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LARGE CLOSED-CYCLE WATER REACTOR
RESEARCH AND DEVELOPMENT PROGRAM

DEVELOPMENT OF REACTOR COOLANT SYSTEM

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Plant Development

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TABLE OF CONTENTS

	<u>Page No.</u>
List of Figures	iii
List of Tables	iv
1.0 ABSTRACT	1
2.0 INTRODUCTION	2
3.0 PROGRESS OF SYSTEM DEVELOPMENT	4
3.1 Development of the Initial Reference Design	4
3.2 Development of A Three-Loop Configuration	16
4.0 DESCRIPTION OF SYSTEM CONCEPTUAL DESIGN	28
4.1 General Description	28
4.2 Description of Equipment	30
4.3 Operation	36
4.4 System Parameters	44
5.0 REFERENCES	52

LIST OF FIGURES

<u>Figure No.</u>		<u>Page No.</u>
1	Process Flow Diagram, 1150 MWt, 4-Loop System	5
2	Plan-View - Reactor Coolant Piping Layout for the 4-Loop, 1150 MWt System	9
3	Elevation - Reactor Coolant Piping Layout for the 4-Loop, 1150 MWt System	10
4	Three-Loop System with Canned Motor Pumps	21
5	Initial Three-Loop System Layout.	24
6	Reference Layout of the Three-Loop System	25
7	Process Flow Diagram - Three Loop System with Controlled Leakage Pumps	29
8	Reactor Coolant T_{avg} Set Point Function	50
9	Pressurizer Level Control Set Point Function.	51

LIST OF TABLES

<u>Table No.</u>		<u>Page No.</u>
1	Parameter List for the Initial Reference Design of the 1150 Mwt - 4-Loop System	6
2	Reactor Coolant System Parameters	17
3	System Parameters (Final Concept)	45

1.0 ABSTRACT

This report is a description of the development work on the conceptual design of the Reactor Coolant System for large closed-cycle water reactors with chemical shim control.

Significant areas of development are discussed and descriptions of the system conceptual design are included for a plant rated at 1176 MWt.

2.0 INTRODUCTION

The Reactor Coolant System in a closed-cycle water reactor transfers heat from the reactor core to the secondary system to produce steam for the turbine. The system consists of identical heat exchange loops connected in parallel to the reactor vessel, each containing a reactor coolant circulating pump and a steam generator. The system also includes the pressurizer, pressurizer relief tank, and connecting piping, valves and instrumentation necessary for operational control. Essentially all of the system equipment is located within the reactor containment vessel.

This study, Development of Reactor Coolant System, was incorporated in the Large Closed-Cycle Water Reactor Research and Development Program with the basic objectives of; (a) producing a plant conceptual design consistent with operating criteria for a chemical shim core, and (b) establishing optimum system parameters and developing plant layout concepts with a view toward reduction of equipment cost.

In addition to these objectives, the new configurations of fuel assemblies, control rods and reactor vessel internals associated with the Rod Cluster Control (RCC) core concept being developed under the base program necessitated changes in the configurations of fuel handling equipment. The development of conceptual designs for the various tools and equipment needed for refueling of an RCC core was also included as a objective of this study.

During the course of work, a system conceptual design was prepared for a large reactor having a thermal output of approximately 1176 MWt. The configuration of the reactor coolant loops and the equipment of the 1176 MWt plant were altered considerably as the result of continued efforts on the part of equipment manufacturers to produce larger individual items of equipment such as the steam generators and reactor coolant pumps. At the onset of the program, the system concept was a

canned motor coolant pumps and having a gross rated output of 376 MWe based upon a thermal power of 1150 MW. The reference conceptual design that evolved during the period of development is a three-loop plant using the more efficient controlled-leakage reactor coolant pumps and having a gross rated output of 395 MWe based upon a thermal power of 1176 MW. This report summarizes the significant areas of development leading to this final conceptual design.

3.0 PROGRESS OF SYSTEM DEVELOPMENT

3.1 Development of the Initial Reference Design

Work was begun with the selection of an initial reference design of a Reactor Coolant System for a closed-cycle water reactor rated at 375 MWe (gross) with a core thermal output of 1150 MW. This reference design was the fundamental concept upon which development of this system could proceed and also provided the basis for the related development of auxiliary systems consistent with chemical shim operation.

A process flow diagram for the initial reference design is shown in Figure 1. The equipment used includes four vertical, U-tube steam generators, each located in one of four reactor coolant piping loops arranged symmetrically around the reactor vessel. A canned-motor reactor coolant pump with an integral center-guided check valve is included in each loop for forced circulation of coolant water through the reactor core and steam generators.

A tabulation of major system parameters is given in Table 1. The parameters selected for this reference design were based upon optimum values of piping pressure drop, steam generator configuration and pumping cost consistent with the largest available canned-motor pumps and vertical steam generators.

3.1.1 Equipment Layout

Layout studies were performed for the initial reference design resulting in the equipment arrangements shown in Figures 2 and 3.

TABLE 1

PARAMETER LIST FOR THE INITIAL REFERENCE DESIGN
OF THE 1150 MWt - 4-LOOP SYSTEM

General

Plant rating, MWe gross	375
Total heat transferred, Btu/hr	3925×10^6
Number of heat transfer loops	4
Coolant flow rate, lb/hr	69×10^6
Reactor core flow rate, % of total	90%
Nominal operating pressure, psia	2200
Hot leg temperature, °F	590.5
Cold leg temperature, °F	547
Coolant temperature rise, F°	43.5
Steam pressure, psia	680
Steam temperature, °F	500
Total system pressure drop, psi	64.5
Total system volume, ft ³	7371*

Reactor Vessel

Design pressure, psia	2500
Design temperature, °F	650
Size of coolant nozzles, inches, I.D.	28.5
Reactor thermal output, MWt	1150

Piping

Design pressure, psia	2350
Design temperature, °F	650

* Based on preliminary pressurizer volume of 1250 ft³.

