to be in contact with the water-steam environment. As Inconel did not possess the required strength at high temperatures, a bimetallic tubing was used - initially mechanically bonded but as the Inconel liner tended to extrude on rolling the tubes into the tube-sheets this was later abandoned in favor of metallurgically bonded Inconel to type 316 stainless steel. Flat tube-sheets are used in each case with the tubes rolled and seal welded to trepanned risers machined into the clad surface. An additional complication then arises in that the stainless outer diameter of the tubes extending into the water and steam spaces also has to be overlaid with Inconel.

The advantages and disadvantages of the Alco prototype steam generator design are summarized:

<u>Advantages</u>	<u>Disadvantages</u>
1. Geometrically simple unit with a straightforward assembly procedure.	1. Bimetallic tubes need to be metallurgically bonded which with the Inconel overlay of all water-steam surfaces greatly increasing costs.
2. Extra tube sheets eliminated by continuous tubing from water inlet to steam outlet.	2. Inconel cladding on the inside of all tubes increases wall thickness and reduces the heat transfer effectiveness.
3. Design allows complete draining of both sodium and water.	3. Flat tube sheets impose a size limitation - for the spherical tube sheets would probably be required.
4. Sodium stratification is essentially eliminated.	
5. Access to both tube sheets and tube ends is provided.	
6. By the use of the sine wave curves, the axial differential thermal expansion of each individual tube should be accommodated.	

The tabulated parameters for the Alco prototype steam generators are given in Table 2.

Table 2

Steam Generator Design Characteristics - Development Units to be Tested in the SCTI Loop

Unit	Alco Once-Thru	Atomics International Modular Concept		B&W Prototype	
		Evaporator	Superheater	Evaporator	Superheater
Full load heat transfer per unit, MW	30	7.4	3.4	19	6.5
Number of units	1	2	2	1	1
Steam pressure, psia	2500	2600	2500	2550	2450
Shell side fluid	sodium	sodium	sodium	sodium	sodium
Flow rate, lbs/hr	8.55×10^5	3.06×10^5	3.06×10^5	5.83×10^5	5.83×10^5
Temp "In", °F	1175	975	1100	1013	1140
Temp "Out", °F	777	700	975	650	1013
Tube side fluid	water & steam	water	steam	water	steam
Flow rate, lbs/hr	1.16×10^5	3.67×10^4	3.67×10^4	8.88×10^4	8.88×10^4
Temp "In", °F	600	500	715	530	750
Temp "Out", °F	1050	715	1050	750	1050
Heat transfer area ft ²	1257	265	242	857	432
Number of tubes	300	37	37	25	45
Outer tube size, O.D., ins	.50	.63	.63	1.00	.88
Wall thickness, ins	.072	.095	.095	.120 - .165	0.120
Inner tube size, O.D., ins	.36	(Single walled tube)	(Single walled tubes)	(Single walled tube)	(Single walled tube)
Wall thickness, ins					
Material: Water side	Inconel	5Cr - 1/2 Mo	321 SS	2-1/4 Cr-1 Mo	316 SS
Na side	316 SS	5Cr - 1/2 Mo	304 and 321 SS	2-1/4 Cr-1 Mo	316 SS

In 1962, Atomics International received authorization to design and develop fabrication techniques for supercritical modular steam generators. In 1963, the scope of the work was redefined to give steam conditions of 2400 psi and 1050°F at outlet, compatible with standard power industry practice.

The modules are divided into separate evaporator and superheater sections designed to be series connected and rated at 14.8 and 6.9 MWt, respectively. The two units are essentially mechanically identical except that three rupture membranes are used in the evaporator section as opposed to one in the superheater section -- due to the more violent sodium - water reaction possible, compared with the sodium-steam reaction⁽¹³⁾.

The units are constructed with an outer shell of 7 inch diameter pipe, approximately 50 ft long, with 37 straight, 5/8 inches O.D., water tubes extending between the heads. The modules are counter-flow, once-through units with almost entirely axial sodium flow with external piping being used to convey the steam and sodium between units. The steam-water tubes are restrained by segmented support castings so arranged as to minimize possible tube vibration and sodium cross flow. The heads are hemispherical to the water-steam side and flat to the sodium side to reduce tube sheet thickness but permit full penetration, radiographed butt-welds to be made between the tubes and trepanned risers machined into the flat side of the tube sheet. The tubes are straight throughout their entire length with no design devices used to accommodate axial differential thermal expansion between the tubes and the shell. However, due to the modular concept and the comparable stiffness between the shell and the tubes, it is claimed that the resulting stresses will not be excessive⁽¹⁴⁾. With the small diameter involved, the outer shell can be made to contain full steam pressure for a short time and, it is claimed, operate in the sodium environment without the benefit of thermal shielding.

Thermal shielding is also not provided for both the tubesheets and the sodium nozzles. The evaporator section is constructed of ferritic material for cost reasons and to guard against the possibility of chloride stress corrosion. A number of Croloy material grades were studied and, based on considerations of potential carbon transport, allowable code stresses, resistance to chloride stress corrosion, and economics, the 5 Cr - 1/2 Mo grade was finally selected. The primary reason for rejecting the more common 2-1/4 Cr - 1 Mo grade was because it was felt that potential carbon transport (decarburization of this material) would not be tolerable at design temperatures⁽¹⁴⁾. Austenitic stainless steel is used for the superheater unit due to the elevated temperatures and the compatibility of the material with sodium at these temperatures. Type 321 H was selected for the tubes and tube sheets in preference to type 216 H due to a higher allowable stress and in preference to type 347 H due to a superior weldability. Since type 321 H has a reputation as a "dirty" steel, vacuum melt material only was specified. Type 304 H stainless steel was used for the outer shell, sodium nozzles and the internal structural components. As a precaution against chloride stress corrosion the steam is partially superheated in the ferritic evaporator section before entering the superheater unit.

For use in the SCTI loop, only the superheater and evaporator units will be used. For use in power plants for the steam conditions of 2400 psi and 1050°F, a second superheater unit is specified for use as a sodium heated-steam reheater. Sodium flow to be in parallel through the superheater and reheater before passing into the evaporator section.

No ultimate combined rating limitation is discussed for the modular units in terms of mechanical or economic feasibility. In a 1000 Mwt power plant loop, for example, 35 pairs of series connected evaporator - superheater units plus 35 reheaters would be required - a total of 105 separate units per loop, each unit with four external piping connections, rupture disc relief lines and individual instrumentation.

The design parameters are given in Table 2.

The advantages and disadvantages of the modular concept are summarized:

<u>Advantages</u>	<u>Disadvantages</u>
1. Simple mechanically and easy to assemble	1. For large ratings, the cost of the units and the cost and complication of the manifolding and piping could make the concept uneconomic.
2. Repetitive manufacturing operations.	2. For large ratings, there may be flow distribution problems.
3. Units are easily handled and transported.	3. Complete duplication of the instrumentation required for each of the units.
4. Versatility in rating - possible to make up any overall rating by combining units.	4. Removal of a complete modular unit may be more difficult in a complex assembly than plugging tubes in a larger unit.
5. Small diameter outer shell allows unit to withstand full steam pressure and/or the effects of a sodium water reaction.	5. Large space and housing costs for large capacity installations.
6. Possible to isolate leaks and remove an entire unit.	

Development work so far on these units has included a photoelastic study of tube sheet configuration, a fatigue study of the Croloy and stainless steel tube sheet and tube to tube-sheet welds⁽¹⁵⁾ and manufacturing welding development on the Croloy tube sheet welds.

Babcock and Wilcox Sodium-Steam Generator - AEC Contract AT(11-1)-1280

B&W was awarded the contract to design a large, 1000 MWt, sodium-steam generator and to design and build a 30 MWt prototype in 1962. The preliminary design report⁽¹⁶⁾ for the large unit was issued in July 1964.

