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Volume II of II

MASTED

HEAVY WATER ORGANIC COOLED REACTOR

HWOCR 1000 Mwe
Nuclear Power Plant
Preliminary Conceptual Design

VOLUME II
PLANT DESCRIPTION

COMBUSTION ENGINEERING, INC.
Nuclear Division

ATOMICS INTERNATIONAL

A Division of North American Aviation Inc.

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Issued October 1, 1965

COMBUSTION ENGINEERING, INC.

Nuclear Division

ATOMICS INTERNATIONAL

A Division of North American Aviation Inc.

HWOCR 1000 Mwe Nuclear Power Plant

FOREWORD

This report describes a preliminary conceptual design and cost study of a 1000 Mwe, heavy-water moderated, organic-cooled reactor (HWOCR) power plant performed jointly by Combustion Engineering, Inc., and Atomics International Division of North American Aviation, Inc., for the U. S. Atomic Energy Commission under the direction of the Savannah River Operations Office.

This report has been prepared to provide the basis for Oak Ridge National Laboratory's review and evaluation of the 1000 Mwe HWOCR preliminary conceptual design relative to the advanced converters previously evaluated and reported in ORNL-3686*. The report consists of two volumes. Volume I contains general information regarding the study, a summary description of the plant, and cost data. Volume II is a detailed description of the plant.

*M. W. Rosenthal, et al., "A Comparative Evaluation of Advanced Converters", ORNL-3686 (January 1965)

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I. INTRODUCTION AND SUMMARY

The overall objective of the HWOCR program is to develop an advanced converter type of reactor which will generate energy at competitive cost in the near future, and which will yield increasing economic benefits because of the inherent superiority of those characteristics which will increase in importance as nuclear plants provide a greater fraction of the nation's energy requirements. The most important of these characteristics is high fuel utilization: the ability to produce a large amount of energy per unit of fissile isotope expended. So far as is currently known, the nation's resources of natural fissile isotopes are small in relation to the expected nuclear power demand, but they can in principle be stretched to meet the demand comfortably through the judicious use of high-utilization converters, such as the HWOCR, and breeders.

The steps planned toward the accomplishment of the broad purpose include the design of an HWOCR plant capable of economic power generation in the near future when built in sizes which will lie in the upper range of near future utility practice, i. e., 1000 Mwe and larger, and the design and construction of a smaller 300 to 500 Mwe plant which will demonstrate the essential features of the larger plants.

The specific objectives of this report are to document an interim step towards achieving the overall HWOCR program objective and to provide 1000 Mwe HWOCR plant preliminary conceptual design information to ORNL for comparative evaluation with other reactor concepts having similar goals.

During the past decade, considerable effort has been devoted to the development of two independent reactor types: heavy-water moderated

reactors and organic-cooled-and-moderated reactors. Especially when applied to the generation of power in large plants, the excellent neutron economy of heavy water as a moderator offers a potential for achieving improved fuel utilization with a low inventory of fissile material. However, the use of heavy water as the reactor coolant results in a costly inventory of D₂O and a high capital cost of the primary coolant loop piping and components. Organic fluids, on the other hand, are much less costly and have useful properties as high temperature coolants, e. g., low vapor pressure and non-corrosive characteristics. They are less desirable as moderators since radiation damage requires continuous makeup.

The development of a reactor which combines the advantageous features of heavy water moderation and organic cooling to reduce costs is an attractive possibility. The elimination of heavy water from the main heat transfer loop would reduce its inventory cost substantially. Restricting the quantity of organic fluid in the radiation field to that required for coolant would reduce organic makeup expense. Thus, the excellent fuel utilization properties and low fuel costs of heavy water systems would be coupled with the higher temperature obtainable at comparatively low pressure with the relatively inexpensive, non-corrosive organic coolant.

In a large heavy-water-moderated, organic-cooled reactor, only one to two percent of the neutrons are lost to parasitic absorption in the moderator. The neutrons thus conserved are utilized to convert additional fertile material to fissile fuel atoms within the fuel elements. This results in two distinct advantages: considerably less of the relatively expensive U-²³⁵ isotope need be loaded into the reactor to be "burned" per unit of heat output, and the investment in the inventory of fissile material needed to initiate and maintain the

chain reaction is markedly reduced. Utilization of separate fuel channels in an HWOCR makes possible a third benefit; that of continuous on-line refueling with the core having no excess reactivity for burnup compensation. Thus, neutrons are not lost to parasitic capture in lifetime control poisons and the fissile fuel inventory is never larger than that needed to just maintain criticality.

Considerable technology exists both in the use of heavy water as a moderator and in the use of organic liquids as reactor coolants. Much of the D_2O work has been done by E. I. du Pont at Savannah River, and much of the organic coolant technology has been developed by Atomics International. The Piqua Nuclear Power Facility (PNPF), an organic-cooled-and-moderated reactor plant, first achieved full power in January 1964. Canada has worked extensively in both areas.

Although no heavy water moderated and organic-cooled reactor has yet been constructed in this country, and no power plant of this type has been built anywhere, the WR-1, a heavy-water moderated and organic-cooled test reactor, has been built in Canada. Test and operating experience will be gained from this reactor. A similar reactor, ESSOR, is being built under Euratom's ORGEL Program in Italy.

While considerable experience has been gained in the use of organic coolants in the Canadian reactors and at PNPF, and also in the Organic Moderated Reactor Experiment (OMRE) which preceded construction of the PNPF, these installations are considerably smaller than power plants which would be large enough to capitalize on the inherent HWOCR advantages, i. e., 1000 Mwe and larger. Consequently, a research and development program and construction of a 300 to 500 Mwe demonstration plant are planned to precede construction of large plants.

The bases for the preliminary conceptual design reported here are the following:

- a) The primary design objective is the achievement of lowest power generating costs.
- b) The reactor is heavy-water moderated with fuel assemblies and organic coolant in process tubes insulated from the moderator.
- c) The technology utilized is that which will result from the successful completion of the HWOOCR development program now in progress.
- d) The reactor will operate in the period 1970-1980 using uranium fuel.
- e) The plant lifetime is 30 years and fuel costs are based on the number of fuel cycles closest to 30 years.
- f) Plutonium is to be sold without recycling back to the reactor.
- g) For capital cost estimates, it is assumed that many such plants are to be built, and that all components are fully developed.
- h) Capital cost breakdowns are to follow AEC Handbook TID-7025.
- i) Fixed charges are 12% per year for investor-owned plants and 7% per year for public ownership. Heavy water costs are assumed to be \$20/lb with corresponding fixed charge rates of 10% and 5% per year.
- j) Private ownership of fuel is assumed.
- k) Average plant factor is 0.8 over the life of the plant.

The HWOOCR power plant* generates a gross electrical output of 1088 Mw utilizing a 3093 Mwt reactor. Operating with an organic coolant temperature

*A detailed list of the plant characteristics is given in the Appendix.

of 750°F at the reactor outlet, the plant generates superheated steam which is delivered to the turbine at 725°F and 900 psig. A nuclear reheat steam cycle is employed yielding a net plant efficiency of 34.8%. Using turbine-driven pumps, the net output is 1076 Mwe.

The reactor consists of 492 fuel channels, each containing a stack of five SAP-clad slightly enriched UC fuel assemblies in the process tube. These are arranged vertically in a calandria vessel which contains the heavy water moderator. "Pigtail" piping connects the process tubes to the coolant-inlet and -outlet headers at the top and bottom of the reactor. Reactivity shutdown control is provided by 84 horizontal neutron-absorbing elements which are held out of the core region by D₂O hydraulic pressure during reactor operation and are inserted by compression springs for shutdown; control of xenon and power level is provided by 17 adjustable absorber rods supported by stainless steel tapes.

The heat generated in the heavy water moderator is used to heat the boiler feedwater. The heavy water inventory is maintained at a high purity level by filtration and ion-exchange facilities. The deuterium and oxygen released by decomposition are collected by an inert sweep gas system and are delivered to a recombiner for recovery as heavy water.

The reactor coolant is a mixture of terphenyls which is non-corrosive and which has several desirable properties. Among these are low cost, low vapor pressure, and low induced radioactivity. Three coolant loops are provided, each consisting of a circulating pump, evaporator, superheater and reheater with interconnecting piping. The coolant flow rate in each loop is 90,000 gpm. The core inlet and outlet coolant temperatures are 595°F and 750°F respectively.

Coolant composition control is maintained by several process systems. Decomposition gases are removed by degasification while particulate impurities are removed by filtration and film-forming impurities are removed by adsorption on clay. High boilers, which are high-molecular-weight coolant decomposition products, are removed by coolant distillation. These are then converted to usable coolant by catalytic hydrocracking.

The steam turbine is a tandem-compound, six-flow, 1800-rpm four-casing unit with 52-in. last stage buckets, and is designed for a reheat cycle. Steam from the superheaters enters the double-flow high-pressure casing at 900 psig and 725°F. The discharge passes through the reheaters, returning to the three double-flow low-pressure casings at 152 psig and 725°F. Final exhaust to the condensers is at a pressure of 1.5-in. Hg abs. Feedwater is heated using moderator heat and extraction steam from the turbine to a final temperature of 420°F. The turbine drives a 24 kv, 1280 mva, 1088 Mw, 0.85 PF, 3 Phase, 60 CPS generator.

The reactor and moderator systems and the refueling machine are housed in a cylindrical pressure containment building which is approximately 140 ft in diameter and 187 ft high, above grade. All other plant systems and components, including the steam generators, are located outdoors or are housed in conventional buildings which are appropriately grouped around the reactor building. The main coolant piping is equipped with double shut-off valves where it penetrates the reactor building.

A number of HWOCR plant features contribute to the objective of low-cost power production either directly or indirectly. A summary of the principal features follows:

a) The reactor design with fuel in separate process tubes permits continuous, on-power, bi-directional refueling which results in high plant availability, high fuel burnup, and low fuel cycle cost.

b) The use of heavy water as moderator minimizes fissile material inventory requirements, results in high fuel utilization, and permits an alternate choice of natural uranium fuel.

c) The low vapor pressure and non-corrosive characteristics of the organic coolant permit the use of low-pressure carbon steel coolant piping and components.

d) The reactor configuration, with its individual calandria and shields, process tubes, pigtails, and headers, is amenable to on-site assembly.

e) The low induced-activity level in the organic coolant results in reduced shielding requirements and permits personnel access to much of the plant during operation.

f) The organic coolant temperature attained yields an efficient steam cycle with nuclear superheat and reheat resulting in a compact turbine arrangement.

II. REACTOR DESIGN

The design of the reactor complex, including the biological shielding, the fuel elements and the refueling machines, is described in this section. The material is divided as follows:

- A. General Description and Design Bases
- B. Core Design
- C. Reactor Structures and Overall Layout
- D. Process Tube Design
- E. Refueling Machine
- F. Reactor Instrumentation and Control

A. GENERAL DESCRIPTION AND DESIGN BASES

The reactor complex contains moderator and shielding calandria tanks through which the process tubes pass. The process tubes contain the fuel element assemblies in tandem. The fuel is hyperstoichiometric uranium carbide clad in SAP, a dispersion strengthened aluminum material. The column of fuel is cooled by an organic terphenyl mixture; i. e., Santowax OM* containing 10% high boilers.

The orientation of the reactor is vertical and the process tubes which contain the organic coolant are normally at higher pressures and temperatures than the surrounding structures. The heavy-water moderator is contained in a cylindrical calandria provided with external cooling circuits. A separate calandria is located at each end of the moderator vessel to provide axial shielding from radiation sources within the core. The radial biological shield is concrete which supports

*Monsanto Company trade name.

the reactor and end shields. Refueling is performed with the reactor at power by two refueling machines which are located above and below the reactor structure. The machines are supported vertically from rail structures by carriages which position them opposite the ends of any fuel channel.

The core utilizes one-pass, bi-directional coolant flow with bi-directional, on-power refueling. The coolant flows in opposite directions in adjacent process tubes to maintain flow in the same direction as the fuel movement. This arrangement results in lower coolant temperatures in the higher power regions of the core, thus improving the thermal performance. Process tubes are orificed to match coolant flow rates to the basic radial power distribution resulting in a uniform coolant temperature rise across the process tubes.