TABLE 1 (Cont'd)

Sizes, inches

Main loop, except pump suction

Inside diameter 22.5

Outside diameter 26.4**

Pump suction piping

Inside diameter 24.0

Outside diameter 28.2**

Pumps

Design flow rate, gpm, each 45,700

Design head, ft. 198

Electrical input, volts 4160, 3 ϕ

Power consumption, KW, each

Operating conditions 2450

Cold 3050

Starting current, amperes, each 2500

Power factor 0.88

Cooling water flow, gpm, each 170

Maximum cooling water inlet temperature, °F 90

Approximate cooling water temperature rise, °F 28

Nozzle size, inlet and outlet I.D., in. 24

Steam Generators

Primary Side

Design pressure, psia 2500

Design temperature, °F 650

Inlet temperature, °F 590.5

Outlet temperature, °F 547

Flow rate, lb/hr each 17.25×10^6

Nozzle size, I.D. in. 28.5

** Tentative. Depends on selection of material.

TABLE 1. (Cont'd)

Secondary Side

Design pressure, psia	1000
Design temperature, °F	600
Steam pressure, psia*	680
Steam temperature, °F*	500
Flow rate, lb/hr, each*	1.1875×10^6
Feedwater temperature*	400
Maximum moisture carryover, % weight*	0.25
Steam nozzle size, I.D., in.	16.5

General

LMTD, F°	66.5
Heat transfer area, ft ² , each	20,200
Number of tubes	2636
Tube size O.D. x wall thickness, in.	3/4 x 0.058 avg.

* At full power design conditions.

PLAN ABOVE OPERATING FLOOR
VIEW CC

PLAN BELOW OPERATING FLOOR

Figure 2

Plan View - Reactor Coolant Piping Layout for
the Four-Loop, 1150 MWt System

NOTES:

1. CONCRETE DIMENSIONS SHOWN ARE NOT NECESSARILY THOSE REQUIRED FOR RADIATION SHIELDING OR STRUCTURAL PURPOSES.
2. DETAILED PIPING IS SHOWN ON ESB P&ID.
3. REACTOR VESSEL SUPPORTS NOT SHOWN.
4. FUEL TRANSFER MECHANISM SHOWN IS SCHEMATIC.
5. ADDITIONAL SERVICE HATCHES MAY BE REQUIRED FOR EQUIPMENT BELOW OPERATING FLOOR.

Figure 3

Elevation - Reactor Coolant Piping Layout for the Four-Loop, 1150 MWt System

In these studies, efforts were made to reduce piping and structural cost and reactor coolant volume to a minimum. A minimum volume results in minimization of the contained reactor coolant thermal energy and hence minimizes containment vessel volume and design pressure requirements.

3.1.2 Flow Transients

Calculations were performed to approximate the reactor flow transients following loss of electric power to one or more reactor coolant pumps. This loss of flow data was prepared as input for subsequent analog computer studies performed under another portion of the program to investigate the possibility of departure from nucleate boiling (DNB) conditions in the core following a power failure.

3.1.3 Check Valve Elimination Study

A study was initiated on the initial reference system concept to determine the need for reactor coolant check valves. Removal of these valves was believed to have both economic and technical advantages. Economically, the capital and maintenance costs associated with the valves could be saved with their deletion. Technically, the presence of the valves increases resistance to coolant flow and hence pumping power. In addition, a hydraulic shock occurs each time a valve is closed, suddenly stopping the column of water in the affected loop piping.

The primary concerns in the check valve elimination study were:

- (a) The ability of the reactor coolant pumps to withstand reverse flow and attendant reverse rotation without incurring bearing damage.

- (b) The effect of the increased flow bypassing the core via the de-energized loop(s) during a loss-of-flow accident.
- (c) The ability of the reactor vessel outlet nozzle and steam generator hot-leg channel head to withstand the sudden cooling caused by reverse flow of reactor coolant through a steam generator.
- (d) The ability of the reactor coolant pumps to withstand re-starts while "wind-milling" due to reverse flow.

The concern over the possible damage to pump thrust bearings led to an experimental investigation on the nature of the coefficient of friction at various speeds for water lubricated, center-pivoted, Kingsbury-type bearings. This work was reported in a separate topical report,¹ and led to the conclusion that prolonged rubbing contact between bearing shoe and runner, without a lubricant film, was extremely unlikely in the event of reverse rotation of the de-energized pump. Hence, the concern over bearing damage was alleviated.

Transient studies indicated that the presence or absence of check valves has no significant effect upon the maximum fuel cladding temperature during a loss-of-flow accident.

The sudden cooling of the hot leg of a reactor coolant loop due to reversal of flow through a relatively cold steam generator was found by the equipment manufacturers not to materially affect the transient performance of the reactor vessel or steam generator.

The re-starting of a reactor coolant pump while spinning in reverse was judged to present no severe problems for as many as 8000 start cycles with reverse flows approximately 50 per cent of the normal forward flow.

The overall conclusion reached was that check valves were not required in the reference system, but for plants differing in configuration, studies of the reactor core and loop equipment thermal transients caused by partial loss of flow, and investigations of pump starting capabilities against reverse flow conditions would be required.

Additional details of the check valve elimination study have been reported in the two quarterly progress reports^{2,3} for the period from January 1 to June 30, 1963.

3.1.4 Feasibility of "Hot-Rated" Reactor Coolant Pumps

The initial Reactor Coolant System reference design served as a model upon which to test the feasibility of using canned motor pumps having motors rated for duty at normal plant operating temperatures of approximately 550°F. Under this condition the pumped fluid is water having a specific gravity of approximately 0.75. Because the pumps are essentially constant volume flow devices, about one-third more power is required when the pumped fluid is cold water at a specific gravity of 1.0. A unit rated for service only with hot reactor coolant would thus overheat and possibly suffer permanent damage to the motor winding insulation if operated continuously or for long periods with cold reactor coolant water.