B&W have made a considerable effort to integrate the design of the large unit into a power plant system and the effort has included the design of a separate sodium-heated, steam reheater such that the generator and reheater make up one loop of a three loop 1000 MWe generating station. As presently proposed, the steam generator evaporator and superheater sections are located in one vessel with the steam reheater in a separate vessel. Sodium flow is in parallel between the two vessels.

The generator, 76 ft high and 13 ft in diameter, consists of helical ferritic evaporator and austenitic stainless steel superheater tube bundles. The evaporator and superheater tube bundles have separate inlet and outlet tube sheets and the connections between the two sections are made by means of external welded piping such that the bimetallic welds are not located in the sodium environment. Croloy, 2-1/4 Cr - 1 Mo, in the form of 1 inch O.D. tubes is used for the evaporator section and type 316 austenitic stainless steel in the form of 7/8 inch O.D. tubes constitutes the superheater section of the generator.

The unit follows current practice in being once-through forced circulation with sodium counter-flow. To guard against the possibilities of chloride stress corrosion cracking in the superheater under normal operating conditions, the steam leaves the evaporator section at 750°F (approximately 90°F superheated). Under start-up conditions, the water is recirculated through the evaporator and an external steam separation drum, dry steam only passing to the superheater, until the evaporator produces dry steam at which time the external system is by-passed. Multiple flat tube sheets are used and the tubes are butt welded, and subsequently radiographed, to trepanned risers machined into the tube-sheet face.

The design contains a number of unique features:

1. The outer shell is of bolted construction, designed for field assembly, and such that the evaporator and superheater tube bundles are individually removable.
2. The tube sheets are not exposed to sodium and are all located in the inert gas volume to guard against thermal transients.
3. The helical coil design allows individual differential tube expansion to be accommodated, requires a fewer number of longer tubes and is effective in prolonging the Nucleate Boiling Region (DNB increased to about 60 percent steam quality⁽¹⁷⁾).
4. Using progressively increasing design temperatures, three different tube wall thicknesses are used in the evaporator section.
5. Each of the tube bundles is enclosed in a separate liner containing the sodium and a 2-inch, inert gas filled, annulus is provided between the sodium and the vessel wall.
6. The 30-inch diameter center section of the generator, within the smallest tube coil diameter, is a central full length pipe employed as a sodium control by-pass system.

In the design generally, considerable effort has been expended to guard against the problems encountered in sodium-steam generator design and this conservatism has resulted in considerable mechanical complexity and an increase in size. The prototype, not yet fully designed, would appear to reflect most of the features of the large unit and uses full size tubes. Whether or not it is intended to decrease the conservatism and size of a production unit by simplifying the design and/or going to a single tubing material, following a demonstration of feasibility in the prototype testing, is not known.

The basic parameters of the prototype unit and the combined MWt generator and reheater are given in Tables 2 and 3 respectively.

Table 3

Steam Generator Design Characteristics - Design Proposal for Large Capacity Units

Babcock and Wilcox Full Size Generators (1000 MWe)				
Unit	Evaporator	Superheater	Reheater	
Full load heat transfer per unit, MW	508	174	90	
Number of units	3	3	3	
Steam pressure, psig	2650	2450	475	
Shell side fluid	sodium	sodium	sodium	
Flow rate, lbs/hr	15.6×10^6	15.6×10^6	2.41×10^6	
Temp "In", °F	1013	1140	1140	
Temp "Out", °F	644	1013	690	
Tube side fluid	water	steam	steam	
Flow rate, lbs/hr	2.40×10^6	2.40×10^6	1.71×10^6	
Temp "In", °F	530	750	655	
Temp "Out", °F	750	1050	1000	
Heat transfer area ft ²	23,255	11,330	29,140	
Number of tubes	676	1220	752	
Tube size O.D., ins	1.00	0.88	1.50	
Wall thickness, ins	0.120-0.165	0.120	0.052-0.225	
Tube material	2-1/4 Cr-1 Mo	316 SS	2-1/4 Cr-1 Mo	

The relative merits of the concept are listed below:

Advantages

1. Heat transfer effectiveness improved by helical coil design.
2. Helical coil design accommodates individual coil thermal expansion.
3. Helical coil design permits a fewer number of longer tubes.
4. Superheater and evaporator tube bundles individually removable.
5. Shell and tube sheets well protected against thermal transients.

Disadvantages

1. Large overall size, complex, difficult to fabricate and costly - \$17/kwe.
2. Not possible to drain water side of unit.
3. Limited access to tube ends.
4. Six welds are required for each tube length through the generator.
5. Separate tube sheets required for evaporator and superheater sections.

Future Design

The steam generator design concept developed for this study is a projection of the present design status into the future. It departs from present designs primarily in the direction of greater simplicity in order to achieve both greater reliability and lower cost.

The Westinghouse design incorporates the five basic concepts previously noted as common to the current designs. These are:

1. Sodium as the preferred heat transfer fluid
2. Once-through forced circulation
3. Sodium on shell side, water on tube side
4. Single wall tubing
5. Elimination of austenitic stainless steel from the evaporator of the generator.

In addition, the Westinghouse design incorporates the following advances:

1. A single tube material
2. Fully drainable water-steam side tubing
3. Small number of different tube bending patterns.

BIBLIOGRAPHY - APPENDIX B

1. J. J. Morabito, APDA and H. W. Savage, ORNL, "Major Components and Test Facilities for Sodium Systems", Presented at the April 1965 ANS Meeting, Detroit, Michigan.
2. "The Evaluation of Incoloy 800 as a Structural Material for Use in Large Sodium Steam Generators", Westinghouse Proposal to the AEC, January 1964.
3. J. H. Ammon and T. S. Sprague, "Liquid Metal Show New Promise for Nuclear Plants", Babcock and Wilcox, August 1960.
4. R. W. Dickinson and J. B. Willaims, "Trends in Sodium Equipment", Atomics International, January 1961.
5. Atomics International, NAA-SR-5700 (1961).
6. Atomics International, Hallam Nuclear Power Facility Reactor Operation Analysis Program Monthly Report, No. 15-(1963)-56.
7. Preliminary Design Report Full Size Steam Generator, Babcock and Wilcox, Report No. BW 67-2, July 1964.
8. Westinghouse Proposal - Second Sodium Steam Generator, Sodium Components Development Program for USAEC-COO, November 1962.
9. Intermediate Heat Exchanger and Steam Generator Final Design, APAE No. 78, Vol. I. Alco Products, Inc., September 1960.
10. 30 Megawatt Heat Exchanger and Steam Generator for Sodium Cooled Reactor System.
11. Roy D. Seifert and L. E. Phillips, "Design of Reliable and Economical Heat Exchangers for High Temperature Service", Alco Products, Inc., 61-SA-41.
12. 30 Megawatt Heat Exchanger and Steam Generator for Sodium Cooled Reactor System, APAE-112 (Vol. 1), Alco Products, Inc., January 1962.
13. D. F. Casey, "Modular Steam Generators", Atomics International, April 1964.
14. Final Design of Sodium-Heated, Modular, Steam Generators for the SCTI, NAA-SR-9826, February 1965.

BIBLIOGRAPHY - APPENDIX B (Cont'd)

15. Fatigue Characteristics of 37-Tube, Modular Steam Generator Fluid, NAA-SR-9827, April 1965.
16. Preliminary Design Report Full Size, Steam Generator, Babcock and Wilcox Report No. BW 67-2, July 1964.
17. Sodium Components Development Program Information Meeting, Babcock and Wilcox, April 1964.

APPENDIX C

STEAM GENERATOR DESIGN CRITERIA AND PROCEDURES

This Appendix summarizes some of the more important criteria and procedures to be used in the design and development of a large, sodium steam generator.

Thermal Shield Design Criteria

Unless due design consideration is given, relatively rapid changes in fluid temperature which accompany various operating transients can lead to high thermal stresses. Although suitable shutoff and control features can alleviate conditions considerably, emergency situations such as a reactor scram or a loss in feedwater or sodium flow are likely to be particularly severe. For example, the steam generator sodium inlet temperature would rapidly drop about 400°F following a reactor scram. This would result in a similar drop in steam exit temperature and a surge of water flow into the steam header. On the other hand, a water pump failure would result in a rapid 400°F increase in steam generator sodium exit temperatures.