The reactor produces a total fission power of 3,093 Mwt of which 2,921 Mwt are transferred directly to the coolant. The organic inlet temperature is 595°F and the outlet is 750°F with a maximum cladding surface temperature of 850°F. The power removal capability of an individual process tube is 7.30 Mwt and the total number of tubes is 492. Each tube contains five fuel assemblies consisting of 37 fuel rods.

UC fuel is selected on the basis of its high uranium density, high thermal conductivity, and demonstrated irradiation performance at the thermal conditions used as a basis for this design. The selection of SAP as the fuel cladding material is based upon its demonstrated compatibility with coolant and the fuel at design thermal conditions as well as its low thermal neutron absorption cross section and high thermal conductivity. The high thermal conductivity of the SAP permits designing with finned cladding to more fully utilize the thermal capabilities of the UC fuel. A brief discussion of the characteristics of these materials follows.

1. Materials Characteristics

a. UC Fuel

UC fuel has a thermal conductivity of approximately 13 Btu/hr-ft-°F, and a density of approximately 13.6 gm/cm³, with a metal density of about 13 gm/cm³. UC feedstock is arc-melted and cast into fuel slugs; composition is adjusted by addition of uranium metal to the casting charge. Hyperstoichiometric UC, which contains some second phase UC₂, is compatible with SAP up to 950°F which is well above the maximum anticipated fuel-clad interface temperature.

Irradiation data on UC fuel indicates a mean swelling rate of about 2% $\Delta V/V^*$ per 10,000 Mwd/MTU and a mean fission gas release of 0.1% at 2000°F. These data reflect time-weighted maximum fuel temperatures during operation and not sustained peak power. Experience with the EXP-NRX-721, a SAP-clad, UC irradiation experiment in the NRX Reactor at Chalk River, Canada, has shown that initial temperatures greater than 3000°F do not significantly affect total fission gas release or fuel swelling for extended burnup operation.*

b. SAP

HWO CR fuel-cladding and process-tube materials must have a low thermal neutron absorption cross section, adequate elevated temperature mechanical properties, and corrosion resistance in organic coolants. It is also desirable that the cladding have a high thermal conductivity. In addition, the alloys should be suitable for fabrication into desirable design configurations, such as finned tubing. Present SAP alloys are considered most promising with respect to these qualifications and are capable of sustained operation at fuel cladding temperatures of 850°F and short term operation to 950°F.

*J. E. Frank et. al., NAA-SR-TDR-11135, "Fuel Element Design, Analysis, Specifications, and Examination Procedures for the HWO CR EXP-NRU-305 Experiments", (March 9, 1965)

The 850°F yield strength and ultimate tensile strength of SAP material containing nominally 10% Al₂O₃ are approximately 11,000 and 13,000 psi, respectively, or higher, with an elongation of about 3% or greater. Extrapolated creep data predict 100,000 hr, 850°F rupture strengths of approximately 5000 psi or greater. Data on present SAP alloys indicate conservative low-strain-rate ductility of about 0.5%, which dictates fuel element design with very little or no cladding strain up to maximum fuel burnup. Development efforts to improve the low-strain-rate ductility of SAP are in progress at ORNL. The 750°F tensile and creep strengths of the 10% Al₂O₃ alloys are approximately 25-30% higher than the 850°F strengths listed above.

2. Design Bases

With the selection of UC as the fuel material and SAP as the cladding and process tube material, the following bases have been selected for the design.

- a) The maximum fuel centerline temperature should not exceed 2400°F and the fuel growth should not strain the cladding.
- b) The maximum fuel-cladding surface temperature should not exceed 850°F.
- c) The maximum coolant velocity should not exceed 30 ft/sec.
- d) The minimum DNB (Departure from Nucleate Boiling) ratio should not be smaller than 2.0.
- e) There should be no sub-cooled nucleate boiling in the core.
- f) The average discharge burnup of the fuel shall be 15,000 Mwd/MTU.
- g) The refueling shall be on-power, bi-directional.

- h) The plant shall be base loaded.
- i) Process-tube or calandria-tube leaks must be easily located.
- j) The process tube must be replaceable.
- k) Fuel element failures must be easily located.

More detailed design bases have been formulated for each of the reactor-complex components. The above list underlies the detailed bases which are included in the following sections.

B. CORE DESIGN

The core design description is divided into three separate sections:

1. Core Performance
2. Fuel Element Design
3. Nuclear Design

A summary of the reactor characteristics is included in Table A-1 (App. A).

1. Core Performance

Reactor thermal analysis is based on the fission energy distribution shown in Figure II-1. The gross fission power is 3093 Mwt, of which 2921 Mwt is supplied to the coolant. In order to insure an adequate thermal performance for all the fuel channels, a "hot channel" concept has been employed to evaluate performance. The hot channel is comprised of the fuel elements and associated flow channel in a fuel assembly experiencing the most limiting thermal conditions with respect to geometry, nuclear power peaking and engineering factors. Design factors which have been applied to determine these conditions are shown in Table II-1.

FIG II-1. Energy Distribution

TABLE II-1
THERMAL DESIGN FACTORS

Nuclear Factors		
Basic Axial		1.33
Basic Radial		1.17
Local Radial (Max.)		1.31
Local Axial (Max.)		1.17
Flux Tilt		1.05
Engineering Factors (not including those due to fuel assembly flow redistribution)		
F (ΔT_c)		1.09
F (ΔT_f)		1.21
F (Q/A)		1.12
Mixing		64%

Gross axial values have been calculated which apply to all the process tubes in the core and include local axial factors to account for peaking at the ends of the fuel assemblies. The basic-radial factor applies to the power variation with core radius. The local-radial factor accounts for the flux depression across the fuel elements in the process tube. The flux-tilt factor provides for an increase in process tube power due to local flux variations caused by control rod action.

In developing the engineering hot channel factors, consideration is given to fuel slug density, tolerances, eccentricity and enrichment. In addition, allowance is made for fuel bundle positioning and individual fuel rod orientation and bowing. Included in the hot channel factor for film drop is an uncertainty factor for the heat transfer coefficient correlation. Engineering hot channel factors are applied to the hot sub-channel temperature rise (ΔT_c), film drop (ΔT_f), and heat flux (Q/A). In addition to the local hot channel factors, allowances are made for a four-percent process-channel flow maldistribution. Other hot channel factors for ΔT_f and ΔT_c due to flow maldistribution within the fuel assembly are not listed, since these are internally computed by a three-dimensional, thermal-hydraulic computer code which is used for this analysis.

For these studies it is conservatively assumed that there is 64% mixing within the fuel assembly. Percent-mixing is defined as:

$$\left(\frac{\Delta T_{HC} - \Delta T_{HC}^M}{\Delta T_{HC} - \Delta T_A} \right) \times 100$$

where:

ΔT_{HC} is the temperature rise of the fuel element hot channel without mixing

ΔT_{HC}^M is the temperature rise of the fuel element hot channel with mixing

ΔT_A is the overall temperature rise of the entire fuel element

Section views of the fuel assembly are shown in Figures II-2 and II-3. Basically, the fuel rods are arranged in a triangular pitch. Six of the 37 rods are smaller than the rest, to obtain a better configuration within the process tube, resulting in a more uniform coolant flow distribution. The 72 flow channels within the fuel assembly are made up of four different basic flow channel geometries. As indicated in Figure II-2, channel No. 8 is the hot channel.

FIG II-2. Fuel Element Subchannel Designation

FIG II-3. Fuel Assembly

Variations of maximum fuel cladding surface temperature and coolant temperature with length in the hot channel are shown in Figure II-4.

Because of the various flow channel geometries, heat inputs and mixing that occurs within the fuel assembly, coolant flow rates and temperature rises vary throughout the fuel assembly. This can be seen in Table II-2.

TABLE II-2
FLOW AND TEMPERATURE RISE PATTERNS

Channel No. (refer to Figure II-2)	W_c/W_{HC}	$\Delta T_c / \Delta T_{HC}$
1	1.01	0.78
2	1.01	0.86
3	1.01	0.92
4	1.01	0.99
5	0.90	0.96
6	1.52	0.79
7	1.97	0.85
8	1.00	1.00

where:

W_c refers to coolant flow rate in a particular channel
 W_{HC} refers to coolant flow rate in the hot channel
 ΔT_c refers to coolant temperature rise in a particular channel
 ΔT_{HC} refers to coolant temperature rise in the hot channel

FIG II-4. Hot-Channel Coolant and Surface Temperature vs Core Length

It can be seen that, although channel No. 5 has the lowest flow rate, it does not have the highest coolant temperature rise, since it does not have a high heat input. Coolant mixing of the hotter channels No. 5 and No. 8, with the cooler channels, No. 6 and No. 7, helps keep maximum temperatures down.

Critical heat flux, or DNB, ratios were computed for the reactor hot channel. These DNB ratios are shown in Figure II-5. The minimum DNB ratio is approximately 4.0. This occurs at 60% of core length downstream of the inlet. These high DNB ratios indicate that burnout is not a controlling design limitation in the HWO CR.

Critical heat fluxes were computed using the relationship described in NAA-SR-Memo-7343* which follows the form:

$$(Q/A)_c = 129,000 + 11 (\Delta T_{sub}) G^{0.8}$$

where (Q/A) is critical heat flux (Btu/hr-ft²)

ΔT_{sub} is sub-cooling ΔT (°F)

G is mass velocity (lb/sec ft²)

It should be pointed out that in the design of the core, maximum cladding temperatures of 850°F are based on local "hot spot" temperatures which occur just at the time of fuel loading. No credit has been taken for the fact that the 850°F cladding temperature limit is actually based on long term conditions and that this temperature only occurs locally for a very short period of time in this design. The DNB margins in this core are such that one could accommodate a higher short-term power rating, permitting situations where the maximum surface temperature might be slightly more than 850°F, and the local heat release rating of the fuel somewhat higher than the design value.

*NAA-SR-Memo-7343, Organic Reactor Heat Transfer Manual, pg. V-2

FIG II-5. Hot Channel DNB vs Core Length

As shown in the general reactor arrangement in Figure II-18, coolant from the primary system piping enters the reactor inlet header and flows through the header riser pipes and pigtails to the process tube extensions, into the process tubes, through the shielding plugs and over the fuel elements, discharging through the outlet shielding plugs, pigtails and header risers to the outlet headers.

The arrangement of the shield plugs and spacers in the process tubes at each end of the fuel region is shown in Figure II-25. The fuel in the core is divided into five axial assemblies. Details of the fuel assemblies are shown in Figures II-6 and II-3 and described in B.2, "Fuel Element Design."

A summary of reactor pressure drop follows:

Across Fuel Assemblies, (max), psi	142
Headers, Risers, Pigtails, Orifices and Process Tube Extensions (psi)	<u>42</u>
Total Reactor (header-to-header), psi	184

Since orificing is used to match process-tube coolant flow rate with the basic radial power distribution, velocities and pressure drops vary from tube to tube. The maximum pressure drop across the fuel assemblies occurs in the central process tube, which has the highest heat release rate. The maximum velocity in the fuel region of the process channel has been set at 30 ft/sec, to minimize possible fuel element vibration problems. The maximum velocity in the pigtails is 25 ft/sec. The fuel assembly pressure drop shown above includes an allowance for end plates and fuel assembly misalignment.

FIG II-6. Fuel Element Isometric Drawing

2. Fuel Element Design

The reference fuel element consists of 37 SAP-clad fuel rods filled with cast hyperstoichiometric uranium carbide fuel. Cladding is 0.020-in. -thick, is extruded with integral fins and is free-standing under the external pressure of the coolant. The fuel element design is shown in Figures II-3 and II-6. The outside diameter (not including fins) of the thirty-one larger rods is 0.521 in., while the remaining six are 0.324 in. in diameter to achieve a circular configuration at the outer periphery. The corresponding UC slug diameters are 0.476 and 0.277 in., respectively. Each fuel assembly has an overall length of 44.133 in.* and a diameter over the fins of 4.260 in. Five fuel assemblies are stacked to fill one process channel. Radial clearance between the outer edge of the fins and the 4.320 in. ID process channel is 0.030 in.