Consequently, past plant designs have used pumps rated for continuous service with cold water. These pumps are thus over-designed for normal operating temperatures. Capital and operating expenses are higher, in general, than would be the case if smaller motors could be used.

The study undertaken for investigation of the feasibility of hot-rated pumps therefore was directed at those transient conditions where such units would be subjected to temporary overloads due to low reactor coolant temperatures (i.e., plant startup, plant shutdown, and initial startup and physics tests).

Winding temperature transients were calculated for the conditions of heating during cold running and cooling during shutdown periods. Using this information, the feasibility of "cycled" operation of the pumps was investigated. Cycled operation consists of the sequential operation of individual pumps for short duty periods. Each pump is run until its winding temperature limit (220°C) is reached. Each operating period is followed by a cooling period during which three pumps are shut down while the other is used to circulate the reactor coolant.

For the pumps in the initial reference design the study of cycled pump operation considered such factors as the increased number of start-stop cycles on the pumps, the introduction of cooler water into the core upon starting an inactive pump, and the overall time required for raising system temperature using pumping energy, if required.

Procedures were prepared for reactor plant heatup with cycled pump operation but using nuclear core heat to raise system temperature at a nominal $50\text{ F}^{\circ}/\text{hr}$. It was concluded that the use of the hot-rated pump in this manner is feasible but requires close attention to operation.

An alternate Reactor Coolant System heatup procedure consistent with the hot-rated pump concept and using only nuclear power and natural circulation was also investigated. The reactor coolant temperature transient associated with initiation of reactor coolant natural circulation and the reactor stability and control characteristics were

analyzed for this condition and were reported in the quarterly progress report⁴ for the period from December 1, 1961 to February 28, 1962. Analysis of the results of the study showed the reactor to be controllable under the low-temperature, low-power conditions postulated for natural circulation heatup with a moderator coefficient of reactivity as high as $+5 \times 10^{-5} \text{ } \frac{\text{k}}{\text{F}^{\circ}}$.

3.2 Development of A Three-Loop Configuration

3.2.1 The Basic Three-Loop Reference Design

Reactor Coolant System development based upon the initial reference design for a plant rated at 1150 MWt was suspended during a period when customer negotiations for a plant of this size were delayed. Activity was resumed on the 1150 MWt plant about a year after completion of the reported effort on the initial four-loop reference design. Because of advances in the manufacturing capability for primary components such as the reactor coolant pumps and steam generators, it became apparent that these components could be obtained in larger sizes, making practical a change in system configuration from a four loop design to a three-loop design.

Because economics for a system using the larger components were favorable, development work was resumed using the three-loop concept as the new reference design.

Parameter studies were made for the new configuration, leading to an increase in plant rating from 375 MWe at 1150 MWt for the initial reference design to 395 MWe at 1176 MWt. As in the initial reference design, parameters were selected based upon optimization of flow, piping and steam generator pressure drop, and pump cost. These parameters are given in Table 2.

The process flow diagram for the three-loop reference design is given in Figure 4. In addition to differences in number of loops and size of steam generators and reactor coolant pumps, this three-loop reference design differs from the initial reference design in the following respects:

TABLE 2

REACTOR COOLANT SYSTEM PARAMETERSGeneral

Plant design life, years	30
Total heat transferred	4013×10^6 Btu/hr (1176 MW)
Number of heat transfer loops	3
Coolant flow rate, total	73.8×10^6 lb/hr
Reactor core flow rate, % of total	90
Design pressure	2485 psig
Nominal operating pressure	2050 psig
Coolant temperature leaving reactor vessel at full power	592.7°F
Coolant temperature entering reactor vessel at full power	551.4°F
Coolant temperature rise at full power	41.3°F
Steam pressure, full power	695 psig
Steam temperature, full power	504.7°F
System pressure drop at full power operating temperatures	73.6 psi
Allowable heating and cooling rate	100 F°/hr
Total system volume, including pressurizer	7800 ft ³
System liquid volume, including pressurizer (water level at full power)	7150 ft ³

Reactor Vessel

Design pressure	2485 psig
Design temperature	650°F
Number of coolant nozzles	6
Inside diameter of coolant nozzles (at vessel inside wall)	33-3/4 inches

TABLE 2 (Cont'd)

Inside diameter of coolant nozzles (at pipe weld)	27-1/2 inches
Pressure losses through vessel	45.3 psi
<u>Piping</u>	
Design pressure, loop piping, spray and surge lines	2485 psig
Design temperature, loop piping and spray lines	650°F
Design temperature, surge line	680°F
Design pressure, discharge lines	500 psig
Design temperature, discharge lines	470°F
<u>Pumps</u>	
Number	3
Design flow rate, each	65,500 gpm
Design head, nozzle to nozzle	225 feet
Design pressures	
Casing (volute)	2485 psig
Motor casing	2485 psig
Cooling jacket	150 psig
Design temperatures	
Casing (volute)	650°F
Motor casing	300°F
Cooling jacket	200°F
Electrical power supplied, volts-phase-cycles	4160, 3φ, 60
Cooling water flow, each	300 gpm
Maximum continuous cooling water inlet temperature	100°F
Inlet nozzle inside diameter	29 inches
Outlet nozzle inside diameter	27-1/2 inches

TABLE 2 (Cont'd)

Steam Generators

Number	3
Heat transfer rate at full power, each	1337.7×10^6 Btu/hr
<u>Primary Side</u>	
Design pressure	2485 psig
Design temperature	650°F
Inlet temperature	592.7°F
Outlet temperature	551.4°F
Flow rate, each	24.6×10^6 lb/hr
Pressure loss at normal operating conditions	24.4 psi
<u>Secondary Side</u>	
Design pressure	985 psig
Design temperature	600°F
Steam pressure at full power	695 psig
Steam temperature at full power	504.7°F
Flow rate, each	1,629,000 lb/hr
Feedwater temperature	402.7°F
Maximum moisture carryover, % weight	1/4