The design philosophy of the proposed steam generator reduces constraint between adjacent thermally expanding or contracting metal parts to the point where stresses are sufficiently low to meet long life requirements. For example, the serpentine tube represents a highly flexible design from thermal expansion considerations. Tube support hardware will also be free to expand, as will various baffles and wrappers. This hardware is light, and will not be subject to thermal shock damage. Suitable thermal isolation will be provided at tube to steam tube-sheet joints.

In regions where a high degree of constraint is unavoidable, thermal shielding is provided to reduce the rate of change of temperature of the protected surface to a level where thermal stresses are not severe.

Such shielding is necessary on all portions of the shell, headers and nozzles that contact sodium. Liquid sodium is such a good heat transfer medium that thermal shock to these heavier metal parts would be severe without such shielding.

Metal components in contact with the cover gas will respond slowly to sodium temperature changes and therefore should not require thermal shielding. The steam side of the steam header, however, requires thermal shielding for protection following a reactor scram. The water side of the water header would not experience any severe transients except for a sudden decrease in pressure following scrams. This is similar to transients occurring in present conventional power plants.

The water tube-sheet is protected by thermal shields on the sodium side. These shields act primarily as fluid baffles to create a stagnant pool of sodium between the flowing sodium and the tube plate. The most severe transient condition for this tube-sheet would be the stoppage of feedwater flow while sodium flow continues. Heat would then flow from the hot sodium in the sodium outlet region downward through the stagnant pool of sodium to the tube-sheet. Since the heat flow is downward, there would not be any tendency to create convective fluid currents and the heat would be transmitted by conduction alone. Holes in the baffles are provided to prevent pressure build-up from a tube or tube plate leak into the sodium. The hydrogen thus evolved will vent through the baffles and up to the top of the generator.

Shielding protects the shell walls from rapid transients. It is intended that the shell shielding follow principles similar to that of the water tube-sheet, i.e., it would utilize the conduction resistance and heat capacity of the sodium itself to decrease heat transmission. Since the shell is vertical, there will be a convection tendency during transients. This will be inhibited by breaking up the sodium zone of the shield into a cellular matrix.

A considerable portion of the design for thermal stress protection is conventional, thereby lending itself to calculation procedures with a high degree of certainty. In other regions, calculations can provide only a rough approximation of the degree of design adequacy. In these areas, it is considered necessary to initiate a small-scale component development program, to check out the design calculations.

Mechanical Design Criteria

All types of mechanical behavior from elastic through creep must be considered in the proposed steam generator design. The unique conditions imposed by the excellent heat transfer rates result in metal temperature gradients several times greater than those encountered in more conventional boilers and heat exchangers. In view of this, high thermal stresses will exist.

The preliminary analysis was based on the following criteria:

1. Sufficient thermal shielding will be provided to minimize transient thermal stresses.
2. Steady state thermal stresses will not govern the design. For example, the maximum steady state radial temperature gradient of about 100⁰F in the tube wall will allow more than one start per day throughout the 30-year life of the plant without failure.
3. Creep, rather than thermal fatigue, will govern the design.

Heat Transfer Considerations

The conceptual design of the steam generator was based on the sodium and steam conditions, and the required corresponding heat transfer area was calculated to meet these conditions. For a given set of sodium and steam conditions, the overall heat transfer coefficients for once-through, counter-flow conditions are developed from consideration of the individual

heat transfer coefficients on the shell side and the tube side, fouling, and conductivity through the tube wall. The shell side conditions are primarily a function of liquid sodium flow across tubes, while the tube side considerations must consider five distinct regions of heat transfer. These five regions are: 1. initial preheating of the feedwater; 2. boiling in the 0-40% quality range; 3. boiling in the 40-60% quality range; 4. boiling in the 60-100% quality range; and 5. superheating of vapor. A discussion of the heat transfer relationships for sodium and water/steam in each of these regions follows.

Preheating of the Feedwater - Several correlations for the case of fully developed turbulent heat transfer (inside film coefficients) have been compared with experimental data for water being heated inside of tubes. The most representative correlation of the experimental data is the Heat Exchange Institute relation:

$$Nu_m = 0.027 Re^{0.8} Pr^{0.4}$$

where

Nu_m = mean Nusselt number

Re = Reynolds number

Pr = Prandtl number

and fluid properties are evaluated at the mean bulk temperature. Another aspect of the heat transfer situation in this particular region which demands attention is the sub-cooled boiling mechanism. The local inside tube wall temperature, due to the excellent heat transfer coefficients on the sodium side, will reach and even exceed the saturation temperature of the water; hence local boiling will occur over a portion of this preheat range. The correlation used does not include any allowance for such heat transfer and is therefore somewhat conservative.

Boiling in the 0 to 40% Quality Range - Surface area for this range is determined from calculation of the overall heat transfer coefficients at the 0 and 40% quality points. The procedure used shows little variation in the overall heat transfer coefficient in this range, thereby permitting the use of an average coefficient and the conventional log mean temperature difference for area requirement definition.

The inside heat transfer coefficient at the 0% quality point is evaluated by assuming it as the end of the continuous local boiling region involved in preheating the water to its saturation temperature. At this point, nucleate boiling exerts the predominant effect. A total heat transfer resistance at the 40% quality point is calculated and is averaged with that determined at the 0% point. Previous calculations have shown very little variation between the 0% and 40% points, so that such an average is quite satisfactory. The reciprocal of this average resistance then provides the average overall heat transfer coefficient for the 0 to 40% boiling range. This coefficient, together with the conventional log mean temperature difference, is used in determining the surface area required for the 0 to 40% region.

Boiling in the 40 to 60% Quality Range - The heat transfer characteristics in this range are least certain since the range encompasses the "transition boiling" region. As a reasonably accurate correlation for determining the point of transition has not been established at this writing, the determination of the extent of the various boiling regimes is not precise. Using the best expression available (from WCAP-2040)⁽¹⁾, the transition point was estimated to occur at approximately 40% quality. From the same reference, plots of the heat transfer coefficient about this point show the trend of a precipitous drop from values in the regime of nucleate boiling to the regime of stable film boiling. It was therefore decided to consider the film boiling coefficients as appropriate to the region after transition. The correlative expression of Swenson⁽²⁾

was used to determine the stable film boiling coefficients at both 40 and 60% quality. A log mean $\overline{UAT}$ was determined for these end points and then applied to determine surface area requirements. In these considerations, proper cognizance was taken of the design flow rate and pressure level, since both of these parameters affect the magnitude, as well as the shape, of the heat transfer function.

Boiling in the 60% to 100% Quality Range - Again a log mean $\overline{UAT}$ was determined; in this case between the stable film boiling coefficient at 60% quality and the dry and saturated coefficient at 100% quality. The latter coefficient was determined from the normal Dittus-Boelter⁽³⁾ expression used for gaseous heat transfer with high temperature differences. The film boiling coefficient indicates a rising characteristic with increasing quality.

Superheated Steam Heat Transfer - A Dittus-Boelter type correlation was utilized at the dry and saturated point and throughout this region of high ΔT gaseous heat transfer. Fluid property values were evaluated at the gas film temperature, while the velocity term was taken as the bulk value. A rising characteristic is exhibited in this range; however, due to the slow rate of change of the heat transfer coefficient, an average value was determined and the area requirement established on this basis.