The fuel shown in Figures II-3 and II-6 is hyperstoichiometric uranium carbide, nominally 5% by weight carbon, cast into slugs approximately three in. long. One end of the pellet is dished. The dish depth is 0.040 in. and the land width is 0.020 in. This will provide a uniform bearing-surface on the pellet interfaces and contribute to a symmetrically located pellet. The large rods have 12 fins (0.080-in. -high x 0.030 in. wide) equally spaced on the periphery of the tube. These spiral at 90°/ft. The small rods have six axially straight fins (0.060 in. -high x 0.030 in. -wide) and two taller fins (0.128 in. high x 0.040 in. wide) which maintain the spacing between the adjacent larger rods, as shown.

The fuel rods are restrained at each end by Zircaloy-4 end plates attached to 12 large rods on the periphery of the bundle. The smaller rods and 19 inner rods are free-floating in the axial direction to allow for thermal expansion due to the temperature gradient across the bundle. All rods are restrained from rotating by dowel pins pressed into the end caps and extending into the Zircaloy end plate with a slip fit. The dowel pins are trapped by the end plates and sized to accommodate the relative expansion of the outer rods. Short SAP end caps

*All dimensions given in this section are for hot conditions.

are used on the six small rods and all inner floating rods, with longer end caps for the 12 outer rods. End cap closures are attached to the SAP cladding by magnetic-force resistance welding.

The overall length of the fuel assembly is 44.133 in., with an overall fuel length of 42.158 in. on the outer rods and 42.783 in. on the inner rods. The fuel-to-fuel distance between adjacent bundles is 1.975 in. on the outer rods and 1.350 in. on the inner rods.

The taper on the outer surface of the end plate is utilized to accommodate latches to support the fuel column during the refueling operation. Adequate clearance for latches pulling the fuel is provided by the undercut in the outer bank of end caps.

Twenty mils are machined from the fins following assembly at the outer periphery of the fuel assembly, maintaining a nominal hot clearance between the bundle and fuel channel of 0.030 in. This provides a continuous fin-surface-bearing area for each outer fuel rod along the length of the process channel.

Maximum allowable linear heat rate (kw/ft) to obtain zero cladding strain at the end-of-life for an initial 0.0025 in. radial helium gap is 33 kw/ft. This value is obtained using a 2% volume growth rate per 10,000 Mwd/MTU burnup for fuel temperatures up to 2400°F. The analysis accounts for increasing gap conductance with burnup. Although dilution of helium resulting from fission gas release reduces the gas gap conductivity between the fuel and cladding, the gap conductance increases with burnup because of fuel growth. A cladding surface temperature of 820°F is used in this analysis since the highest power density does not occur in the region of the maximum surface temperature. Figure II-7 shows the radial temperature distribution within a fuel rod having a 0.0025 in. helium gap and a heat rating of 33 kw/ft.

FIG II-7. Temperature Distribution Through Fuel Rod With a Linear Heat Generation Rate of 33 kw/ft

At design conditions of 26.7 kw/ft, a slight gap theoretically will exist between the fuel and cladding at end-of-life. Tolerances of ± 0.0005 in. on the pellet outer diameter and ± 0.001 in. on the cladding inner diameter result in a maximum cladding strain of less than 0.3%. Canadian experience* indicates that a plastic strain of 0.5% or greater is required to produce cladding failure in SAP. Figure II-8 was used to compute fission gas release from the fuel.** For a burn-up of 20,500 Mwd/MTU, which corresponds to the maximum burnup rod in a fuel assembly exposed to 16,700 Mwd/MTU (average), 0.31% of the gas produced is released. A 0.600 in. axial gap is required at the upper end of the fuel rod to accommodate fuel volume growth and fission gas. Internal pressure in the fuel rod at the end-of-life is 300 psi, maximum.

Loads on a fuel assembly are a result of hydraulic and frictional drag forces and weight of fuel assemblies in the channel. Highest loads are encountered with down-flow in the process channel. With bi-directional flow and refueling, the highest hoop stress occurs, due to external pressure, when the fuel is in its initial position. Axial stress on the fuel cladding increases, and hoop stress decreases as the fuel assembly is moved down the process channel. Maximum cladding stress is a result of axial compressive stress, net hoop stress due to external and internal pressure, and bending stress due to rod bowing. These are combined into a biaxial stress by the distortion energy theory.*** Table II-3 presents cladding stress as a function of fuel assembly position.

Stress rupture limits the allowable transverse design stress to 4000 psi for SAP. The allowable biaxial stress is somewhat higher. Even though during operation, the end plates will deflect allowing a portion of the load to be transmitted to the inner rods, it was assumed in the calculations that all loads were supported by the 12 outer rods.

*Development of Fuel and Coolant Tubes for a Reactor Cooled by Organic Liquid, Third United Nations International Conference on Peaceful Uses of Atomic Energy, A/Conf. 28/p/23 May 1964

**NAA-SR-TDR-11135 (See page II-3.)

***"Mechanical Behavior of Engineering Materials," J. Martin - pg. 120, 1962

FIG II-8. UC Fission Gas Release as a Function of Temperature

TABLE II-3
STRESS TABULATION
(psi)

Fuel Assembly Position	S _{compressive} + Bending	S _{hoop}	Biaxial Stress
0	- 400	-3150	-2970
1	-1500	-2850	-2460
2	-2000	-2500	-2290
3	-2700	0	-2700
4	-1514	+1400	+2970
5	-2414	+2205	+4000

3. Nuclear Design

The list of nuclear characteristics is given in Table II-4.

a. Fuel Management

The fuel management program for this reactor employs the biaxial or bi-directional feed-through of fuel elements while operating at power. Movement of the individual fuel elements with time (burnup) is in opposite directions for any two adjacent fuel channels. Feed-through rate in any one channel is dependent upon the power generation and the discharge burnup desired in that channel. The core is divided into inner and outer regions, with each region having the same number of fuel channels. The central region has a higher discharge burnup so that a high degree of radial power flattening is achieved.

(1) Initial Core

Each fuel channel in the equilibrium core normally contains five fuel elements of differing degrees of burnup. Consequently, in order to preserve the axial and radial power distribution patterns and permit full power operation in the initial core, axial and radial variations in enrichment are employed. Table II-5 summarizes the enrichments to be employed in the individual fuel elements for each fuel channel in both the inner and outer radial regions. In addition, the fissile plutonium and U^{235} content of each fuel element (at discharge) is given. It is

TABLE II-4
REACTOR CHARACTERISTICS⁽¹⁾

1. D ₂ O/UC volume ratio ⁽²⁾	15.2 (hot),	15.4 (cold)
2. Organic/UC volume ratio ⁽²⁾	1.1066 (hot),	1.12083 (cold)
3. D/U ⁽²⁾ (fresh fuel, hot conditions)	30.32	
4. Organic Volume Fraction	0.446 (hot),	0.448 (cold)
5. Power Peaking Factors		
a. Basic Radial		1.17
b. Basic Axial		1.40
c. Local Radial (fresh fuel)		1.30
d. Local Axial (fresh fuel) ⁽³⁾		1.175
e. Local Flux Tilt		1.05
6. Reactivity Changes		
a. Cold to Zero power ⁽⁴⁾		
(1) Moderator, 68°F to 190°F; Fuel and Coolant at 190°F		0.6 mk
(2) Fuel and Coolant from 190°F to 534°F		13.4 mk
b. Zero to Full Power (no decay heat)		
(1) Fuel from 534°F to 1000°F		-3.3 mk
(2) Coolant from 534°F to 675°F		+6.3 mk
c. Zero to Full Power (decay heat present)		
Fuel from 595°F to 1000°F		-2.9 mk
d. Zero to Equilibrium Xenon		-27.0 mk
e. Zero to Equilibrium Samarium		-7.0 mk
7. Excess Reactivity		
a. Hot, Full Power, Equilibrium Xenon and Samarium		2 mk
b. Zero Power, Fuel and Coolant at 190°F, Moderator at 68°F, No Xenon, with Equilibrium Samarium		10 mk

- (1) For the equilibrium core unless otherwise indicated
(2) Characteristic value in an active fuel segment of a fuel element based on 0.472/0.275 in fuel diameters in the cold condition
(3) For outer fuel element in the element
(4) No Xenon, with Equilibrium Samarium

8. Reactivity Worth of Control System

a. Dissolved Boron

(1) Equilibrium Xenon 27 mk

(2) Emergency Shutdown 63 mk

b. Vertical Control Elements 3 mk

c. Horizontal Control Elements 40 mk

9. Reactivity Coefficients⁽⁵⁾

a. Fuel Temperature	$-0.48 \times 10^{-5} \Delta k/k/^{\circ}F$
b. Coolant Temperature	$+0.53 \times 10^{-4} \Delta k/k/^{\circ}F$
c. Moderator Temperature	$+0.44 \times 10^{-5} \Delta k/k/^{\circ}F$
d. Moderator Purity	$-1.6 \times 10^{-2} \Delta k/k/\%H_2O$
e. Coolant Void	$+0.11 \times 10^{-2} \Delta k/k/\% \text{ void}$
f. Power	$+0.22 \times 10^{-4} \Delta k/k/\% \text{ power increase}$

10. Fuel Inventory and Burnup

a. Uranium Total	123 MTU
b. Feed Enrichment	1.16 w/o
c. Discharge Exposure ⁽⁶⁾	15000 MWD/MTU
d. Discharge Enrichment (w/o U^{235}) ⁽⁶⁾	0.205
e. Discharge Fissile Plutonium (gr/Kg U initial) ⁽⁶⁾	3.18

11. Neutron Average lifetime (equilibrium core) $5.7 \times 10^{-4} \text{ sec}$

12. Effective Delayed Neutron Fraction (equilibrium core) 0.00489

(5) At full power operating conditions

(6) Core averaged value

expected that refueling operations will begin immediately upon achieving full-power operation. The refueling pattern will be dictated by the on-line computer summary of channel-by-channel power generation.

TABLE II-5
INITIAL CORE ENRICHMENTS AND FISSILE CONTENT AT DISCHARGE

Axial Position*	Initial U ²³⁵ Enrichment (wt%)		Fissile Pu Content at Discharge (g/KgU)		U ²³⁵ Content at Discharge (wt%)	
	Inner†	Outer†	Inner†	Outer†	Inner†	Outer†
1	1.06	1.06	3.12	3.02	0.16	0.24
2	0.90	0.95	2.93	2.78	0.18	0.27
3	0.73	0.79	2.60	2.36	0.23	0.34
4	0.62	0.69	1.95	1.70	0.33	0.40
5	0.57	0.63	0.99	0.70	0.47	0.57

*Axial position defined relative to direction of movement of fuel within a given channel.

†Inner and outer refer to the two burnup regions of the reactor.

(2) Equilibrium Core:

The transition from initial core to a near equilibrium core will take place in approximately two and one-half years. When the core is operating as an equilibrium core, the power fractions in the inner and outer regions will be 0.57 and 0.43, respectively. Table II-6 summarizes the pertinent data associated with fuel management in the equilibrium core. The residence time of a fuel element in any given channel is determined by the following equation:

$$T \text{ (days)} = \frac{EL}{PFR}$$

where:

E is the design burnup (Mwd/MTU) of the fuel discharged from the channel

P is the average fission power per channel (Mw)

F is the plant factor (0.80)

R is the radial power peaking factor for the channel

L is the fuel loading per channel (MTU)

TABLE II-6
FUEL MANAGEMENT IN THE EQUILIBRIUM CORE

	Region	
	Inner	Outer
Feed Enrichment (w/o U^{235})	1.16	1.16
Average Discharge Burnup (Mwd/MTU)	16,700	13,300
w/o U^{235} in Discharge	0.163	0.257
Fissile Plutonium in Discharge (gr/KgU)	3.22	3.10
Residence Time* (days)	Min	709
	Max	747
	Avg	728
		574
		1405
		768

*Fuel Element In-Core Lifetime

(3) Final Core

Table II-7 summarizes the regionwise average data on the fissile content of the final core.