Pressurizer

Internal volume	1300 ft ³
Design pressure	2485 psig
Design temperature	680°F
Steam volume (at full power)	650 ft ³
Water volume (at full power)	650 ft ³
Installed heater capacity	1300 KW

TABLE 2 (Cont'd)

Safety and Relief Valves

Pressurizer Safety Valves

Number	2
Relieving capacity, each, at 3% accumulation	240,000 lb/hr
Set pressure, first valve	2485 psig
Set pressure, second valve	2510 psig
Constant backpressure (normal plant operation)	3 psig
Maximum backpressure (during discharge)	500 psig

Power Relief Valves (Pressurizer)

Number	2
Relieving capacity, each, at 2160* psig	(later)

Steam Generator Safety Valves

Number	(by others)
Total relieving capacity	(later)
Nominal set pressure, first valves	985 psig
Highest set pressure	1015 psig

Pressure Relief Tank

Internal volume	1050
Design pressure	100 psig
Design temperature	340°F
Normal operating pressure	3 psig
Normal operating temperature	120°F
Normal water volume	860
Normal gas volume	190
Cooling time required following design maximum discharge	60 minutes
Capacity of rupture disc.	480,000 lb/hr

Figure 4
Three-Loop System with Canned Motor Pumps
21

- (a) The results of the check valve elimination study, discussed in Section 3.1.3, were applied to the three-loop plant. Accordingly, the canned-motor pumps in this reference design contain no provision for the integral center-guided check valves used in the initial reference design.
- (b) An additional power relief valve actuated from another independent pressure channel is included on the pressurizer to give positive assurance that pressure will not rise to the point where the core heat transfer margin to departure from nucleate boiling (DNB) is reduced during design load transients.
- (c) An additional pressurizer spray line and control valve insures operation of the surge spray when the plant is operating with one reactor coolant pump out of service.

Additional description of the three-loop reference design was given in the quarterly progress report⁵ for the period July 1, 1963 to September 30, 1963.

3.2.2 Development of Three-Loop Layout

The development of a practical and economical layout of the three-loop plant was necessary for coordination with development of associated auxiliary systems and for input information for use by the architect-engineer for containment vessel design purposes. Particular emphasis was placed upon developing a minimum loop volume consistent with the need for space for refueling equipment and shielding structure. The effect of contained volume of reactor coolant upon the containment sphere volume

and design pressure and upon capacity of waste disposal system and other auxiliary systems makes reactor coolant system layout a significant part of the development of an economical plant. Figure 5 shows an initial concept of the three-loop system, and Figure 6 shows the layout adopted as the basis for the remaining fluid systems development.

3.2.3 The Controlled-Leakage Pump and Other Developments

Following the work on establishment of the basic three-loop reference design, additional effort was expended upon refinement of the system concept resulting primarily from advances in component technology. This work was reported in the quarterly progress reports ^{6,7,8} for the periods from October 1, 1963 to June 30, 1964, and culminated in the issue of the functional system description. This system description and the associated process flow diagram are summarized in Section 4.0 of this report.

The most significant changes from the basic three-loop reference design resulted from the adoption of the controlled-leakage reactor coolant pump in place of the canned motor pump and in the shortening of the reactor vessel (hence reduction of system volume) made possible by the development of the Rod Cluster Control (R.C.C.) core concept under Sub-task 3.00.

The controlled-leakage reactor coolant pump design was included in the three-loop plant concept as a result of the following advantages over the canned motor pump.

- (a) Higher motor efficiency results in lower power consumption at the design point.

Figure 5

Initial Three-Loop System Layout

Figure 6

Reference Layout of the Three-Loop System

- (b) Conventional motor design allows repair at local maintenance and repair facilities and reduces the need for specialized service.
- (c) Flywheel inertia can be added to prolong flow coastdown and improve core heat transfer safety margins in the event of failure of auxiliary electric power.

Additional discussion of the controlled-leakage pump and its effects upon the related auxiliary systems concepts is contained in the quarterly progress report⁸ for the period from October 1, 1963 to December 31, 1963.

The effects of the addition of the controlled leakage pump and the shortened reactor vessel had no significant effect on the system layout shown in Figure 6.

Final parameters and the process flow diagram resulting from the above developments and the interrelated auxiliary systems and control effort are described in section 4.0.

3.2.4 Refueling Concepts for the R.C.C. Core

The refueling aspects of a large, closed-cycle, water reactor plant employing the R.C.C. control element concept were studied to determine the significance of this new concept on the design of refueling tools and equipment. This study indicated that two tool designs were affected by the introduction of the R.C.C. concept, and required development for new large plant applications. These tools are:

- (a) The R.C.C. Change Fixture - A device used to extract R.C.C. elements from spent fuel assemblies and replace them into new assemblies during refueling.
- (b) Reactor Internals Handling Device - A device for removing the upper core support assembly from the reactor during refueling.

Design studies including conceptual layouts were completed for each of these tools. A refueling procedure based upon the use of these tools was also prepared.

A study was also conducted on a method to protect reactor vessel studs if they are kept in place in the vessel flange during refueling. An internally pressurized reactor vessel stud protective sleeve was evolved. A prototype sleeve was manufactured and successfully tested under simulated conditions.

4.0 DESCRIPTION OF SYSTEM CONCEPTUAL DESIGN

4.1 General Description

The final concept of the Reactor Coolant System is shown on the process flow diagram, Figure 7. The system consists of three identical heat transfer loops connected in parallel to the reactor vessel, each containing a controlled-leakage circulating pump and a steam generator. The system also includes the pressurizer, the pressurizer relief tank, the connecting piping, and instrumentation necessary for operational control. All system equipment, except the pressurizer relief tank nitrogen pressure regulator and the demineralized water supply valve is located in the vapor container.