Sodium Side Heat Transfer - Coefficients for the sodium side thermal film were determined from WCAP-4402⁽⁴⁾. The analysis of several typical tube bundles is presented, along with the appropriate expressions developed for the average heat transfer coefficient. For the sodium properties (evaluated at an average sodium temperature) and the tube bundle geometry presently envisioned, several coefficients were computed (for different circumferential tube temperature distributions) and compared. Values of this coefficient, h , ranged from 9760 to 10,520 Btu/hr ft² °F. Due to oxide contaminants that might be present in the sodium, coefficients might

be lowered by perhaps 20%; however, removal of the oxides by cold trapping has been shown to restore the original heat transfer coefficients. A comparison of several expressions for sodium heat transfer presented in Westinghouse report RD-D-M 1897⁽⁵⁾ indicates about the same coefficients. Therefore, a value of 10,000 Btu/hr ft² °F was chosen and was held constant throughout the heat transfer analyses.

Fouling Resistance - Fouling resistance is incorporated in a heat transfer calculation to account for an increase in heat transfer resistance with time as caused by a combination of solids deposition on the tube surface and by oxidation of the tube metal surface.

Fouling on the outside of the tube which is in contact with sodium would be caused by oxidation. However, since sodium has a much higher affinity for oxygen than the tube metal, the presence of oxygen would lead to formation of an impurity in the liquid metal. This would take the form of sodium oxide rather than a tube metal oxide. Brooks and Rosenblatt⁽⁶⁾ have indicated that after two and one-half years of reactor operation with NaK under a wide range of test conditions, no deterioration in heat transfer coefficient had been observed as a result of fouling in either the liquid metal heat exchangers or the steam generators (evaporator and superheater). In LAMS-2462⁽⁷⁾ it is reported that observed data taken during the first 1,500 hours of steam generator operation have not indicated any appreciable heat transfer loss due to fouling. Accordingly, a fouling factor of zero has been selected for the sodium side.

On the inside of the tube which is in contact with water, only fouling in the form of oxidation may be expected since only volatile chemicals are used for water treatment. In recirculating steam generators using non-volatile chemicals for water treatment, fouling is caused by both solids deposition and oxidation. Fouling resistance of these units is of the order of 0.0003 to 0.0004 ft² hr °F/Btu. It is believed the

oxidation contribution forms only a small part of the total. Since oxidation increases with tube metal temperature, the following fouling resistances based on inside surface have been utilized. The 40% quality point has been selected as the temperature break point since it is expected that a very rapid decrease in the inside heat transfer coefficient will occur near this point due to the onset of film boiling. This will be accompanied by a rapid increase in inside tube metal temperature.

Up to and including the 40% quality point, fouling resistance based on inside surface is taken as $0.0001 \text{ hr ft}^2 \text{ }^\circ\text{F/Btu}$. Beyond this point, the fouling resistance based on inside surface is taken as $0.00015 \text{ hr ft}^2 \text{ }^\circ\text{F/Btu}$.

Maintenance Design Criteria

The steam generator maintenance philosophy is based on the principle that a carefully designed and manufactured unit will require a minimum of maintenance. Hence, extreme care will be exercised in performing these functions to insure that the installed unit will withstand the rigors of the intended operation.

The proposed once-through unit incorporates several design features which will significantly aid maintenance. Access manways are provided in the water and steam headers to permit inspection and repair work in those areas. The unit is designed so as to be completely drainable on both water and sodium sides. Thus washout, flushing and chemical descaling operations are facilitated by elimination of hold-up pockets. The proposed design is compact and of relatively light weight: two features which simplify handling problems in both installation and removal operations. Tube weld repair is also simplified by the use of a single metal tube in lieu of a more complex duplex tube.

Fabrication and Installation Design Criteria

The comparatively small size and low weight of the steam generator is a direct consequence of the principles incorporated in the design. The overall dimensions are 14 feet diameter by 52 feet long and the dry weight is 233 tons. This compact design is achieved by the use of serpentine tube bundles, and once-through counter-flow heat transfer. Closely packed serpentine tube bundles result in minimum exchanger volume and prevent axial tube temperature gradients from causing either high tube stresses or axial tube sheet reactions. The once-through heat transfer eliminates the additional complexity and volume required for recirculation water flow. The compactness of the unit results in relatively small component parts, which reduce general material cost, handling, welding and machining with a consequent reduction in overall cost. Direct shipment by rail and ease of installation are made possible by the compact design.

BIBLIOGRAPHY - APPENDIX C

1. A. A. Bishop, L. E. Efferding, and L. S. Tong, "A Review of Heat Transfer and Fluid Flow of a Water Substance in the Once-Thru and Supercritical Regions," Westinghouse Atomic Power Division, WCAP-2040-P.
2. H. S. Swenson, J. R. Carver and G. Sgoeke, "The Effects of Nucleate Boiling Versus Film Boiling on Heat Transfer in Power Boiler Tubes," ASME Paper 61-Wa-201.
3. W. H. McAdams, "Heat Transmission", Third Edition, McGraw Hill, Chapter 9.
4. L. E. Efferding and A. A. Bishop, "Review of Liquid Metal Heat Transfer and Pressure Drop," WCAP-4402 October 1963. AEC Contract AT(30-1)-3251 with the New York Operations Office of the United States Atomic Energy Commission.
5. A. A. Bishop, "Heat Transfer Correlations and Thermodynamic Data for Liquid Metals," Westinghouse Atomic Power Division, RD-D-M-1897.
6. Brooks, R. D. and Rosenblatt, A. L., "Nuclear Power Plants," Mech. Engr., May 1953, page 363.
7. Los Alamos Quarterly status Report on 2,000 KW Sodium Test Facility, LAMS-2462, August 20, 1960.

APPENDIX D

PRESENT USAEC SODIUM COOLED FBR DEVELOPMENT PROGRAM

The present AEC program for the development of sodium cooled fast breeder reactors can be discerned by reviewing various progress reports and news releases and by personal contacts. The program areas of interest to this study are discussed below:

Steam Generator

The development work and operating experience during the period 1947-1963 has evolved a general philosophy of steam generator design which is reflected in the current prototypes to be tested in the Sodium Components Test Installation (SCTI). As early as 1954, an APDA study⁽¹⁾ showed the superior economic potential of the single wall tube, once-through, forced circulation design which, with more information and confidence about the behavior of materials in the sodium, water, and steam environments, has allowed the double tube-monitored annulus concept to be abandoned. With information on and confidence in the behavior of materials in liquid metal environments, sodium, with its lower cost and superior heat transport characteristics, has replaced NaK as the preferred heat transfer fluid. The design, fabrication, and operating experience with the Hallam, EBR-II, and Fermi steam generators⁽²⁾, while not completely successfully (notably at Fermi), has pointed out basic concepts which are now included in the three SCTI designs:

1. Sodium as the preferred heat transfer fluid.
2. Once-through, forced circulation.
3. Sodium on the shell side, water on the tube side.
4. Elimination of annular tubing in favor of single wall tubing.
5. Elimination of austenitic stainless steel from the evaporator water side of the tubes.

The present development of sodium steam generators is directed toward the fabrication and testing of three prototype units in the Sodium Components Test Installation (SCTI). These designs are being pursued by Alco^(3,4), Atomics International⁽⁵⁾, and Babcock and Wilcox⁽⁶⁾. The only true prototype of a large generator is that being developed by Babcock and Wilcox. The Atomics International concept is small modular units of about 20 MWt. While this modular approach is attractive for certain ratings, it is not apparent that it would be economically or operationally attractive for large (1000 MWe) installations. The concept of the Alco prototype unit differs radically from the larger unit it is supposed to prototype, and reflects a significant updating in design thinking between the time of the larger unit final design (September 1960) and the prototype final design (January 1962). In effect, the test of the Alco unit becomes a test of a prototype for which no full size design exists. Thus, it appears that the present program is not a threefold attack on the problem because only one of the designs hold promise of application for large installations. This one possibility is the B&W prototype.