TABLE II-7
FISSILE CONTENT OF FINAL CORE

Axial Position*	Fissile Pu Content (g/KgU)		U^{235} Content (wt%)	
	Inner†	Outer†	Inner†	Outer†
1	0.80	0.63	1.01	1.04
2	1.98	1.70	0.71	0.78
3	2.74	2.48	0.44	0.54
4	3.08	2.88	0.27	0.37
5	3.20	3.06	0.18	0.28

*Axial position defined relative to direction of movement of fuel within a given channel from insertion to discharge.

†Inner and outer refer to the two burnup regions of the reactor.

c. Power and Burnup Distribution in the Equilibrium Core

(1) Axial Power Distribution

The axial power distribution in any given channel is illustrated in Figure II-9 for two cases: (a) just prior to insertion of a fresh fuel element, and (b) just after insertion of a fresh fuel element. Some measure of the local axial power peaking due to the presence of non-fuel-bearing end-cap regions of the fuel element is contained in the power distribution of Figure II-9, since these regions were represented explicitly in the calculations. The local axial peaking within each fuel rod in the channel is calculated more accurately as described in the next section. The basic axial power distribution, i. e. without local axial effects, for the worst case of Figure II-9 is estimated to have a maximum-to-average power peak of 1.33.

One other axial power distribution of interest is that occurring in one phase of the refueling process. During the time interval following the removal of the fuel element to be discharged and the replacement of the down-channel spacer element, the entire fuel column is displaced downstream by the length of one fuel element. As a consequence, a fresh fuel element is positioned in an axial region of normally higher power density. Figure II-10 illustrates the axial power distribution in the fuel channel during this transition period. It should be noted that the maximum value of the power peak in Figure II-10 is comparable to that of Figure II-9.

Detailed calculations of the local power peaking effects arising from the presence of end-cap regions were carried out by an R-Z cell calculation. In this calculation, a detailed cylindrical geometric representation of the lattice cell was employed, as is illustrated in Figure II-11. It should be noted that the active fuel length of the fuel pins in the outer ring of the 37-rod cluster is less than that in the remaining pins of the cluster. Figure II-12 illustrates (for the fresh fuel condition) the local variation in power in individual fuel pins as a function of distance from the fuel interface for various pin positions within the assembly. The local axial peaking factor relative to the pin average for a fuel pin positioned at the periphery of the fuel assembly is seen to be 1.175, whereas, for the central pin of the assembly, it is 1.43. Figure II-13

Axial Power Distribution Change with New Fuel

FIG II-9. Axial Power Distribution at Start and End of Fuel Cycle

Axial Power Distribution with Fuel Column Displaced
One-Element-Length Downstream

FIG II-10. Axial Power Distribution Change Resulting from One-Element-Length Downstream-Displacement of the Fuel Bundle

Lattice Cell Geometry Employed in Calculation of
Local-Axial-Power Peaking Effects

FIG II-11. Lattice Cell Geometry Employed in Calculation of Local-Axial-Power
Peaking Effects

Element Axial Power vs Distance From Fuel Interface (inches)

FIG II-12. Element Axial Power vs Distance from Fuel Interface
(As Defined in FIG II-11)

Element Local Power vs Distance From Fuel Interface (inches)

FIG II-13. Local Power Distribution vs Distance From Fuel Interface

illustrates combined effects of the local axial and the local radial power peaking in the channel (fresh fuel condition). The cluster averaged power distribution includes both the local axial and the local radial power variation which is discussed below.

(2) Radial Power Distribution

The basic radial power distribution in this reactor can be flattened significantly; the radial peaking factor can be decreased to as low as 1.17, by exposing the fuel in the inner half of the core to a higher average discharge burnup, with only a small loss in reactivity or core average discharge burnup. Figure II-14 illustrates the dependence of the basic radial peaking factor on the reactivity change required to obtain a given degree of radial power shaping. The conditions imposed on the calculations are as follows: (a) the feed enrichment and the core averaged-discharge-burnup remain constant; (b) the maximum in the radial power distribution must occur in the inner region of the reactor; and (c) the inner and outer radial burnup regions are of equal volume. The zoning arrangement selected for this reactor is based on an average discharge of 16,700 Mwd/MTU in the inner zone and 13,300 Mwd/MTU in the outer, which provides a basic radial peaking factor of 1.17. Figure II-15 shows the basic radial power distribution for this case.

(3) Local Radial Power Distribution

The local radial peaking factor is a measure of the decrease in power density towards the center of the fuel element, as a result of hardening of the neutron spectrum and flux depression. This radial change in power density varies with fuel burnup due to a preferential depletion of U^{235} in the peripheral fuel pins, as well as a non-uniform production and depletion of fissile plutonium along the radial direction in the fuel element. Figure II-16 shows the dependence of the average power density variation with burnup, for fuel pins located at the edge of the cluster and for fuel pins located in the ring adjacent to the outermost fuel ring.

d. Reactivity Changes and Control In The Equilibrium Core

(1) Reactivity Coefficients

Table II-8 summarizes the reactivity coefficients for the equilibrium core under hot operating, full power conditions.

Basic Radial Peaking Factor vs Reactivity Change

FIG II-14. Radial Peaking Factor vs the Reactivity Change Required to Obtain a Given Degree of Radial Power Shaping

FIG II-15. Radial Power Distribution for the Two Region Core

FIG II-16. Burnup vs Local-to-Average Power Density
(Second and Third Fuel Rings Only)

TABLE II- 8
REACTIVITY COEFFICIENTS IN THE EQUILIBRIUM CORE

Fuel Temperature	$-0.48 \times 10^{-5} \Delta k/k/^{\circ}F$
Coolant Temperature	$+0.53 \times 10^{-5} \Delta k/k/^{\circ}F$
Moderator Temperature	$+0.44 \times 10^{-5} \Delta k/k/^{\circ}F$
Moderator Purity	$-1.6 \% \Delta k/k/\%H_2O$
Coolant Void	$+0.011 \% \Delta k/k/\%void$
Power	$+0.22 \times 10^{-2} \% \Delta k/k/\% \text{ power increase}$

The fuel temperature coefficient includes Doppler broadening of the U^{238} resonances and thermal energy spectral effects resulting from a change in the fuel temperature. The coolant temperature coefficient of reactivity is approximately ten times larger than the fuel temperature coefficient, hence it is the dominant factor in a determination of the power coefficient. The moderator purity coefficient is negative and linear down to a D_2O purity of 97%. At hot operating conditions, the coolant void coefficient is linear over the range from zero to full density. Complete voiding of all coolant channels in the equilibrium core, under full power hot operating conditions, results in a positive reactivity change of 11 mk.

(2) Reactivity Changes

Table II-9 summarizes the reactivity changes associated with variations in the equilibrium core conditions.

(3) Worth of Dissolved Boron in the Moderator

Table II-10 summarizes the reactivity worth of natural boron and boron-10 dissolved in the moderator of the equilibrium core.

e. Radiation Effects

(1) Shield Design

Radiation shields are required, to protect plant personnel and out-of-core equipment from radiation damage. The dose rate levels throughout the plant

TABLE II-9
REACTIVITY CHANGES IN THE EQUILIBRIUM CORE

a. Cold to zero power, no xenon, with equilibrium samarium		
1) Moderator, 68°F to 190°F; fuel and coolant at 190°F		0.6 mk
2) Fuel and coolant from 190°F to 534°F		13.4 mk
b. Zero to full power (no decay heat present)		
1) Fuel from 534°F to 1000°F		-3.3 mk
2) Coolant from 534°F to 675°F		+6.3 mk
c. Zero to full power (decay heat present)		
1) Fuel from 595°F to 1000°F		-2.9 mk
2) Coolant from 595°F to 675°F		+3.7 mk
d. Zero to equilibrium xenon		-27 mk
e. Zero to equilibrium samarium		

TABLE II-10
REACTIVITY WORTH OF BORON IN THE MODERATOR
OF THE EQUILIBRIUM CORE

Reactivity Change (mk)	Natural Boron Conc. (10 ⁻¹⁸ atom/cc)	Boron ⁻¹⁰ Conc. (10 ⁻¹⁷ atom/cc)
20	0.26	0.49
40	0.52	0.97
60	0.78	1.48
80	1.08	2.04
100	1.45	2.74

are limited to values that will allow personnel to carry out normal operations, maintenance, and inspections without exceeding tolerance levels. In areas outside the biological shield requiring limited occupancy, the operating dose rate has been limited to 2.5 mrad per hour, at approximately three feet from the shield surface. Upper and lower shields are provided in the HWOCR design, to protect the headers and refueling equipment

from radiation damage during reactor operations, to reduce the neutron flux sufficiently so that activation of the shields and equipment in the refueling vault will not prevent entry for limited periods with the reactor shut down, and to reduce the after-shutdown dose rate from the reactor sufficiently to allow limited access within one hour after shutdown. A further purpose of the end shields is the removal of heat generated by the nuclear radiation and heat loss through the process tubes. An additional reduction of the dose rate through the shield is not useful, since the dose rate in the area will be relatively high in any case because of the radiation from the discharged fuel in the refueling machine. The dose rate in the refueling machine vault directly above the refueling face has been limited to less than 100 Rad/hr during reactor operation and 12 mrad/hr one hour following reactor shutdown.

The calculated radial shield thicknesses are shown in Table II-11. The inner face of the concrete biological shield is protected from overheating by use of a composite steel-water thermal shield made up of three concentric steel cylinders, with the annuli between the cylinders filled with ordinary water.

TABLE II-11
RADIAL SHIELD THICKNESSES

Description	Material	Thickness (in.)
Composite thermal shield		
Inner wall	Steel	1
First water gap	H ₂ O	3.5
Middle wall	Steel	0.75
Second water gap	H ₂ O	3.5
Outer wall	Steel	1
Biological shield	Ordinary concrete	114

Although the upper and lower shield tank contains many penetrations, the shields in the penetrations have been designed with enough conservatism that limiting the dose rate through the shield tank is the controlling parameter. The shield plugs are designed to have a minimum of 12 in. of steel along any radiation path through the coolant channel. This shield plug, like the organic coolant, attenuates the gammas and neutrons more effectively than the end-shield tanks. Table II-12 shows the materials and thicknesses of the upper and lower shield tanks.

TABLE II-12
UPPER AND LOWER SHIELD TANKS

Description	Material	Thicknesses (in.) from Reactor Face	
		Upper	Lower
Tank Wall	Steel	2	1
Water	H ₂ O	14	14
Shot Retainer Wall	Steel	1	1
Steel balls and Water	65% steel 35% H ₂ O	18	18
Tank Wall	Steel	1	1
	TOTAL	36	36

Shielding around the refueling machine vault is determined by the shielding required for the discharged fuel in the refueling machine. To reduce the dose rate to 2.5 mrad/hr around the refueling vault, six feet of ordinary concrete is required.

(2) Radiation Energy Deposition

Energy deposited in the organic coolant directly from nuclear radiation is important in determining the radiolytic damage to the organic coolant. As the damage rates per unit of energy deposited by gammas and neutrons are different, the contribution from each type of radiation is included. The calculated energy deposition rates are 10.0 Mw from neutron slowing down and 3 Mw from gamma absorption. The 13 Mw is approximately 0.42% of the total fission power.

Energy deposited in the moderator determines the size of the moderator cooling system and the net plant efficiency. The total gamma and neutron energy deposited in the moderator and calandria tank is 156 Mwt.

C. REACTOR STRUCTURES AND LAYOUT

1. Reactor-Complex Layout (Figures II-17 through II-21)

The calandria is a right-cylinder with a vertical axis, and is surrounded by an annular, concrete, biological shield. Circular openings above and below the calandria are closed by steel and water end shields.