During operation the reactor coolant pumps circulate pressurized water through the reactor vessel and the three loops. The water, serving as both coolant and moderator, is heated as it passes through the core. It next flows to the steam generators, where the heat is transferred to the secondary (steam) system, and then back to the pumps to repeat the cycle.

Pressure in the system is controlled by the use of the pressurizer, where water and steam are maintained in equilibrium through the use of electrical heaters. Steam can be formed (by the heaters) or condensed (by the pressurizer spray) to reduce pressure variations due to contraction and expansion of the coolant. Two power-operated relief valves limit the pressure rise during coolant volume surges, which accompany large design step reductions in plant load. Two spring-loaded steam safety valves are connected to the pressurizer and discharge to the pressurizer relief tank, where the steam is condensed and cooled by mixing with water.

Figure 7 Process Flow Diagram - Three Loop System with Controlled Leakage Pumps

4.2 Description of Equipment

4.2.1 Reactor Vessel

The reactor vessel is a cylindrical vessel with a hemispherical bottom head and a flanged and gasketed removable upper head with provisions for seal welding. The vessel contains the core, core support structure, control rods, thermal shield, and other parts directly associated with the core. The control rods are positioned by hermetically sealed magnetic-latch type drive mechanisms which are mounted on penetration adapters on the reactor vessel head. The reactor vessel has three inlet and three outlet nozzles located in a plane just below the flange and above the core. Coolant enters the inlet nozzles and flows downward along the vessel wall, then turns at the bottom and flows upward through the core to the outlet nozzles. The vessel is low alloy steel with only austenitic stainless steel clad surfaces or Inconel parts exposed to the coolant.

4.2.2 Steam Generators

The three steam generators are vertical shell and U-tube evaporators with integral moisture separating equipment. The reactor coolant flows through the inverted U-tubes, entering and leaving through the nozzles located in the hemispherical bottom head. The head is divided into inlet and outlet chambers by a vertical partition plate extending from the head to the tube sheet. Manways are provided for access to both sides of the divided head. Steam is generated on the shell side and flows upward through the moisture separators to the outlet nozzles at the top of the vessel. Structurally the units are primarily carbon steel; the heat transfer tubes are Inconel, the interior

surfaces of the reactor coolant heads and nozzles are clad with austenitic stainless steel, and the primary side of the tube sheets is clad with Inconel. With the exception of the tubes, the secondary side surfaces in contact with the feedwater are primarily carbon steel.

4.2.3 Pumps

The three reactor coolant pumps are identical single-speed units driven by air-cooled, single-speed three-phase induction motors. The shaft is vertical with the motor mounted directly above the pump. The pump inlet is at the bottom and the discharge is on the side. Leakage from the Reactor Coolant System is controlled by mechanical shaft seals. High pressure seal injection water is supplied by the Chemical and Volume Control System to protect the seals by preventing leakage of high-temperature reactor coolant water into the seal chamber. Component cooling water is supplied by the Auxiliary Coolant System to the motor bearing oil cooler and to the thermal barrier cooling coil. The motor, shaft and impeller can be removed from the casing as a unit without disturbing the reactor coolant piping. The pump design contains provisions to prevent reverse rotation of the shaft when subjected to reverse flow. Pump surfaces in contact with the reactor coolant are austenitic stainless steel except for seals, bearings and special parts.

4.2.4 Pressurizer

The pressurizer provides a point in the Reactor Coolant System where liquid and vapor can be maintained in equilibrium for pressure control purposes. Steam is generated by electrical heaters installed through the vessel lower head. The heaters

are removable for maintenance or replacement. A spray nozzle is located at the top of the pressurizer. A small continuous flow is normally maintained through the spray line. A much larger spray flow is used during increasing pressure transients. The vessel is carbon steel with austenitic stainless steel cladding on the internal surfaces. The heater sheaths are type 304 stainless steel.

4.2.5 Pressurizer Relief Tank

The pressurizer relief tank condenses and cools the discharge from the pressurizer safety and relief valves. Discharge from smaller relief valves located inside the containment sphere is also piped to the relief tank. The tank normally contains water and a predominantly nitrogen atmosphere. Steam is discharged under the water level, to condense and cool the steam by mixing it with water at or near ambient temperature. The tank is equipped with a spray system and drain which are operated to cool the tank following a discharge. The tank is protected against a steam discharge exceeding the design value by a rupture disc which discharges into the containment sphere. The tank is carbon steel with a corrosion resisting coating on the wetted surfaces. A flanged nozzle is provided on the tank for the pressurizer discharge line connection. The discharge piping and sparger within the vessel are austenitic stainless steel. An additional stainless steel nozzle is provided between the flange and the tank connecting the letdown line relief valve and auxiliary coolant relief valve lines to the main stainless steel discharge pipe.

4.2.6 Piping

The large reactor coolant piping and fittings which make up the three loops are type 316 austenitic stainless steel. The pressurizer relief line, which connects the pressurizer safety and relief valves to the discharge nozzle flange on the pressurizer relief tank, and the discharge lines from the component cooling loop relief valves located inside the containment sphere are carbon steel. Smaller piping, including the regenerative heat exchanger relief valve discharge line, drains, and connections to other systems are austenitic stainless steel. All joints and connections are welded, except for the pressurizer safety valve connections and for the stainless steel connections to the carbon steel pressurizer relief tank, where flanged connections are used. Thermal sleeves are installed at points in the system where high thermal stresses could develop due to rapid changes in fluid temperature during normal operational transients. These points include:

- (a) The charging line connection from the Chemical and Volume Control System.
- (b) Return line from the Residual Heat Removal Loop (Auxiliary Coolant System).
- (c) Pressurizer spray line connection to the pressurizer.
- (d) Both ends of the pressurizer surge line.