B&W has made a considerable effort to integrate the design of the unit into a power plant system and the effort has included the design of a separate sodium-heated, steam reheater such that the generator and reheater make up one loop of a three loop 1000 MWe generating station. As presently proposed, the steam generator evaporator and superheater sections are located in one vessel, with the steam reheater in a separate vessel. The evaporator tube material is 2-1/4 Cr - 1 Mo; the superheater material is 316 stainless steel. The unit follows current practice in being once-through forced circulation with sodium counter flow. Pertinent features of the design include:

1. Spiral tubes
2. Separate tubesheets for evaporator and superheater sections
3. All tubesheets in gas spaces
4. Tubes butt-welded to the tubesheets

Generally in the B&W design, considerable effort has been expended to guard against the performance deficiencies encountered in sodium-steam generator design, and this conservatism has resulted in considerable mechanical complexity and an increase in size. The prototype would appear to reflect most of the features of the large unit and uses full size tubes. It is not known whether the conservatism and size of a production unit will be decreased by simplifying the design and/or going to a single tubing material, following a demonstration of feasibility in the prototype testing. In any event, the large size, complexity, and possible fabrication difficulties tend to make this unit quite costly.

An important problem to be solved to achieve the successful design and operation of a sodium steam generator is the accommodation of a possible sodium water reaction. In this country, experimental programs to assist in the understanding of this reaction and its consequences are under way at AI⁽⁷⁾ and APDA⁽⁸⁾. In addition, England, France, and Germany have active programs in this area. The program at AI is being supported by ESADA, while the APDA program is under Commission sponsorship.

The objectives of the AI program are to: (a) assure the safety of the modular steam generator under all operating conditions; (b) minimize the risk of damage to associated equipment, in the event of a sudden major tube failure; and (c) study the relative effectiveness of several pressure relief devices, and optimize the number and location of such devices. This program encompasses an extensive test schedule to investigate the effects of tube rupture on the surrounding tube bundle, relative locations of the leak with respect to relief devices, multiple reliefs, and the effects of the reaction on the sodium piping. The test facility can accommodate units up to 80 feet long. The APDA program is directed towards, (a) establishing a means of estimating the extent of tube wastage (a corrosion-erosion type phenomena leading to rapid removal of tube material) during a small leak of water into sodium in a sodium steam generator and (b) determining the dominant parameters affecting tube wastage under these

conditions. It appears that the approach here is more scientific than that of AI. On the other hand, the more empirical results from the AI program might prove to be more immediately applicable. The experimental work on both programs began in the summer, 1965. B&W engineers are following closely the APDA program, and intend to revise their design as the experimental results indicate⁽⁹⁾.

Intermediate Heat Exchangers (IHX)

Performance of the IHX in several installations has been quite satisfactory⁽⁶⁾. As a result, there does not appear to be a specific Commission program for development in this area. Performance at Fermi and EBR-II has been without mishap. At Hallam, initial operation indicated the presence of flow-induced vibrations. Installation of baffles eliminated this problem.

Pumps

In 1963, Westinghouse evaluated the then current state of pump development, determined future requirements, and outlined a development program to satisfy these requirements⁽¹⁰⁾. At that time the largest sodium pumps in operation were those at Fermi (10,000 gpm). These are still the largest. Pertinent data on the larger pumps is shown below:

<u>Location</u>	<u>Flow (gpm)</u>	<u>T_{max} (F)</u>	<u>Head (feet)</u>	<u>Number</u>
EBR-II	4250	700	200	2
HNPf-pri. & sec.	7200	945	160	6
Fermi-primary	10,000	550	330	3
-secondary	10,000	-	80	3

Each of these pumps is of the vertical, centrifugal type. The EBR-II pumps utilize a totally enclosed motor and labyrinth seals. The others are of the mechanical seal, open motor type.

In general, mechanical operation of the Fermi primary pumps has been very satisfactory⁽¹¹⁾. As of June 1965, each of the three pumps has logged an average of over 16,000 hours with no unusual incidents. The shaft seals have presented some operational difficulties through excessive oil leakage. On all occasions, however, repair and/or replacement has been carried out as a routine maintenance function. As originally manufactured, these pumps had integral, undamped, check valves. Severe shock stresses had been created in the piping of the primary sodium system by too sudden stoppage of flow. New valves with dashpot damping were fabricated and installed to correct the condition. During replacement of the check valves the pump components were inspected for wear and damage. There were no wear marks inside the casing suction nozzle. The upper and lower pump shaft journals had slight surface wear marks. The journal bearings showed no wear or damage.

Experience at EBR-II has not been as satisfactory. Binding of both primary pumps occurred early in operation. It was found that the shafts had not been properly annealed during manufacture. The shafts were replaced, and clearances between the shafts and labyrinth seals were increased. One of the pumps continued to have an unusually high starting torque. This was traced to sodium buildup in the region of the labyrinth seal. The pump was modified to permit a downward purge of argon through the seal. Recent experience has been satisfactory⁽¹²⁾.

During the shakedown of the Hallam system, several pump problems occurred. Binding of the pumps occurred because of foreign materials in the system and because of improper shimming of the bearings. High sodium levels were found in the primary pumps. Although these difficulties have been cured, additional problems have plagued the pumps throughout their operation. These include rubbing as a result of thermal warping of the pump cases and general reliability problems with oil seals. These problems have not prevented pump operation⁽¹³⁾.

In summary, pump performance to date has been essentially up to expectations, and the malfunctions have been corrected without total pump replacement. The present status of pump technology appears to offer a sound base from which to proceed to the development of larger pumps for future requirements.

From the review of current designs and future trends, conducted during the Westinghouse study⁽¹⁰⁾, it was concluded that it may be reasonably expected that future large reactor plants will require pumps with a capacity of 50,000 to 100,000 gpm, developing heads of 200 to 350 feet of fluid. Based on an evaluation of the relative reliability, design predictability, and cost of pumps, and on the consideration of reactor systems requirements, the mechanical shaft sealed pump was selected as the most desirable type of pump for future development. An overall pump development program was defined, which included the development of the fundamental design characteristics of critical pump components, the design and fabrication of development pumps of various sizes and types for testing, and the construction and operation of a Sodium Pump Test Facility. The first phase of the recommended development program included work in sodium lubricated bearings, mechanical seals, and pump hydraulics.

The Commission is presently initiating work in several of these recommended areas. Request for Proposals have been issued for (a) Large Sodium Pump Design Program⁽¹⁴⁾, and (b) Bearing and Seal Test Program⁽¹⁵⁾. The objectives of the pump program are to perform design studies of large mechanical centrifugal type sodium pumps to permit design, development, manufacture, and testing of pumps for installation in a prototype fast reactor in the early 1970's. For the bearing and seals program, the objectives are to develop fundamental design data and characteristics of large diameter bearings and seals to the extent necessary to permit the design of large mechanical centrifugal pumps for high temperature sodium service to proceed with a reasonable degree of assurance. In addition, AEC has requested authorization for FY 1966 funds for construction of the

Sodium Pump Test Facility⁽¹⁶⁾. The facility will consist of two flow loops and associated tanks, and the pump test beds, equipment handling systems and overall system characteristics will be designed to permit installation and testing of pumps of varying sizes and design.

Sodium Technology

In general support of developments in these three component areas, the Commission has several contractors working on what is classified here as Sodium Technology. This work is summarized below where appropriate to this study.

Work in corrosion is being conducted over a wide range of variables at several sites - both industrial and national laboratory. One of the major programs is that at General Electric⁽¹⁷⁾. This program considers velocity, time, temperature, ΔT , oxide content, and pipe material as variables which are being investigated in six pumped loops. The program at MSAR⁽¹⁸⁾ considers the effect of sodium on the mechanical properties of austenitic and ferritic steels. The underlying basic philosophy of the MSAR program is to determine if the allowable stresses, as established by mechanical property tests in air and inert gases, are adequate for the design of long-time systems and equipment in sodium.