The weight of the calandria, end shields, and fuel assemblies is supported by the biological shield. The calandria rests on the upper tubesheet of the lower end shield, which has peripheral skirt supports bolted to the concrete. Support for the fuel channels is provided by flanges on the upper pressure tube extensions. These flanges are bolted to the upper tubesheet of the upper end shield, which also has peripheral skirt supports bolted to the biological shield. The fuel channels (Section II. D) are located on a 10.5-in. square grid; in any grid square, one diagonally-opposed pair of channels has upward flow of organic coolant and the other pair has downward flow (Figure II-20). The fuel channel assemblies pass through tubes in the end shields and calandria, which, respectively, isolate the light water in the shield from the process tube extensions, and the heavy water moderator in the calandria from the process tubes. The 0.274-in. annulus thus formed

FIG II-17. Reactor Complex, Section Through Center of Reactor

FIG II-18. Reactor Complex, Section A-A

FIG II-19. Reactor Complex, Section B-B

PLAN VIEW OF THE JUMPER TUBE CONNECTIONS TO THE PRESSURE
TUBE EXTENSIONS OF A ONE PASS BI-DIRECTIONAL REACTOR

○ INDICATES AN
UPFLOW TUBE

● INDICATES A
DOWNFLOW TUBE

FIG II-20. Plan View of Pigtail Connections

FIG II-21. Pigtail and Header Arrangement

around the fuel channel also serves to contain a CO_2 gas atmosphere around the fuel channels as a thermal barrier. Fuel channels in this design are guided in sliding bearings in the upper and lower end shields and are free to expand downwards. A gasket at the upper support flange, and a packed gland at the lower end shield face on each channel, isolate the CO_2 atmosphere from that in the refueling machine rooms. The calandria cavity is also filled with CO_2 , which can interchange freely with the gas around the fuel channels at the top of the calandria.

Eight segmental steel and water thermal shield tanks, form a complete protective cylinder around the inner face of the biological shield. The thermal and biological shields are penetrated by inlet and return ducts for CO_2 circulation, and by connections to the calandria for moderator cooling and draining, moderator overflow, horizontal control rods, and in-core instrumentation. Provision is also made for access through the shields to the calandria cavity during construction, and for the insertion of remote inspection and maintenance equipment after plant start-up. All penetrations, and all joints between the vessels forming the outer envelope of the calandria cavity, have steel plate seals to isolate the atmosphere within the cavity from that outside.

The fuel channels terminate in flanges at the refueling faces above and below the end shields. Each channel is connected to an inlet and outlet header by pigtail(jumper)pipes welded to tees on the process tube extensions and to riser pipes which are part of the header fabrications. These pigtails can be readily disconnected and reconnected at the tees by a remotely operated cutting and welding operation for fuel channel replacement. (See Figure II-20.)

The reactor is divided into four quadrants for organic coolant distribution. All upflow fuel channels in a quadrant are connected to an inlet header in the lower refueling machine vault, and to an outlet header in the upper refueling machine vault. Similarly, all the downflow channels in the quadrant are connected to an inlet header in the upper refueling machine vault and to an outlet header in the lower refueling machine vault. Thus, there are four pairs of headers in each vault.

Pigtails are run out from the fuel channels in vertically stacked columns between the process tube extensions. Each vertical stack contains pigtails in which the coolant flow is all in the same direction. Individual pigtails run parallel to the process tube extensions, in towards the end shields, until they reach the allocated elevation in a vertical stack at which point the pigtails bend into the stack. The vertical stacks proceed straight outwards to a point above the thermal shields, and then make a right angle turn towards the headers (see Figure II-21). Further turns near the headers bring the pigtails to the risers on the headers. This routing of the pigtails provides sufficient flexibility to absorb the operating temperature differential expansion between the pigtails and the end shields, without deflecting the process tube extensions more than 0.25 in. at the refueling flanges.

The process tube extensions and associated pigtail stacks are insulated by means of special 2-in. -thick insulating blocks resting on collars attached to the process tube extensions. These blocks are one-lattice-grid-pitch wide and three-pitches-long, with cutouts to fit the extensions, and are installed by being passed edgewise between the extension refueling flanges and then being rotated into the correct position. The blocks are removable in the same manner, should it become necessary to replace a fuel channel. Two such layers of blocks are used. The banks of pigtails outside of the fuel channel area are enclosed in insulated ducts, which also surround the headers.

Power regulation and equilibrium xenon control assemblies operate vertically between certain fuel channels, and extend through the upper calandria tubesheet, the upper end shield and the upper insulation blocks, to the control assemblies drive mechanisms, just below the process-tube refueling flanges. Each assembly is removable for maintenance, or to permit the replacement of an adjacent fuel channel assembly.

Both refueling machines are suspended from overhead tracks (Figure II-18). Each machine has a main carriage rotating above or below the refueling faces, on a main rotary track. The fueling head proper is suspended from a carriage which runs on parallel tracks in the main carriage across the center of the main

rotary track. Thus, by a combination of rotating the main carriage and traversing the fueling head carriage, the fueling head can reach any fuel channel in the reactor.

To pick up new fuel or deposit spent fuel, the traversing tracks on the main carriage are lined up with a transfer bridge track. The fueling head carriage can then be run out over the transfer bridge track, onto traversing tracks on a service carriage which can rotate on a service rotary track. The new fuel loading and spent fuel transfer stations, and the fuel channel hardware (e.g., seal and shielding plugs) transfer station are located on the circumference of a circle whose center is coincident with that of the service rotary track. New fuel is stored in rooms immediately above and below the lower and upper refueling machine vaults, respectively. Spent fuel is lowered in organic-coolant-filled containers, on a winch cable, into a water-filled storage pool in the containment building, at grade level, where it is hung in storage racks. After the fuel has decayed sufficiently, it is transferred through an underwater revolving door in the containment wall into an outside storage area, from which it is loaded into a cask for shipping.

Access to the refueling machine vaults is possible only during reactor shutdown, so that vault fires which might occur due to organic coolant leaks during operation would have to be extinguished by an automatic dousing system. Such dousing tends to cause more widespread equipment damage than conventional fire-fighting methods used by trained operators with access to the vaults; therefore, during reactor operation, the oxygen content in the atmosphere is held below 5% by nitrogen displacement, to prevent the possibility of a fire erupting. To enable safe performance of shutdown maintenance, a normal air atmosphere can be established. Under these circumstances, normal firefighting procedures can be used if necessary.

Both refueling machine vaults are provided with gutters and drains for returning organic coolant to the primary coolant storage tank, in the event of large leaks. A similar drain arrangement is made in the calandria vault. This system is used also to collect heavy-water leakage.

Since the refueling machine heads may require routine maintenance at fairly short intervals, it is desirable to be able to perform such maintenance without shutting the reactor down. Shielded rooms for this purpose are connected to the refueling machine vaults by moveable shield doors. The refueling machine carriages can be run out into these maintenance rooms, over maintenance tracks connecting with the service carriage tracks, when the latter are lined up with the transfer bridge tracks.

A dummy fuel channel assembly, similar in all respects to the reactor fuel channel assemblies, and with provision for circulating hot organic coolant under pressure, is provided between the maintenance rooms, with one refueling face in each room. This allows refueling machine heads to be checked out after maintenance and before being returned to the fueling machines vaults. It is also useful for operator training.

2. Component Descriptions

a. Calandria

The calandria (Figures II-22 and II-23) is a high-integrity vessel which contains the heavy-water moderator and encloses the process tubes. It is an austenitic-stainless-steel, cylindrical, vessel consisting of a 1-in.-thick shell welded to flat-end tubesheets. Tubesheet thicknesses are 1.5 in. at the upper end and 1.75 in. at the lower end. The overall dimensions of the vessel are 26.16-ft OD and 20.25-ft high. Through-tubes of Zircaloy-2 are rolled into the tube sheets on a 10.5-in.-square grid arrangement. The tube-to-tubesheet joint is a landed-type sandwich joint which has been proven in similar applications to be satisfactory. The calandria tubes are 5.094-in. ID. Through each tube passes a process tube, 4.552-in. OD and 0.116-in.-thick, which contains the fuel bundles. The inside dimensions of the calandria provide a 12-in. reflector in both axial and radial directions outside the active core. The D₂O flow is fed into the discharge nozzles through annular flow channels built into the calandria shell. These channels are designed to provide uniform cooling throughout the vessel. An emergency D₂O spray system is provided by means of a circular header and branch feed

FIG II-22. Reactor Components Elevation

FIG II-23. Reactor Components Plan

channels built into the top of the upper tube sheet. The spray nozzles are located inside the vessel, directly under the tubesheet. The nozzles direct D₂O against the tubesheet, the process tubes and the shell in case of a drop in moderator level. About 5% of the total moderator inlet flow is supplied continuously through the spray system during normal operation; this is increased to 20% of total normal flow if a drop in moderator level is detected.

The calandria operates full of heavy water maintained at 2 psig at the upper tubesheet level. This pressure is maintained by means of a level control tank connected to the vessel by a 7-in. header fed by four 3-in. pipes passing through the upper tubesheet and opening directly into the moderator. Removal of radiolytic decomposition gases from the system is also accomplished with this arrangement. A helium gas blanket is maintained over the moderator in the level control tank.

The calandria shell contains 84 penetrations to house control rods; 42 horizontal penetrations on each of two opposite sides. There are also 15 penetrations through the calandria for instrument tubes. The upper tubesheet has penetrations for 17 vertical control rod assemblies. An 8-in., normally closed, horizontal drain line is located near the bottom of the vessel. A 1-in. vertical drain is provided in the bottom tubesheet to provide for complete drainage if the need should arise. This drain is normally capped with a shielding plug. A gridwork of supporting bars, provided on the under-surface of the lower tubesheet, bears on mating bars provided on the top surface of the lower end shield (Figure II-24). The bars are welded to the tubesheet and are machine-finished after the tubesheet has been completed. In this way, the bearing surfaces of the bars are brought into a single plane, assuring uniform load distribution. Similar treatment is rendered the mating bars of the lower end shield. In order to prevent rotation and displacement of the calandria due to thermal cycling, a system of keys is provided on the bottom shield; corresponding key-seats are cut in the bottom tubesheet on the underside. These keys and key-seats are located at the

FIG II-24. Calandria Support System

outer extremity of the tubesheet and are radially disposed so that the calandria can expand and contract, relative to the bottom shield, without having its center displaced from the original position. The total area of the bar contact surfaces is large enough to ensure that the direct-bearing unit stresses are reasonably low. As a further safeguard against galling between the bearing surfaces, a thin layer of tungsten diselenide is applied to the surfaces of the bars and the keys on the lower shield. Tungsten diselenide is an excellent solid lubricant and serves to reduce friction and prevent galling.

The support-bar gridwork also isolates the CO₂ gas space around each process tube where it passes between the calandria and the lower end shield. This is to facilitate fuel channel leak detection by gas sampling.

Table II-15 lists the basic calandria information:

TABLE II-13
BASIC CALANDRIA DATA

Calandria tube inside diameter and tolerances (in.)	5.094 .005 0.030 max ovality
Required straightness of the calandria tube (in.)	T.I.R. at any point not to exceed 0.200
Tube corrosion allowance	Zero
Nominal clearance between the calandria and process tubes (in.)	0.274
Design pressure of the calandria tube (moderator pressure, psig)	12
Design temperature of the calandria (°F)	250
Number of calandria tubes	492
Number of control channels (horizontal)	84
Expected 30-yr-average failure frequency of the calandria tube	Zero
Operating temperature of the calandria (°F)	180 avg

b. End Shields (Figures II-17, II-18, II-19 and II-24)

The upper and lower end shields are carbon-steel structural vessels which furnish both shielding and structural support. Adequate shielding is provided for the refueling machine vaults to permit maintenance after shutdown and to prevent radiation damage of equipment. Process tube and control rod support is supplied by the upper end shield, while the lower end shield supports the calandria vessel.

The shields are circular in plan and flat two-section slabs in elevation, and are 30.00-ft OD by 3-ft high. Each shield has two, equal-depth, horizontal compartments; a light-water-filled section located next to the calandria, and a section filled with steel balls and light water located away from the calandria. Each shield is supported by skirt-type supports (Figure II-24) which serve to absorb the differential thermal expansion between the shield and the support, while maintaining alignment of the vessels. Each shield has 564 vertical sleeves which pass through the vessel and are welded to the top and bottom plates. These sleeves project beyond the bottom surface of the lower shield, and gas-sniffer connections are made laterally in these projections. The upper shield contains sleeves for the passage of the 17 control rod assemblies.