4.2.7 Valves

With the possible exception of trim and other special parts, all valves in the Reactor Coolant System are stainless steel

where surfaces are wetted by the coolant. Connections to stainless steel piping are welded with the exception of the pressurizer safety valves which have flanged connections. The valves have features, such as stem leakoffs and/or backseats, which maintain essentially zero leakage to the atmosphere.

Local vents, capped with blind flanges, are provided on the reactor vessel head, the pressurizer (relief valve inlet), pressurizer relief line, and pressurizer relief tank. In addition, each control rod mechanism housing is equipped with a valved vent connection which can be capped to prevent leakage. The vents are arranged so that water discharged during the initial venting operation may be directed by a hose to a drain or suitable container without wetting nearby equipment.

The two pressurizer safety valves are the self-actuated, spring-loaded type with back pressure compensation. The two pressurizer surge spray valves and the two-power relief valves provide automatic control of system overpressure. Two remotely controlled stop valves permit isolation of the power relief valves if excessive leakage develops. Two locally-adjusted throttling valves, in parallel with the surge spray valves, permit a small continuous circulation spray flow through each spray line and the pressurizer.

Remote manual valves allow control of water makeup, venting and draining of the pressurizer relief tank.

Overpressure protection of the secondary side of the steam generators is provided by conventional self-actuated steam safety valves located on the main steam piping outside the containment sphere and are supplied as part of the secondary plant.

4.2.8 Thermal Insulation

All Reactor Coolant System valves, piping and equipment (except as specified below) which operate at elevated temperatures are covered with thermal insulation to minimize system heat losses. Auxiliary system piping connections are provided with insulation up to, and including, the first isolation or check valve. Exceptions are as follows:

- (a) Safety and relief valve discharge lines are insulated only where necessary to provide personnel protection.
- (b) No insulation is provided on parts of instrumentation and electrical equipment or connections, such as control rod drive mechanisms, pressurizer heater electrical connections, reactor coolant pump motors including the motor flange, reactor vessel refueling level detection connections, etc. Equipment manuals specify where insulation should not be applied.
- (c) No insulation is provided on the pressurizer relief tank or associated fill, vent, and drain piping.

4.3 Operation

Operation of the Reactor Coolant System is described for the various phases of reactor plant operation presented below.

4.3.1 Plant Startup

Plant startup is defined as the operations which bring the reactor plant from cold shutdown to normal operating temperature and pressure.

Prior to initiation of plant heatup, the reactor coolant loops and pressurizer are filled completely with water containing the correct concentration of boron. The steam generator shells are filled to startup level with water which meets the secondary plant water chemistry requirements. Reactor coolant pumps are operated as required to complete the venting operation. During operation of the reactor coolant pumps, the minimum loop pressure of 205 psig is maintained by operation of one charging pump and the low-pressure letdown line. The charging pump provides the seal injection water necessary for the pump seals. The nitrogen atmosphere and normal operating temperature, pressure and water level are established in the pressurizer relief tank. The reactor vessel refueling water level instrument is prepared for normal operation, with the vent and loop connections closed and the inner leakoff connection from the reactor vessel flange open to the detector.

Upon completion of venting, all reactor coolant pumps are shut down. Reactor Coolant System pressure is maintained above atmospheric pressure by the Chemical and Volume Control System

prior to forming a steam bubble in the pressurizer. The pressurizer heaters are then energized to start heating the pressurizer contents. When pressurizer temperature exceeds 212°F, formation of the steam bubble is begun by opening the low pressure letdown valve (Chemical and Volume Control System) and diverting reactor coolant flow to the Waste Disposal System by way of the Residual Heat Removal Loop and the letdown line. When the pressurizer has been drained to the normal water level, the low pressure letdown valve is closed. The rate of pressure rise is regulated by manual control of the pressurizer heaters.

When pressure exceeds 205 psig, the residual heat removal operation (if in service) is discontinued. Charging and letdown flow at the normal purification flow rate is initiated to provide seal injection water for the reactor coolant pumps and to adjust reactor coolant boron concentration and add hydrogen to the reactor coolant. At low pressure, before isolation of the Residual Heat Removal Loop, pressurizer water level is maintained by manual control of the low pressure letdown valve. The reactor coolant pumps are started, one at a time, to insure proper mixing of the coolant and to cool the core during the heatup operation.

The reactor is brought to criticality by operation of the Reactor Control and Protection System. Reactor power is used to raise system temperature to the hot standby temperature of 535°F. As the reactor coolant temperature increases, the pressurizer heaters are controlled manually by the operator to increase the pressure as necessary to maintain adequate suction head for the reactor coolant pumps. When the normal operating pressure of 2050 psig is reached, pressurizer heater control is transferred to the pressurizer pressure controller.

4.3.2 Normal Operation

Normal operation includes the power generation and hot standby operating phases, when the reactor plant is at normal operating temperature and pressure. Power generation includes steady state operation, loading and unloading at a rate of 3-6 percent of full power per minute, and step load changes of plus or minus 10 percent of full power (not exceeding full power), and step load reductions as great as 50 percent from full power with controlled discharge of secondary plant steam to the atmosphere.

During all phases of normal operation, pressure is maintained by the pressure control equipment at or near 2050 psig, and normal pressurizer water level is maintained by the letdown flow control in the Chemical and Volume Control System.

When the reactor is generating power, system temperature is controlled by the Reactor Control and Protection System. When the reactor power is less than approximately 20 percent, the reactor is controlled manually. At power levels above approximately 20 percent, the Reactor Control and Protection System automatically maintains an average coolant temperature-power relationship as shown in Figure 8, Section 4.4. At zero load the hot and cold leg temperatures are equal at 535°F. As plant load (MWe) is increased, the coolant average temperature set point is increased linearly to its proper value at 100 percent of full power. Similarly, the pressurizer water level set point is increased linearly from a value adequate to cover the heaters at zero power to a point at 100 percent of full power where the pressurizer is approximately half filled with water. See Figure 9, Section 4.4, for the set point function.