The area of sodium instrumentation is covered by several contractors, including APDA, UNC and ANL. The APDA effort⁽¹⁹⁾ is directed toward the in-line evaluation of the Rhometer and the UNC meter for detection of oxygen in sodium, and with the investigation of sodium system cleanup processes, chemical and physical behavior of sodium impurities, and laboratory analysis. The UNC meter⁽²⁰⁾ is an in-line, electrochemical device for detection of oxygen in sodium. The laboratory development was carried out at United Nuclear, and field evaluation tests are presently being conducted at APDA, LASL, and ANL. The ANL work⁽²¹⁾ is being carried out in support of the FARET program. Pertinent topics being covered under this program include high temperature thermocouples, high temperature in-

Materials Development

Incoloy 800 has been selected as the reference material for the steam generator tubing. This selection is based upon a comparative evaluation of the high temperature properties and sodium and steam corrosion characteristics of the material. However, to design this steam generator with the required level of confidence, it is necessary to obtain more applicable materials properties data at operating conditions.

Mechanical Properties - The long time creep, fatigue, and creep-fatigue properties up to 10,000 hours will be determined after exposure to sodium. In addition, extensive metallographic examination will be made on the samples after test to determine the effect of temperature on structural stability.

Stress Corrosion - Comparative tests will be carried out in boiling MgCl_2 and boiling NaOH solutions to determine the time to failure as a function of stress for both Incoloy and stainless steel.

Corrosion - The mass transfer and corrosion of Incoloy 800 as a function of time, up to 1000 hours, will be studied in sodium and steam under static and dynamic conditions. Based upon results of autoclave and thermal convection loop tests, dynamic loop tests will be conducted under conditions similar to those expected in steam generator operation.

Liquid Metal Surface Embrittlement - Tests will be run in conjunction with the mass corrosion tests and will consist of subjecting samples to stress in liquid sodium and determining whether cracking has occurred. After exposure to sodium, the structures of the samples will be determined.

Fabrication Development

Work will consist of developing satisfactory welding electrodes and techniques to suit the particular requirements of a large steam generator preliminary design and materials.

Weld Electrode - Preliminary work indicates that satisfactory welds can be obtained using available weld electrodes. This will be verified to a higher level of statistical significance. Where indicated, alternate or modified weld electrodes will be investigated to yield the optimum weld.

Weld Procedure - Using the weld electrode developed above, proper joint designs will be evaluated for manufacturing practicability.

Weld Properties - Cyclic testing of various configurations of the tube to tube sheet weld will be carried out. The tensile properties and creep characteristics of the welds will be determined.

Design Development

Engineering problem areas requiring additional R&D effort include elements of heat transfer, flow distribution, materials properties, transient analysis, mechanical design, thermal shielding, and system control.

Heat Transfer - The two-phase boiling region for once-through flow is of particular interest over the full operating range. The temperature gradient across the tube wall over the entire tube length will be determined for all operating conditions both transient and steady state. A heat transfer development program should be conducted to provide fundamental data on once-through boiling heat transfer in the quality region. This information is required to eliminate uncertainties and to provide a technically sound thermal and hydraulic design basis. Accurate data will permit heat transfer surface and cost to be minimized.

Hydraulics - Sodium flow distribution in the shell side of the tube bundle will be carefully analyzed. Detailed analysis of sodium pressure, temperature, and mass distributions will be made for all load conditions. Small scale water flow studies will be carried out as required to support this analytical effort.

Design - Specifications and design property requirements for all materials will be determined and supported by the necessary test programs. Mechanical design will be referenced back continuously to the materials properties. Very extensive analysis of thermal shielding systems will be compared with related experimental programs to establish that the systems are sufficient to protect the steam generator and assure reliability under all imposed conditions of operation. Thermal shielding schemes will be experimentally evaluated in test rigs utilizing liquid sodium environments. Thermal performance of various shielding schemes during typical prototype transient situations will be measured. The test section would consist of a relatively small plain section of shield in which the internal details can be readily varied.

Three-tube Model Test

It is deemed to be an important part of the steam generator development program to construct and test a three tube model steam generator which incorporates many of the features of the 30 MWt and 1000 MWt designs. Information gained in these tests will be factored into the design and used to specify the test program in the SCTI. Design and materials data derived from the test would also be used in the final 1000 MWt design. The immediate objectives of the three-tube model test are to obtain the following:

1. Materials corrosion and suitability proof test at operating conditions.
2. Verification of design features under operating conditions.
3. Thermal and hydraulic performance data.
4. Water chemistry requirements.

The initial undertaking in this task will be the design and construction of a three tube model which simulates as nearly as possible the key features of the large design. The materials employed will be identical to those recommended for the reference case.

The model would be equipped with temperature, flow and pressure instrumentation to produce thermal performance and design evaluation data. The sodium and steam instrumentation will permit identification of the various modes of once-through heat transfer and coolant enthalpy distribution throughout the tube bundle at both full load and part load conditions. The effect of tube bend geometry on heat transfer and fluid flow and, the effectiveness of thermal baffles and barriers under transient conditions will be determined.

Upon termination of testing, the unit will be disassembled and examined. Visual examination for corrosion, erosion, pitting, scale location and cracking will be followed by sectioning of tubes, tube sheets, and shell for metallographic and properties testing of materials after lone exposure.

Sodium-Water Reaction

Recognizing that the sodium-water reaction presents one of the major deterrents to the successful operation of a sodium steam generator, appropriate design evaluation must be carried out. The venting and pressure relief characteristics of the large unit will be evaluated. The initiation of tube failure and the propagation of effects to adjacent tubes and the shell will be estimated. An analysis of the operational safety of the design will be performed.

The test data from the current APDA and AI programs will be utilized where available or appropriate. Where additional data is needed, the requirements will be outlined with the intent that they be factored into these programs at an early date.

30 MWt Prototype

The solution of the engineering problems through analytical effort and development will provide the guidance to design the prototype steam generator. Detailed features of the 1000 MWt design requiring proof testing will be factored into the prototype design. The prototype test program objectives will be defined in terms of achieving this proof of performance.

Design, Procurement and Manufacture - Detailed manufacturing drawings will be prepared. All material will be ordered. Manufacture of the prototype will follow, subject to close reliability checks and quality control. The unit will be prepared for final shipment and shipped to the SCTI.

Installation and Test - The prototype steam generator would be installed and the test program carried out. Of primary importance in the test procedures is the evaluating of the heat transfer capabilities of the unit. Full load and part load points will be run on a short and long term basis to evaluate not only performance as a function of load but performance as a function of time as well. During these tests the hydraulic characteristics of the unit will be established.

Dynamic response characteristics of the prototype unit will be determined as a function of impressed changes in flow of either sodium or feedwater. Specific sequences of transient operating conditions will permit an evaluation of the long term service capabilities of the unit.

Evaluation - The evaluation of all data obtained in the prototype test program will be carried out. The prototype will be dismantled and examined. Visual examination for corrosion, pitting, scale location and cracking will be followed by sectioning of tubes, tube sheets, and shell for microscopic, spectrographic, and properties testing of materials after long exposure. The results will be compared to the problem areas and design objectives of the 1000 MWt design.

A revised 1000 MWt sodium steam generator design will be prepared, based upon results of the development program and the 30 MWt test. If warranted by test results, additional development tasks will be defined and conducted.

Intermediate Heat Exchanger (IHX)

Performance of the IHX in several installations has been quite satisfactory. As a result, there does not appear to be a specific AEC program for development in this area. Because of the lack of a large pressure differential across the tubes, the lack of phase change in either fluid, and relaxed materials requirements since sodium is on both sides of the tubes, an approach embodying design review and operational surveillance is being followed. The design of these large units is within the present capabilities of heat transfer engineers.

Pumps

As previously mentioned, performance of pumps up to 10,000 gpm capacity has been essentially up to expectations to date, with the malfunctions being correctable without total pump replacement. This appears to offer a sound base from which to proceed to the development of larger pumps for future requirements. The AEC is presently initiating a development program directed toward design, development, and proof testing of pumps in the 50,000-120,000 gpm flow range. Major features of this program appear to be (a) Large Sodium Pump Design, (b) Bearing and Seal Test Program, and (c) Sodium Pump Test Facility. Summarized below are the major requirements for a complete development program for large sodium pumps. When the AEC program is fully underway, it should include all these tasks.