Both compartments of each shield are essentially of egg-crate-type, having longitudinal and lateral ribs arranged so that the interior is divided into regular connecting compartments. Shield cooling is by circulating light water through an inner header and distribution system which introduces cooling water uniformly over the entire flat area. A similar system collects the hotter outlet water and any entrained air. The cooling water is treated with an inhibitor in order to reduce corrosion.

Several vertical ports are provided through the upper shield for the purpose of introducing remote viewing equipment or repair equipment to the calandria space. Each port is provided with a water-cooled shield plug.

c. Thermal Shields

Eight carbon-steel tanks form a cylindrical thermal shield around the calandria. This shield is designed to reduce the nuclear heating of, and is supported by, the concrete biological shield. Each tank is 26-ft-high, and the outer perimeter of the free-standing thermal shield is flush with the concrete biological shield. The tanks are curved on a 17.5 ft inside radius, and are designed to overlap so as to form a complete cylinder without streaming paths. The cross-section provides 1 in. of steel, 3.5 in. of light water, 3/4 in. of steel, 3-1/2 in. of light water, and 1 in. of steel. Tank cooling is by 1300 gpm of light water entering at the bottom at 95°F and leaving from the top at 100°F. Flexible seals close the vertical joints between the tanks, in order to contain the CO₂ atmosphere of the calandria vault. Seals are also provided between the thermal shield and the upper and lower end shields. The cooling water is treated with inhibitors in order to reduce corrosion.

Sleeves for the heavy-water cooling system for the calandria, surge and spray lines, drains, horizontal shut down rods, horizontal instrument connections, and the CO₂ system are provided by the shield. All these penetrations are provided with flexible seals in order to contain the CO₂ vault atmosphere. These seals are accessible from the 30-in. -wide working area between the calandria and the thermal shield. A manhole is provided through one tank of the shield, for access to this space during erection.

d. Pigtails, Headers, Tees and Instrument Connections (Figure II-21)

The carbon steel pigtails connect the process tube extensions to the inlet and outlet headers. Each pigtail is attached by a tee welded to a reducing outlet-tee connection on the process tube extension. The run of the tee at the process tube extension is parallel to the extension: the pigtail is welded to the end nearer to the end shield and runs parallel to the extension towards the shield. A screw plug closes the end of the tee run facing the refueling end of the extension. By removing the screw-plug, a special combination cutting and welding machine can be inserted into the tee, cutting radially through the

pigtail wall from the inside, to disconnect the pigtail from the extension and enable removal of a fuel channel. When the channel is replaced, the pigtail joint is remade, using the same machine to weld the joint radially outward from the inside. The screw-plug is then replaced in the tee and seal-welded.

Each pigtail is connected at the header end to a vertical riser which is connected to a header. Pigtails connected to an outlet header have a thermowell for outlet temperature measurement close to the header. A coolant sampling line is also connected to the pigtail at the thermowell. Pigtail fabrication utilizes welded joints throughout, in order to ensure leakproof operation.

3. Stress and Deflection Analysis

a. Calandria and Calandria Tubes

In designing the calandria, the shell and tubesheet thicknesses were made greater than required to contain the internal pressure, so as to incorporate a reasonable amount of thermal shielding while lessening the need for shell-opening reinforcement as much as possible. Tubesheet thickness was also influenced by the requirements of the calandria tube rolled joint. In general, therefore, the stresses in the calandria are very low.

The maximum operating pressure due to hydrostatic head (at the bottom of the calandria) is 12 psig. The direct hoop stress in the calandria shell due to this load is 1900 psi.

Weight loads and thermal effects account for the significant stresses in the calandria and calandria tubes. The calandria is supported directly by the lower end shield and, since the calandria tubesheet is relatively flexible, the weight of the moderator makes the calandria tubesheet follow the deflected shape of the endshield (which is loaded by its own weight and that of the calandria). The upper calandria tubesheet is connected to the lower tubesheet by the calandria tubes, and also follows the deflected shape of the lower end shield at ambient temperature. Under steady-state operating conditions, the upper tubesheet is further deflected, because the stainless steel (expansion

coefficient = 9.6×10^{-6} in./in./-°F) shell of the calandria tends more toward expansion than the Zircaloy (expansion coefficient = 3.2×10^{-6} in./in./-°F) calandria tubes. The unperforated peripheral annulus of the tubesheet acts as a flexible joint to minimize this effect.

The following stresses were calculated for a larger reactor of similar geometry, and are typical of the order of magnitude of stresses in a 564-tube reactor:

Total maximum stress at tubesheet/shell junction (psi)	11700
Total maximum stress at center of tubesheet (psi)	4000
Total maximum stress in shell (psi)	10400
Total maximum stress in calandria tube (psi)	6700

These compare with the ASME Boiler and Pressure Vessel Code, Section III (nuclear vessels), allowable stress for A240 type 304 L stainless steel of 16,700 psi and the equivalent Zircaloy-2 allowable stress of 13,000 psi.

b. End Shields

Maximum stress in lower shield tank (psi)	5300
Maximum stress in upper shield tank (psi)	6700
Central deflection of lower shield tank (in.)	0.150
Central deflection of upper shield tank (in.)	0.185
Code allowable stress (SA212) (psi)	17500

d. Pigtails and Process Tube Extensions

Maximum stress in pigtails, excluding intensification effect at bend (psi)	7075
Maximum stress in pigtails allowing for intensification effect at bend (psi)*	23920
Maximum longitudinal stress in process tube extension (psi)	4300
Code allowable stress (SA 106) (psi)	10800

*This has to be compared with an allowable cyclic stress range of 32700 psi.

D. FUEL CHANNEL ASSEMBLY DESIGN

1. General Description (Figure II-25)

An individual fuel-channel assembly consists of a SAP process tube with SAP-stainless steel hot-pressed transition joints at each end. The complete process tube is shop fabricated and the steel end is remotely welded during installation into the steel process tube extensions. Axial support for the assembly is provided by flange-mounting the upper extension piece to the upper end shield. The lower extension piece, as it extends through the lower end shield, is provided with a packed gland both for maintaining a seal and to serve as a radial bearing. This packed gland allows vertical expansion and contraction of the fuel channel assembly to take place with temperature cycling. One other radial bearing is located in each of the shields to isolate the reaction loads caused by pigtail expansion from the thin-walled process tubes. In addition, each extension piece is provided with antirotational keys to resist torsion loads from the pigtails.

The coolant flow enters and exits through pigtails which connect to a tee on the extension tubes. Using a "Tee" connection places the connecting weld in a vertical position near the end of the tubes, thus making a more accessible location. All of the pigtail connection nozzles are at the same relative location on the extension pieces.

Each fuel channel has a refueling-machine-actuated end-closure seal mechanism at each end. These closure mechanisms are operated by a series of push-pull movements by the refueling machines, to perform the on-power refueling functional requirements of (1) connecting, (2) disconnecting, and (3) handling and storage. The closure mechanism is comprised of a system of cams, latches, and springs designed to exert a load on a metal seal disc at the end of the tube and lock it in place. (See Figure II-25.)

The fuel column consists of five 43.2-in. -long fuel elements with 43.2-in. -long spacer shields located above and below the fuel. A spring arrangement

FIG II-25. Process Tube Design

in the shield plugs permits changes in the length of the fuel from thermal expansion. In addition, this assembly is provided with one of several standard orifices to control the flow in the channel according to its position in the reactor core. The orifice is replaceable for flow adjustment.

Latch assemblies mounted in the upper and lower carbon-steel extension pieces position and support the fuel column. The assemblies are spring-loaded, cam-operated, devices which actuate latches by a series of coordinated movements of the refueling machines. For a detailed graphical presentation of the functional characteristics of the latch assemblies see Figure II-30.

Determination of the process-tube wall thickness was made using the calculational methods of Section III of the ASME Boiler and Pressure Vessel Code. The design conditions of 287 psi at a 595°F core inlet temperature were found to be controlling. Using SAP mechanical properties, the required minimum thickness was found to be 0.106 in., with a corrosion allowance of 0.005 in. and a manufacturing allowance of +0.015, - 0.005 in., making the final wall thickness $0.116^{+0.015}_{-0.005}$ in.

2. Leak Detection System

Detection of D₂O and/or organic leakage is accomplished by monitoring the CO₂ gas system; a sampling port is provided from each tube location, at the lower end of each channel, to assist in pinpointing leaks. By use of a multi-port valve scanning device, a sample of the CO₂ insulating gas can be withdrawn from the gas annulus and analyzed as required. The normal gas-flow rate of 50 cc/min is increased to 300 cc/min during the sampling period, to increase line velocity and, thus, reduce response time. After sampling, the gas is cooled and recirculated. The gas inlet temperature is 190°F and exit temperature is 400° to 500°F.

3. Tube Replacement Procedure

Provisions have been made for replacing leaking process tubes without interrupting flow to the other channels. The following procedure is used:

- a) Refueling machines remove end closures.
- b) Refueling machines empty fuel column.
- c) Refueling machines insert plugs in the process tube extensions which seal flow from the pigtails.
- d) With the flow stopped, cooling jackets are installed around the pigtails and a freeze plug is produced within the pigtails.
- e) After coolant flow in the faulty channel is stopped, the lower machine drains the channel.
- f) The faulty tube is then removed by: (1) cutting each pigtail at the tee; (2) cutting the process tube in the area of the transition joints; (3) removing the extensions and the severed process tube.
- g) The replacement tube is installed in the following sequence:
(1) install extension pieces; (2) install process tube section; (3) remote-weld process tube section to the extension pieces; (4) weld the tee connectors to the pigtails.

E. ON-POWER REFUELING SYSTEM

1. System Description

The refueling system (Figure II-26) is designed to control the flow of reactor fuel elements from the time of delivery at the reactor site, until the depleted fuel assemblies are shipped to other areas for processing or disposal. Several subsystems comprise the refueling system, as discussed below:

a) The New-Fuel Handling System (Figure II-27) receives, inspects, stores and prepares fuel assemblies for loading into the refueling machines.

b) Two refueling machines accept delivery of new fuel assemblies from the new-fuel handling system, transport the new fuel to the fuel channels, form leak-tight joints with the ends of the fuel channels, open the fuel channels, insert new fuel elements, remove spent fuel assemblies, seal the fuel channels, and transport and deliver the spent fuel assemblies to the spent fuel handling system.

c) The Spent Fuel Handling System (Figure II 28) receives the spent fuel assemblies from the refueling machines, transports the assemblies to the spent-fuel storage pool, stores the spent assemblies in storage tubes during the cooling period required, and transfers the spent assemblies from the storage tubes into the shipping cask for removal from the reactor site.

d) The Environmental Control System is designed to minimize the thermal shock due to environmental changes experienced by the fuel assemblies during the progression from loading to irradiation, to unloading. This system is also to prevent contaminants from being introduced into the reactor core, and to provide a means for dissipating decay heat given off by the spent fuel assemblies during transportation from the core to the storage pool.

New fuel at ambient conditions (130°F) must be loaded into the core in an environment of Santowax OM at a temperature above 600°F. On removal from the core as spent fuel, the fuel assemblies go from a core temperature of approximately 750°F to a storage pool at ambient conditions.

FIG II-26. Refueling System Flow Diagram

FIG II-27. New-Fuel Handling System

SECTIONAL VIEW
SPENT FUEL HANDLING
SYSTEM

FIG II-28. Spent-Fuel Handling System

Three loops comprise the Environmental Control System as follows:

1) New-Fuel Environmental Control System - The fuel elements are introduced into an atmosphere of HB-40 and heated to 400°F in the new-fuel loading station.

2) Refueling Machine Environmental Control System - The fuel assemblies are transferred from the HB-40 to the refueling machine containing Santowax OM at a temperature of 400°F, and then into the core. From the core, the spent assemblies are moved to the spent-fuel handling system.