During hot shutdown operation when the reactor is subcritical, system temperature is maintained at 535°F by the pressure controller on the steam bypass to the secondary plant condenser, which is set to maintain steam generator steam pressure at or slightly below 908 psig. Residual heat from the core or operation of one or more reactor coolant pumps provides heat to overcome system heat losses.

The pressurizer relief tank functions only when a safety or relief valve discharges or when sufficient leakage accumulates. If a discharge occurs, the normal (maximum) temperature of 120°F may be exceeded and the level in the tank will rise. The tank is restored to normal conditions by operating the spray and/or drain valves, as required. If gas or steam leaks cause the pressure in the tank to exceed the normal value of 3 psig, the tank is vented to the Waste Disposal System. The gas in the tank is periodically analyzed to detect accumulation of hydrogen and/or oxygen.

4.3.3 Plant Shutdown

Plant shutdown is defined as the operations which bring the reactor plant from zero-power operating temperature and pressure to cold shutdown.

Prior to initiation of plant shutdown concentrated boric acid solution from the Chemical and Volume Control System is added to the Reactor Coolant System to increase the reactor coolant boron concentration to that required for cold shutdown.

To cool the Reactor Coolant System, the valve controlling the steam bypass to the turbine condensers is reset continuously to produce the desired cooling rate. One reactor coolant pump

is kept in operation to insure uniform cooldown of all loops. The pressurizer heaters are turned off and spray flow is used to cool the pressurizer, maintaining the required reactor coolant pump suction pressure.

When the reactor coolant temperature and pressure are below approximately 350°F and 400 psig, respectively, residual heat removal operation is initiated, and the Reactor Coolant System is cooled to 140°F or less by the residual heat removal loop of the Auxiliary Coolant System. One reactor coolant pump is kept running until the coolant temperature is below 150°F. During this period, the pressurizer heaters are used to maintain system pressure high enough to provide adequate suction pressure for the reactor coolant pumps.

After the one operating reactor coolant pump is turned off, the pressurizer cooldown is continued by turning off all heaters and initiating auxiliary spray flow from the Chemical and Volume Control System. The pressurizer is filled by the auxiliary spray flow before the pressurizer temperature reaches 212°F. After the pressurizer has been cooled, the spray flow is discontinued and the pressurizer is vented.

4.3.4 Refueling

Prior to removing the reactor vessel head for refueling, system temperature is reduced to 140°F or less. After the pressurizer has been cooled to the desired temperature (less than 212°F) and the vent opened, system draining is initiated. When the pressurizer water level indication reaches zero, the reactor vessel refueling water level detector is placed in service.

When water level has been reduced below the reactor vessel head vent, the vent is opened. Draining continues until water level is below the reactor vessel flange. This indication is verified by observation of the sight glass on the refueling level detector. Upon completion of the refueling operation, the refueling level detector is prepared for normal operation and the system is refilled for plant startup.

4.3.5 Emergency Operation

4.3.5.1 Loss of Coolant Flow

Loss of coolant flow results from the shutdown of one or more reactor coolant pumps due to manual tripout or power failure. The reactor is automatically scrammed by the Reactor Control and Protection System upon loss of flow in one loop when reactor power is above a predetermined level.

The flow coastdown period resulting from the inertia of the reactor coolant pump rotating parts is adequate to prevent damage to the reactor core after scram even in the unlikely event of simultaneous loss of electric power to all three pumps or a fault on a pump bus. When the reactor is at power, all pumps are supplied from the unit auxiliary transformers which are fed from the main generator terminals. Provision is made so that failure of all outside sources of electric power to the station will not result in immediate loss of power to the reactor coolant pumps. The pumps will be driven in direct proportion to generator frequency during the initial turbine overspeed and subsequent coastdown which follow the turbine trip. (Turbine overspeed occurs after turbine trip as the result of expansion of steam in the lines and reheaters

when load is dropped from the main generator.) The generator exciter remains in service to supply power during the coastdown period.

After the reactor coolant pumps have been tripped off and the pump coastdown is completed, flow is built up in the reactor coolant loops by natural circulation. This flow rate is sufficient to remove the residual heat generated in the reactor core without damage to the fuel or cladding.

4.3.5.2 Loss of Electric Power

Total loss of plant auxiliary electric power may result from utility system faults causing failure of power to the station auxiliary transformer, or from a fault in the transformer or its 4 KV feeder. Turbine trip and scram follow upon the interruption of power to the various components necessary to secondary plant operation. The subsequent opening of the 220 KV breakers on the outgoing line from the main generator at a time when power supply from the other external source is interrupted will result in temporary failure of all auxiliary electric power to the plant. Auxiliary electric power is re-established within ten minutes through a unit auxiliary transformer by opening the main generator no-load disconnect switch and reclosing the tie to the 220 KV switchyard.

During the period when there is no external source of power, reactor cooling is maintained by natural circulation in the reactor coolant loops. The steam generators are the system heat sink which removes residual heat by relief of steam to the atmosphere. The period of time before auxiliary power can be returned from one of the normal sources is sufficiently short

to prevent excessive loss of reactor coolant pressure, or loss of heat sink due to the boil-off of all steam generator secondary water.

Instrumentation vital to the system is energized during the interruption by the Preferred A-C Source Units, which are maintained in service using the station batteries.

4.3.5.3 Loss of Coolant

Loss of coolant would result from rupture of a coolant loop or piping connection or rupture of a steam generator tube. Reactor scram is initiated by low system pressure, by the initiation of safety injection, or by manual action. The Safety Injection System is started by a signal resulting from the coincidence of low system pressure and low water level in the pressurizer. The reactor coolant pump operation is continued in order to assure effective heat removal from the steam generators. Reactor residual and stored heat, if not removed from the system in the case of small ruptures, would retard decay of pressure with coolant loss and would delay the effective flow of safety injection water. The reactor coolant pumps are turned off manually.

A steam generator tube rupture is detected by radiation monitor alarms from the condenser air ejector and from relative changes in steam generator and pressurizer water levels.