Bearing Development

Two types of bearings appear promising for this application: the hydrostatic journal bearing and the pivoted-pad journal bearing. The former utilizes a source of pressure outside the bearing, while the latter depends upon the relative motion of the parts to generate pressure within the film.

The performance of the pivoted pad bearing, therefore, depends upon the speed of operation. Normally, the hydrostatic bearing is not dependent on pump speed. However, if the external pressure source for the bearing is the pump itself, the hydrostatic bearing also becomes speed dependent.

The main advantage of the hydrostatic journal bearing for large sodium pumps is its high load capacity at the maximum speed. The load capacity falls off quickly with speed, but is probably still superior to the pivoted-pad bearing up to the point where initial contact occurs. It operates equally well in either direction of rotation and is probably stable with respect to whipping. It is easy to split, thus making for easy assembly and disassembly on the shaft. It has shown reasonable reliability in similar applications in smaller sizes.

The pivoted-pad journal bearing has a number of advantages which are of a practical nature. It is inherently self-aligning and consists of a number of elements, loosely held, so that fouling by dirt is unlikely. It may be easier to make, in that the elements, being comparatively small, are readily available in the sizes required. It provides considerable support area for operation in the low speed range. Moreover, it is inherently stable with regard to whip and operates equally well in either direction of rotation. Finally, it does not require large additional pump flow to satisfy its own bearing requirements.

If a source of sodium under constant pressure were available, a hydrostatic bearing would offer a clear advantage over a pivoted-pad bearing in this application because it can be designed to give a greater load capacity at full speed. If the hydrostatic bearing is pressurized from the pump, however, the more important consideration may be, which of the two bearings can operate best under the low speed conditions.

The final choice of bearing type, configuration, and material will be made after a detailed review of the bearing functional requirements and an analysis of the results of a bearing development program. Major tasks in such a program are:

Model Testing - Water testing will be conducted on half size models of hydrostatic and hydrodynamic (pivoted-pad) bearings to obtain design data so that both types can be evaluated. A comparison of load capacity throughout the entire speed range and general performance during starting and operating conditions will be investigated. This data, and actual pump radial thrust data, will be needed before selection of bearing type or bearing sizing can be made. After water testing, either or both types would be operated in sodium in order to get load, stability, and film data under actual conditions.

A bearing test stand consisting of a variable speed drive, shaft and bearing, suitable water/sodium container, means of varying fluid pressure and temperature, and instruments to collect bearing test data (pressures, stability, film thickness, etc.) will be required. It is anticipated that 1/2 size bearing models will be adequate for these tests.

Bearing Load Determination - As mentioned above, actual pump radial thrust data is necessary in order to select and size the bearings. It is anticipated that this data would be obtained during pump model testing. Load determination apparatus to measure shaft load or bearing reaction loads will either be built into the pump model test stand, or be designed for installation into the test stand during pump model hydraulic testing.

Bearing Materials Selection - Some of the bearing materials known to be compatible with high temperature sodium are listed below, along with some of the possible methods of application.

MaterialMethod of Application

Cobalt base alloys

Hardfacing by oxyacetylene or heliarc

Ceramics (Alumina)

Plasma spray (non-transfer arc)

Tungsten carbide

Plasma spray or flame plate

Titanium carbide

Plasma spray

Nickel base alloys

Spray welded

Separate materials tests will be necessary to select the best combination of bearing materials to assure long life (minimum wear during start-up or low speed operation), dimensional stability, proper surface finish and hardness, and resistance to erosion and corrosion. In order to check various materials and methods of applying or mounting these materials, a thermal shock and cycling test fixture is required. A sodium container capable of receiving large cylinders and a hot sodium supply tank would be used for thermal shock and cycling testing.

Candidate bearings that have passed thermal tests would then be "load" and "stop-start" tested in the bearing test stand (1/2 size bearings).

Seal Development

The criteria which are relevant to shaft seal selection for large, free surface sodium pumps include proven reliability, no contamination of liquid sodium, low leakage, long life, ease of maintenance, low power consumption, ease of manufacture, and low cost. Three types of seals appear promising in meeting these design objectives: liquid seals, mechanical seals and gas seals. Liquid seals utilize a liquid injected at a pressure slightly above the cover gas pressure which forms a sealing film between the shaft and a housing. This type of seal has been used for many years in central station service to contain hydrogen gas in large electric generators. They have proven to be extremely reliable. They have an indefinite life since there are no rubbing parts. There is no gas leakage past the liquid interface. To develop this seal, a liquid compatible with sodium and air is necessary. This would require study and test work.

Mechanical seals, such as those used on the Fermi pumps, are candidates for the application. Lubricant selection and wear problems would require development and test work.

Gas seals were chosen for the conceptual designs for this application since, at the present time, they appear to require the least development to obtain a reliable, long life seal. The need for an auxiliary gas supply for these seals appears to be the major drawback, but until further study and comparison of large seal types is performed, this type of seal is the most attractive.

Shaft seals for gas blanketed liquid sodium pumps are essentially gas seals and with normal operation of the system the sodium below the gas blanket should have little effect on the functioning of the seal. The validity of this point of view depends on the reliability of the sodium level control, the effectiveness of the stilling baffles and thermal barriers above the sodium level and the proper performance of the sealing system in controlling gas leakage. If the pump configuration is such that entry of liquid sodium into the neighborhood of the seal can be prevented at all times and that diffusion of sodium vapor toward the seal can be inhibited by a moderate leakage inflow of inert gas, the real problem becomes entirely the problem of sealing inert gas.

Therefore, the problem areas must be discussed in terms of the two possible operating conditions: those corresponding to the absence of sodium and those which accept the presence of sodium, as liquid or vapor, in some concentration at some time during operation of the seal.

If sodium vapor in appreciable concentration or even liquid sodium might come into the neighborhood of the seal, then all the aspects of the problem are changed: materials problems are introduced and the sealing system might involve significant complexities.

Thus, the problem relates to more than the shaft seal alone. It integrates with the design problems of the pump, the controls of the sodium system, the gas inflow limits allowable and the capacity of the thermal barriers and cooling devices provided between the sodium region and the seal location.

At the present time, there is no positive assurance that sodium vapor or possibly liquid sodium can be kept entirely from the seal area. In this view, it is felt that seal materials which are capable of functioning in such an environment be investigated in case it should be proven that stilling baffles are not completely effective in eliminating sodium vapor contamination. However, the chances of preventing entry of sodium into the seal neighborhood are excellent and therefore allowance should be made to test the more conventional carbon-graphite seal ring material which has a very extensive background of experience with dry gas seal applications.

The test program, like all others of this nature, invariably resolves itself into test work to meet these objectives:

1. Determine and correct difficulties in the operation of the test hardware.
2. Complete the seal design experimentally, that is determine design factors, deformations, etc., that would not be closely evaluated during the analytical design.
3. Conduct assurance running for about 25 hours with each of the several possible seal configurations.
4. Conduct long life tests to determine, especially, the materials compatibility in the presence of inert gas, sodium vapor, and/or sodium droplets.

Pump Hydraulics Development

A hydraulics analysis must first be performed to generate parametric information to allow a comparison of design approaches based on NPSH requirements, efficiency, and economy in size and weight.

The conceptual designs and preliminary thinking indicates that an axial flow design, such as that shown for the intermediate pump, affords economy in size and weight and would be simpler to fabricate and analyze compared to the volute type shown for the primary pump. These designs, along with others such as double suction and multi-staged units, should be analyzed and compared. A final design selection would then be based on the relative merits of each design for the particular system under consideration.

The object of this program is to develop and optimize pump hydraulics (approach channels, impeller inlet areas, impeller blade design, guide vanes, volutes, etc.) to obtain minimum radial thrust and minimum required NPSH.