3) Spent-Fuel Environmental Control System - The fuel assemblies are transferred from the Santowax OM to the spent fuel handling system containing HB-40 at a temperature of 250°F.

e) The Instrumentation and Control System remotely controls, operates, and coordinates the operations of both refueling machines, from the fresh-fuel loading station, through the refueling operation, and to the spent fuel discharge station. The functions of this system are defined by the various subsystems listed below:

- 1) Carriage Positioning System
- 2) Refueling Machine Positioning System
- 3) Coupling System
- 4) Tool Post Positioning System
- 5) Magazine Positioning System
- 6) Environmental Control System
- 7) Interlock and Annunciator System
- 8) Program System

f) Servicing and Maintenance Procedures - All areas dealing with refueling rooms, are accessible during reactor operation. The refueling machines which are normally in the refueling room will be removed to the refueling machine maintenance room for all maintenance.

The refueling machine heads are the most complex part of the system. To eliminate the possibility that malfunctions in the refueling machines might interfere with the normal refueling program, four spare refueling machine heads are provided by the design. The refueling machine is designed with quick disconnects for the refueling head support and all services, to permit rapid replacement of the malfunctioning head. A test stand duplicating the conditions in the reactor fuel channels, with the exception of radiation, will be provided for running operational tests on the refueling machine before the refueling machine is allowed to assume its normal refueling operation. Periodic inspection will be made of those items which have limited-life, such as the coupling seal, flexible hose, and cables; replacements will be made at the first sign of deterioration.

For fuel channel hardware replacement, the refueling machine must be able to:

- a) Remove fuel channel hardware items from the fuel channel,
- b) Store the hardware in the magazine during refueling,
- c) Replace the hardware in the fuel channel after refueling is completed,
- d) Remove and replace the hardware with spares, as part of the maintenance program.

Channel hardware consists of the following items:

Spacer-Shield, Upper	Figure II-29
Spacer-Shield, Lower	Figure II-30
End Seal	Figure II-31

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FIG II-29. Upper Spacer Shield

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SECTION B-B

SECTION D-D

SECTION A-A

SECTION C-C

SECTION E-E

FIG II-30. Lower Spacer Shield

REMOVAL

- 1 TOOL POST ASSEMBLY ENTERS SEAL PLUG BODY
- 2 PISTON MAKES CONTACT WITH CENTER PLUG

REMOVAL CONT.

- 3 LATCH TUBE IS EXTENDED. #1 DETENT BALLS LOCK MECHANICAL RAM TO SEAL PLUG BODY.
4. HYDRAULIC PRESSURE ON PISTON DRIVES THE CENTER PLUG FORWARD RELIEVING THE FORCE ON THE DOGS. THIS MOVEMENT POSITIONS THE CENTER PLUG GROOVE TO ACCEPT #3 DETENT BALLS

REMOVAL CONT.

- 5 HYDRAULIC RAM IS EXTENDED DRAWING CENTER SHAFT FORWARD
- 6 #3 DETENT BALLS ARE FORCED INTO CENTER PLUG GROOVE. FURTHER TRAVEL OF THE CENTER SHAFT WITHDRAWS THE DOGS FROM PROCESS TUBE EXTENSION GROOVE.
- 7 TOOL POST ASSEMBLY RETRACTS TO STORE SEAL PLUG IN MAGAZINE.

REPLACEMENT

8. TOOL POST ASSEMBLY PLACES SEAL PLUG IN PROCESS TUBE EXTENSION
- 9 HYDRAULIC RAM IS RETRACTED UNTIL #3 DETENT BALLS ARE LOCKED IN CENTER SHAFT GROOVE FURTHER TRAVEL OF CENTER SHAFT FORCES DOGS INTO PROCESS TUBE EXTENSION GROOVE.

FIG II-31. End Seal Latching Sequence

2. Refueling Machine

The main function of the refueling machine is to provide a means of safely and efficiently inserting and removing fuel assemblies from the core, with minimum perturbation to reactor operation. The refueling head assembly (Figure II-32) consists of the following assemblies: coupling, magazine, tool post, gimbal and housing. The assembly housing is the common base which ties the various assemblies into an integrated unit. The housing will function as a pressure vessel and mounting structure for the assemblies. It will provide a base for mounting and supporting associated equipment and instrumentation required for monitoring the refueling head pressure, temperature, position transmitters, unit switches, and all other instrumentation required to provide the information necessary for performing the refueling function.

For overhaul and maintenance, the refueling head will be removed from the refueling head support as a complete unit. A spare head will then be mounted on the refueling head support.

A coupling assembly (Figure II-33) is included to form a leak-tight mechanical connection between the fuel channel or the loading and discharge stations and the refueling machine. When the machine is disconnected, the machine closure plug is positioned in the snout to seal the refueling machine.

Figure II-34 shows the magazine assembly which consists of a storage rack, an indexing drive, and a retainer mechanism, plus position sensors and other instrumentation. The storage rack consists of a circular array of tubes mounted between two end plates. This assembly rotates on a bearing-supported shaft.

The indexing drive is an irreversible kinematic linkage consisting of a drive motor, gear box, geneva drive, bevel gears and a worm gear set. In response to a demand signal, the indexing drive rotates the magazine until the desired storage tube is at the action station. The accuracy of the indexing drive response is monitored by a position sensor which transmits a signal to the control room showing the relative position of the magazine.

FIG II-32. Refueling Machine Assembly

FIG II-33. Coupling Assembly

FIG II-34. Magazine Assembly

Since the magazine storage tubes are in a vertical attitude, it becomes necessary to retain the latch cans in the storage tubes. This task is accomplished by a retainer mechanism consisting of an iris-cam arrangement at each storage tube, which will be used for fuel elements or spacer-shield assemblies. Actuation of the iris cam is by a hydraulic piston located at the action station. An off-center spring holds the cam in the open or closed position, as required. A stop-arrangement prevents the cam from accidentally opening at any but the action station; this stop arrangement also prevents rotation of the magazine while the retainer mechanism is open. A limit switch will be used to indicate the state of the retainer.

Normally, the refueling machine closure plug (Figure II-35) is used to seal the refueling machine during periods when the machine is not connected to the fuel channels or to the loading and unloading stations. The closure plug is installed in the snout.

The tool-post assembly (Figure II-36) consists of a mechanical ram, a hydraulic ram and a latch tube. The mechanical ram is a ball screw drive having a 250-in. stroke. The hydraulic ram is a two-stage piston which is carried in the mechanical ram and has a 90-in. stroke which extends beyond the mechanical ram. The latch tube is a latching mechanism actuated by a ball screw drive, and is capable of a very limited stroke (less than 1 in.) in relation to the mechanical ram.

Primarily, the mechanical ram is to: (1) carry the hydraulic ram and latch tube to the required area for manipulations, involving latching and unlatching; and (2) to transport fuel assemblies and spacer shields, in latch cans, from the loading station, into the magazine for storage, and from the magazine into and out of the fuel channel, or from the magazine (in the case of spent fuel assemblies into the spent-fuel discharge station.

The main functions of the hydraulic ram are:

- 1) Release the latch and eject the fuel assembly or spacer-shield.
- 2) Hold the fuel column in a positive hold during refueling.

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FIG II-35. Refueling Machine Closure Plug

FIG II-36. Tool Post Assembly

3) Exert force on the center plug of the end seal, to relieve spring sealing force and permit withdrawal from the process tube extension.

4) Exert force on the center plug of the machine closure plug, to relieve spring sealing force and permit withdrawal or replacement of the machine closure plug into the coupling assembly.

The latch tube is designed mainly to: activate the grapple for removal of the end seal.

Figure II-37 depicts the latch can, which is a container used to transport and handle the fuel elements in the refueling machines. A latch which holds the fuel elements captive until it is actuated by the latch tube is included in the latch can. At the fuel loading station, the new fuel elements are inserted into the latch cans and then stored in the magazine.

3. Refueling Procedure

After a given time-length of power operation, fuel replacement will begin. Normally, the daily refueling sequence will consist of removing and replacing the spent fuel in four fuel channels. This is accomplished by the single refueling cycle described below; the estimated minimum time (minutes) required for each step is shown parenthetically.

a) Loading of New Fuel - Each refueling machine receives two new fuel assemblies at the loading station. (31.5 min)

b) Positioning - The machines are indexed over the fuel channel. (5.0 min)

c) Coupling - The machines are aligned and then coupled with the fuel channel. Figure II-38 shows the two machines coupled to opposite ends of a fuel channel. Leak tests are performed to verify the integrity of the seals between the machine and channel flanges.

The tool post of each machine removes the machine closure plug and the fuel channel end plug and deposits these plugs in the magazine. (11.0 min)

FIG II-37. Latch-Can Assembly

FIG II-38. Refueling Machines Coupled to a Fuel Channel

d) Refueling - Working simultaneously, the two tool posts add one new fuel assembly to the upstream end of the fuel column and remove one spent fuel assembly from the downstream end. The spent assembly is deposited in the magazine. Figure II-39 shows the sequence of operation. (11.0 min)

e) Uncoupling - The tool posts replace the fuel channel end plugs and machine closure plugs. Following leak testing for verification that both plugs are sealing properly, the machines are then uncoupled from the fuel channel. (9.5 min)

f) Refueling of Three Additional Fuel Channels - Steps b, c, d, and e are repeated at three additional fuel channels. (109.5 min)

g) Unloading of Spent Fuel - The machines are moved to the unloading station where the four spent fuel assemblies are discharged. Next, the machines are moved to the new fuel loading stations for the beginning of the next refueling cycle. (37.5 min). The total time for performing a complete refueling cycle is 3 hr, 35 min.

4. New-Fuel Handling System (Figure II-27)

Movement of new fuel from the receiving station to the refueling machines is accomplished with the New-Fuel Handling System. From the receiving station, incoming new fuel is placed in two storage rooms adjacent to the refueling machine loading stations. A two-month supply of new fuel is stored in these rooms (60 fuel assemblies in each room). Figures II-17 and II-19 show the relative room locations in the plant.

As the need arises, new fuel is loaded into the refueling machines; a separate new fuel loading station is provided for each refueling machine (Figures II-17 and II-18). The loading equipment (Figure II-27) consists of a magazine enclosed in a pressure chamber, a transfer tube to which the refueling machine couples, and a hydraulic cylinder used to push the fuel into the refueling machine latch can. Twelve fuel assemblies are loaded into the magazine. The access opening is closed, the chamber is purged with nitrogen gas, and filled with HB-40 which is then heated to 400°F.

FIG II-39. Refueling Sequence (Steps 1 through 5)

FIG II-39. Refueling Sequence (Steps 6 through 9)

FIG II-39. Refueling Sequence (Steps 10 through 12)

FIG II-39. Refueling Sequence (Steps 13 through 15)

FIG II-39. Refueling Sequence (Steps 16 through 18)

FIG II-39. Refueling Sequence (Steps 19 through 22)

Next, the refueling machine is coupled to the transfer tube. The refueling machine tool post advances through the transfer tube, and the loading station hydraulic cylinder pushes one new fuel assembly from the magazine into the latch can on the end of the tool post. The tool post retracts and deposits the fuel element in the refueling machine. At the same time, the loading station magazine indexes to another fuel position. The tool post advances again and similarly receives and deposits a second fuel assembly in the refueling machine.

5. Spent-Fuel Handling System (Figure II-28)

Spent fuel handling, storing and shipping are performed by three subsystems, as described in the ensuing paragraphs.

a. Unloading Station

The refueling machines couple to the extension tubes of the transfer enclosure and discharge the spent fuel assemblies into the transfer container where the fuel assemblies are held captive by a fuel latch. Next, the transfer ram moves the transfer container horizontally from the extension tubes to the vertical tube leading to the storage pool. The clamp on the transfer ram releases the container, which is then lowered by the winch and cable to the pool storage tube coupled to the pool transfer station. This transfer station consists of a seal nozzle and a shut-off valve. The pool storage tube is attached to the seal nozzle while it is being loaded with the six spent fuel assemblies it normally carries, and the shut-off valve is used to prevent leakage of HB-40 into the pool when the pool storage tube is removed.

b. Storage Pool (Figures II-17 and II-19)

As part of the storage pool arrangement, a canal extends beneath the pool transfer station to permit a straight drop for the winch and cable hoist. The body of the pool is so arranged that the spent-fuel flow path in the pool storage racks goes from the transfer station to the revolving door, through the containment shell, and back to the transfer station. Tube arrangement in the storage racks is such as to maintain at least 12 ft of water above the fuel level.

c. Storage Pool Fuel Handling System

Spent fuel assemblies are transferred from the container to the pool storage tubes by lowering the container into the storage tube and activating the fuel latches to deposit the spent fuel. After the storage tube has been loaded with spent fuel assemblies it is uncoupled from the pool transfer station, transported to and deposited in storage racks by the transfer cart.