A steam generator tube rupture requires manual reactor scram followed by boration of the reactor coolant and cooldown and depressurization of the reactor coolant system as rapidly as possible to minimize the leakage of radioactivity to the atmosphere.

4.4

System Parameters

The parameters developed for the final concept of the three-loop plant are given in Table 3, System Parameters.

TABLE 3

SYSTEM PARAMETERSA. General System Parameters

Plant design life, years	30
Total heat transferred	4013×10^6 Btu/hr (1176 MW)
Number of heat transfer loops	3
Coolant flow rate, total	73.8×10^6 lb/hr
Reactor core flow rate, % of total	90
Design pressure	2485 psig
Nominal operating pressure	2050 psig
Coolant temperature leaving reactor vessel at full power	591.2°F
Coolant temperature entering reactor vessel at full power	549.9°F
Coolant temperature rise at full power	41.3°F
Steam pressure, full power	720 psig
Steam temperature, full power	508.6°F
System pressure drop at full power operating temperatures	73.3 psi
Allowable heating and cooling rate	100°F/hr
Nominal system volume, including pressurizer	7127 ft^3
Nominal system liquid volume, including pressure (water at full power level)	6435 ft^3

B. Reactor Vessel

Design pressure	2485 psig
Design temperature	650°F
Number of coolant nozzles	6
Inside diameter of coolant nozzles (at vessel inside wall)	33-3/4 inches
Inside diameter of coolant nozzles (at pipe weld)	27-1/2 inches
Pressure losses through vessel	45.3 psi

TABLE 3 (Cont'd)

C. Piping

Design pressure, loop piping, spray and surge lines	2485 psig
Design temperature, loop piping and spray lines	650°F
Design temperature, surge line	680°F
Design pressure, discharge lines	500 psig
Design temperature, discharge lines	470°F

D. Pumps

Number	3
Design flow rate, each	65,500 gpm
Design head, nozzle-to-nozzle	225 feet
Design pressure	2485 psig
Design temperature	
Casing (volute)	650°F
Pressure housing	300°F
Electrical power supplies, volts - phase-cycles	4160, 3 ϕ , 60
Cooling water flow, each	200 gpm
Maximum continuous cooling water inlet temperature	100°F
Inlet nozzle inside diameter	29 inches
Outlet nozzle inside diameter	27-1/2 inches

E. Steam Generators

Number	3
Heat transfer rate at full power, each	1337.7 x 10 ⁶ Btu/hr
Primary Side	
Design pressure	2485 psig
Design temperature	650°F
Inlet temperature	591.2°F
Outlet temperature	549.9°F

TABLE 3 (Cont'd)

Flow rate, each	24.6 x 10 ⁶ lb/hr
Pressure loss at normal operating conditions	23.7 psi
Secondary Side	
Design pressure	985 psig
Design temperature	600°F
Steam pressure at full power	720 psig
Steam temperature at full power	508.6°F
Flow rate, each	1,632,000 lb/hr
Feedwater temperature	402.7°F
Maximum moisture carryover, % weight	1/4

F. Pressurizer

Internal volume	1300 ft ³
Design pressure	2485 psig
Design temperature	680°F
Steam volume (at full power)	692 ft ³
Water volume (at full power)	608 ft ³
Installed heater capacity (480 V)	1300 KW
Continuous spray rate (nominal)	1.0 gpm
Maximum spray rate	360 gpm
Steady state heat losses (nominal)	68 KW

G. Safety and Relief Valves

Pressurizer Safety Valves

Number	2
Relieving capacity, each, at 3% accumulation	240,000 lb/hr
Set pressure, first valve	2485 psig
Set pressure, second valve	2510 psig
Constant backpressure (normal plant operation)	3 psig

TABLE 3 (Cont'd)

Maximum backpressure (during discharge)	500 psig
Power Relief Valves (Pressurizer)	
Number	2
Relieving capacity, each, at 2170 psig	(later)
Steam Generator Safety Valves	
Number	(by others)
Total relieving capacity at 10% accumulation (1/4% moisture)	7.26×10^6 lb/hr
Nominal set pressure	985 psig

H. Pressurizer Relief Tank

Internal volume	1100 ft ³
Design pressure	100 psig
Design temperature	340°F
Normal operating pressure	3 psig
Normal operating temperature	120°F
Normal water volume	860
Normal gas volume	190
Cooling time required following design maximum discharge	60 minutes
Capacity of rupture disc	480,000 lb/hr
Design flow cooling water spray	95 gpm
Spray nozzle pressure drop	10 psi

Table 3, Continued

Control and Isolation Valves

Valve	<u>Pressurizer Relief Tank Valves</u>				
	<u>Surge Spray Control Valves</u>	<u>Power Relief Isolation Valves</u>	<u>Vent Valve</u>	<u>Makeup Water Valve</u>	<u>Drain Valve</u>
Design conditions	2485 psig 650 °F	2485 psig 680 °F	100 psig 340 °F	100 psig 340 °F	100 psig 340 °F
Flow, gpm maximum	180	} Data supplied for flow control valves only.			
normal	---				
minimum	12 gpm				
Pressure drop psi					
at maximum flow	4.9 psi				
normal	---				
at minimum flow	47 psi				
Head loss coefficient (L/D)* (Stop valves only)	---	(later)	340	340	340
Fluid temperature, °F	550	670	230	230	230
ΔP closed, psi	60	2485	100	100	100
Position after failure of actuating force	closed	closed	closed	closed	closed

* Equivalent length in pipe diameters which will produce the same pressure drop as the valve under the same flow conditions.

NOTE: T_{hot} and T_{cold} curves are
for information only.

Figure 8

REACTOR COOLANT T_{avg} SET POINT FUNCTION

FIGURE 9
PRESSURIZER LEVEL CONTROL SET POINT FUNCTION

5.0 REFERENCES

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