Model testing will be performed to verify design performance (head, flow, NPSH, etc.) while optimizing pump operation from radial thrust and low NPSH standpoints. These tests will determine which pump configuration offers the best combination of size, weight, NPSH, and load factors.

Models (1/3 to 1/4 size) will be made of at least two basic pump designs (single suction and double suction) and various diffuser and volute designs and modifications of these designs will be required. A fully instrumented water test loop will be needed along with the bearing load determination apparatus described in the Bearing Development section.

Engineering Analysis

For the most part, work in the following areas consists of analytical studies, using existing engineering theory and practice. However, a certain amount of testing will be required to prove some of the component designs in order to obtain maximum assurance that, when integrated into the final assembly, each component will function properly.

Thermal Studies - The use of sodium in heat transfer systems results in higher thermal stresses in structural materials than would occur in conventional water cooled systems, due to the low thermal resistance of sodium films. The effects of thermal transient conditions on pump components not only must be analyzed for stress reasons, but also to check the effects of thermal expansion on clearances and fits. A complete thermal stress analysis would be performed during the preliminary design of all components that contact the sodium, and all areas where close clearances must be maintained will be analyzed.

Fluid Stability Studies - The free surface concept of pump design introduces problems of possible gas entrapment due to surface level instability and possible vortexing in the pump tank. A thorough understanding of the dynamic behavior of the liquid and vapor phase in this area under all conditions of pump operation is essential.

Dynamics and Vibration - Due to the long shaft design associated with the free surface pump concept, and the high temperature involved, a dynamics investigation is mandatory. A preliminary analysis would be made based on expected operating requirements, so that a pump layout can be made. A model of the pump end and associated shaft would be based on a theoretical dynamic analysis and tests on the model be made to confirm the shaft analysis.

Mechanical Considerations - Aside from the structural design, consideration must be given to assembly, disassembly and maintenance of the unit. It will be necessary to assure that the pump internals and shaft assembly can be inserted into or removed from the casing and pump tank. With this design the entire inside assembly including the impeller, diffuser, thermal barrier, and lower bearing, shaft and baffling can be withdrawn from the pump tank and casing.

Materials Selection - For cost reasons, it appears desirable to use austenitic stainless steel (304) for the majority of pump structurals. No developmental testing appears necessary for the pump structurals, but the more critical areas such as bearings, seals and shafting may require testing. A survey of literature on existing materials would have to be performed for all pump components and initial material selection would be based on this. At the present time, bearing materials appear to be the only ones which may require any extensive development.

Electrical Analysis - Electrical motors having continuously adjustable speed control systems are proposed for the pump drive. The study of the drive and control systems will comprise: (a) a survey of all practical types of drive motor and speed control systems, (b) an economic study of each system, and (c) reliability studies of each system and component.

Instrumentation and Control - A study of the required instrumentation and control apparatus for the pump motor and auxiliaries will be necessary to assure that proper monitoring of temperatures, pressures, liquid level, vibration, etc. will be available on the prototype unit. At the present time, the only major developmental item envisioned is a high capacity sodium flow meter. While this would not be considered as a portion of the "pump development" program, it will be a necessary instrument for developmental testing of the prototype pump.

Pump Testing

The completion of the above development tasks will provide the input to enable the design, manufacture, and test of developmental pumps. It is expected that the Sodium Pump Test Facility (SPTF) will be available for this test program. The capacity of the SPTF should be such that pumps up to 50,000 gpm can be tested. The test program will include tasks covering: (a) hydraulic and electrical tests, (b) thermal transient tests, (c) speed control tests, (d) life and accelerated life tests and (e) instrumentation tests.

Sodium Technology

In general support of developments in these three component areas (as well as, of course, the entire sodium reactor program) the AEC is conducting a program on what is classified here as Sodium Technology. Topics covered include corrosion, instrumentation, chemical analysis, and purification. The scope of the effort in this area appears to be quite extensive in both depth and breadth. Thus it is assumed that the key development problems will be solved for the large sodium reactors.

System Considerations

Other areas in which development problems must be considered for the development of the VLFBR include the overall secondary system and its analysis, the auxiliary systems and components, and the control system. It is anticipated that the development problems in these areas, for the most part, will be solved for the LFBR. In addition, an area such as auxiliary systems, is very similar to that of primary system which has more stringent requirements. Development of the primary auxiliary system would therefore be applicable to the secondary system. The primary difference will be the increased number of systems and components required for the VLFBR. Therefore the only areas in which development may be required for the VLFBR are those affected by the complexities of multiple units. This would include systems analysis and the control system.

BIBLIOGRAPHY - APPENDIX D

1. APDA study, 1954.
2. Major Components and Test Facilities for Sodium Systems, J. J. Morabito and H. W. Savage, Fast Reactor Technology, Detroit, Michigan, ANS-100, p. 308, April 1965.
3. Intermediate Heat Exchanger and Steam Generator Final Design, APAE 78, Vol. I, Alco Products Inc., September 1960.
4. 30 Megawatt Heat Exchanger and Steam Generator for Sodium Cooled Reactor System, APAE 112, Vol. I, Alco Products Inc., January 1962.
5. Final Design of Sodium-Heated, Modular, Steam Generator for the SCTI, NAA-SR-9826, Atomics International, February 1965.
6. Preliminary Design Report, Full Size, Steam Generator, BW 67-2, Babcock and Wilcox, July 1964.
7. Sodium Water Reaction Tests, A. E. Douglas, Atomics International, Presented at AEC Sodium Components Working Group Information Meeting, Chicago, Illinois, June 1965.
8. Small Leak Sodium Water Reaction Program, H. O. Muenchow, Atomic Power Development Associates, Presented at AEC Sodium Components Working Group Information Meeting, Chicago, Illinois, June 1965.
9. Sodium-Heated Steam Generator Development, P. E. Probert, Babcock and Wilcox Company, Presented at AEC Sodium Components Working Group Information Meeting, Chicago, Illinois, June 1965.
10. Sodium Pump Development and Pump Test Facility Design, WCAP-2347, Westinghouse Electric Corporation, August 1963.
11. Enrico Fermi Atomic Power Plant, Maintenance Report Number 15, 20, 27, 33, 41, 42, 48, 51, 55, 56, 68, 74, 76, and 82. Dated March 1964 to April 1965.
12. Trip Report, J. D. Sutherland, EBR-II Site, Idaho Falls, Idaho, November 16, 1965, Westinghouse.
13. Trip Report, J. D. Sutherland, Hallam Nuclear Power Facility, Hallam, Nebraska, May 5, 1965, Westinghouse.
14. Invitation to Submit Proposals for Large Sodium Pump Design Study, June 7, 1965, San Francisco Operations Office, USAEC.

BIBLIOGRAPHY - APPENDIX D (Cont'd)

15. Invitation to Submit Proposals for Bearing and Seal Test Program, June 7, 1965, San Francisco Operations Office, USAEC.
16. AEC FY 1966 Authorization Bill, Item 66-4-a.
17. Sodium Mass Transfer Program, A. W. Lockhart and R. S. Young, General Electric, Presented at AEC Sodium Components Working Group Information Meeting, Chicago, Illinois, June 1965.
18. Effect of Sodium on the Mechanical Properties of Austenitic and Ferritic Steels, R. C. Andrews and F. Tepper, MSA Research Corp., Presented at AEC Sodium Components Working Group Information Meeting, Chicago, Illinois, June 1965.
19. Quarterly Technical Progress Report, APDA-178, Atomic Power Development Associates, July-September 1965.
20. The Liquid Metal Oxygen Meter, UNC-MTL-4734, B. Minushkin, United Nuclear Corporation, June 1965.
21. Interim Report: Faret Experimental Program, ANL-6708, Argonne National Laboratory, April 1963.
22. Examination of the Enrico Fermi Sodium Cold Trap, WCAP-4321, Westinghouse Electric Corporation, November 1965.
23. Quarterly Technical Progress Report, NAA-SR-11200, Atomics International, January-March 1965.