The storage racks contain 11 storage tubes and are mounted on a conveyor system which moves the racks toward the revolving-door end of the pool. The system is designed so that specific storage racks reach the revolving door sequentially.

After the required cooling period, the storage tubes are lifted from the racks individually and placed on the revolving door which allows removal of the fuel from the containment without violating the containment integrity.

The fuel assemblies are now lifted from the storage tube and deposited in the shipping cask.

6. Fuel Channel Hardware Handling System

The purpose of this system is to load new fuel-channel end-plugs and machine closure plugs into the refueling machines and to receive those plugs being replaced, for repair or disposal. A separate transfer station is provided for each refueling machine (Figures II-17 and II-19).

Figure II-40 shows the station equipment used to accomplish the plug transfers. This equipment consists of a transfer tube to which the refueling machine couples, a shut-off valve, and a shield cask for holding either of the plugs.

7. Fuel Handling Equipment Environmental Control Systems

There are four systems to control the environment in the fuel handling equipment:

- a) Two identical, but separate, Santowax OM systems for the refueling machines.

FIG II-40. Fuel Channel Hardware Handling System

- b) An HB-40 system for the new fuel loading equipment.
- c) An HB-40 system for the spent fuel unloading equipment.

Figure II-41 is a flow diagram of the refueling machine environmental control system. Santowax OM at 400 F and 50 psi is supplied to the refueling machine at a maximum rate of 50 gpm from the source terminal in the refueling machine maintenance room. Potential coolant stagnation areas within the machine have been eliminated by the flow path established for the machine. The rest of the control system is mounted on the refueling machine support carriage and consists of a 150 gallon reservoir, two pumps, a heat exchanger, two flowmeters, two pressure transducers and various valves.

Organic coolant is drawn from the reservoir and pressurized to 400 psia by the two pumps (one backup) operating in parallel. Next, the coolant is pumped through the heat exchanger, for temperature control, and is then injected into the refueling machine head. Although each pump is capable of providing the maximum required flow, both pumps normally are operated below the rated capacity.

During the normal refueling cycle, the maximum heat generated by the load of two spent fuel assemblies is 46 kw. When all five fuel assemblies are removed from the same fuel channel, the maximum heat load is 168 kw.

Whenever the refueling machine tool post is inserted into the fuel channel there would be a reduction of coolant flow across the fuel column without an external coolant supply. To compensate for this interference, up to 40 gpm of coolant are forced from the refueling machine into the fuel channel. This flow is supplied from the external source in the maintenance room. At all other times the equipment on the refueling machine carriage will operate as a closed loop.

Figure II-42 shows the arrangement for transporting the supply of make-up organic to the refueling machines. Also shown is a parallel arrangement for transmitting the electrical power and instrumentation signals to the machine. The supply terminals for both the coolant and electrical lines are located in the

FIG II-41. Refueling Machine Environmental Control System

FIG II-42. Coolant and Power Transmission System

refueling machine maintenance room. The terminals are connected to a movable manifold carriage by means of 24-ft-long flexible lines. During normal refueling operations, the carriage is positioned so that it straddles the shield door opening. The two halves of the shield door are closed around a narrow section of the carriage. Inflatable gaskets on the door provide sealing around the carriage. The electrical and coolant supplies are thus carried through the sealed shield door. Two take-up reels on the portion of the manifold carriage extending into the reactor room each hold 70 ft of flexible line terminating at the refueling machine. Both the reels and the terminal on the refueling machine are free to pivot to prevent twisting of the lines. When the refueling machine is on the main carriage, the two telescopic cable supports are extended under the flexible lines. When the refueling machine is on the service carriage, the telescopic supports are retracted and the reels take up the slack in the flexible lines.

In order to take the refueling machine into the maintenance room, the shield doors are opened and the manifold carriage is moved to the rear of the room. After the doors are closed behind the refueling machine, the room becomes accessible and the supply lines can be easily disconnected, if necessary.

Figure II-43 is a flow diagram of the environmental control system for the new fuel loading equipment. After new fuel is loaded into the two chambers, the chambers are purged with nitrogen gas to remove the air. HB-40 at 400 °F and 25 psia is circulated through the chamber. Prior to the transfer of fuel the pressure of the HB-40 in the loading equipment and the pressure of the OM in the refueling machine are equalized so that the mixing of the two fluids is minimized. HB-40 was selected for this system because it remains fluid at room temperature and is compatible with OM.

Figure II-44 is a flow diagram of the environmental control system for the spent-fuel unloading equipment. HB-40 at 250 °F is alternately circulated through the upper and lower unloading chambers as spent fuel is transferred

FIG II-43. New-Fuel Loading Equipment Environmental Control System

FIG II-44. Spent-Fuel Loading Equipment Environmental Control System

from the upper and lower refueling machines to the storage tubes. The heat exchanger in the system removes up to 23 kw generated by the spent fuel. As in the new-fuel handling equipment, the pressure of the HB-40 is equalized with that of the OM in the refueling machines to minimize mixing of the fluids. The spent fuel storage tubes are also filled with HB-40 to eliminate any need to wash the fuel during the transfer.

8. Carriages

The carriage and structural support system shown in Figures II-17, II-19, and II-42 is provided for accurate positioning of each refueling machine in the various locations necessary to perform the assigned functions. The system consists of the components described in the subsections that follow.

a. Refueling Head Support Assembly

Each refueling machine head, and related accessory equipment, is mounted on a 12 ft x 15 ft support platform. The head is mounted on a gimbal structure designed to allow a slight rotation about the X and Y horizontal axes in order to achieve optimum alignment between the head and each fuel channel or transfer tube.

An electro-mechanical drive is provided for fine adjustments about each axis. The head is carefully balanced to minimize the torque required to produce these rotations. A linear drive provides a limited vertical motion (Z direction), with a constant speed of 1 ft/min. This drive is designed to limit the force exerted on the fuel channel to 1000 lb maximum, in order to prevent overstressing of the channel and its supports.

Each refueling head support is underhung from four trucks that can be transferred over the various tracks and carriages. One truck is electro-mechanically driven to provide positioning. The support assembly is driven horizontally at two different speeds, 10 ft/min and 5 in. /min, to provide rapid transit and fine positioning, respectively.

The complete refueling machine head and support assembly, including the trucks, weighs approximately 13 tons.

b. Main Carriage

Two main carriages are provided for supporting and positioning the upper and lower refueling machines at the various fuel channels. Each carriage consists of two tracks, for supporting the refueling machine, and four trucks, to provide motion. The trucks ride on a circular track concentric with the reactor core. Two of these trucks are electro-mechanically driven at linear speeds of 30 ft/min and 5 in./min to provide rapid transit and fine positioning.

Rotation of the main carriage, and the linear motion of the refueling machine head support assembly riding upon the carriage, are combined to locate the refueling machine at any of the fuel channels.

The main carriage is 29.5 ft long and weighs approximately 8 tons.

c. Transfer Tracks

Transfer tracks are provided to permit the removal of each refueling machine from the reactor face. The transfer is achieved by aligning the main carriage and the service carriage (described below) with the transfer tracks, and then driving the refueling machine head support trucks from the main carriage, over the transfer tracks, and onto the service carriage.

d. Service Carriage

This carriage is used to locate the refueling machine over the three tubes used for the transfer of new and spent fuel and fuel channel hardware. As with the main carriage, the service carriage rides on a circular track, and its design and operation are similar to those of the main carriage. The length and weight of the service carriage are 20 ft and ~6 tons, respectively.

e. Shield Door and Maintenance Tracks

Transfer of the refueling machine and support assembly from the service room to the maintenance room is effected with movable tracks. The tracks are moved aside to permit closing of the shield doors. Two stationary tracks are provided to hold the refueling machine and support assembly in the maintenance room.

f. Fuel Channel Spacer-Shields (Figures II-29 and II-30)

The spacer-shields are fuel channel hardware items which are part of the fuel column. One upper and one lower spacer-shield are located in each fuel channel. The envelope dimensions of the spacer-shields are identical to those of the fuel elements. This permits handling the spacer-shield in the same manner and with the same equipment used for the fuel elements.

The upper spacer-shield is always located at the top of the fuel column and contains a spring to compensate for changes in column length, thus permitting positive support of the fuel column at all times.

Both the upper and lower spacer-shields incorporate an orifice plate which is screwed in place and can be changed to adjust the flow. The end containing the orifice plate is always located away from the fuel column. It provides a minimum 12 in. constant shielding against streaming along the process tube. Use of spacer-shields means that the fuel channel latches can be located outside the process tube and in the shield tank area. The use of the spacer-shields allows the fuel channel latches to bear on the fuel elements only briefly during refueling.

F. REACTOR INSTRUMENTATION AND CONTROL

1. General Design Criteria

The reactivity control and reactor monitoring systems designs are based on the following general criteria:

- a) The power plant shall operate as a base-loaded plant.

b) The reactivity loss due to fuel burnup is compensated by on-line refueling (Section II. E).

c) The reactivity shutdown margin for the most reactive configuration of the core is 2% with coolant and 0.9% with the coolant voided.

d) The reactivity control system contains a minimum of in-core parasitic material, consistent with safety and reliability.

e) All in-core structure which has a lifetime of less than 30 yr, or if subject to damage, is removable for maintenance, repair, or replacement.

f) A back-up reactivity shutdown system is provided to insure shutdown of the reactor under emergency conditions.

Based on the above criteria, the following reactivity control systems are utilized: (a) a system for normal shutdown, (b) a back-up system for emergency shutdown, (c) a control system for regulating the reactivity effects of xenon buildup and decay, and (d) a control system for regulating spatial power oscillations and minor power level changes.

2. Control System Requirements

a. Normal Shutdown System

Since the excess reactivity in this reactor is limited, and the coolant temperature coefficient is positive, the normal shutdown system is required to handle only the following:

1) Reactivity gain associated with the decrease in fuel temperature (0.29%). No additional gain in overall reactivity will occur as the fuel and coolant temperatures decrease, since the coolant temperature coefficient of reactivity is larger and of opposite sign than that of the fuel.

2) The gain in reactivity associated with removal of all shim rods used to regulate spatial power oscillations; this amounts to a reactivity change of 0.2%.

3) A reactivity shutdown margin of 2% under the following reactor conditions: zero power, 190°F moderator temperature, coolant and fuel at 675°F, xenon and samarium at equilibrium concentration (or the reactivity associated with equilibrium xenon and samarium is being held by boron in the moderator).

4) A reactivity gain associated with the loss of all of the coolant under the full-power operating conditions of the reactor which is 1.1%.

Based on the above, the reactivity to be controlled by the shutdown system is 3.59%.

Because of the small amount of excess reactivity, the rate of reactivity addition by the shutdown rods is limited only by the possibility that additional reactivity, normally held by xenon or an equivalent amount of boron in the moderator, has inadvertently been allowed to accumulate in the core. Thus, during a reactor startup after a long shutdown, the withdrawal rate of the shutdown rods will be limited to a reactivity addition of 0.04%/sec; however, withdrawal rates after a shutdown from full power, with equilibrium xenon and samarium in the core, may allow a reactivity insertion rate of the shutdown rods of several times the above values.

The insertion rate for the shutdown rods is based on preventing excessive thermal conditions in the core under accident conditions. With essentially zero excess reactivity available for addition under full-power operating conditions, and because of the long time constant associated with additional coolant heating, shutdown rod insertion need only cause the removal of a minimum of 1% reactivity within the first three seconds following initiation of a scram signal, with essentially complete insertion occurring within 6 seconds.

Additionally, the shutdown rods will be inserted automatically with a complete failure of the drive system since a potential energy source is always available for rod insertion.

b. Backup Shutdown System

The backup shutdown system is provided to shut down the reactor in the event a partial failure of the normal shutdown system occurs. This system is completely independent of the normal shutdown system, and is capable of making the reactor subcritical with all other control or shutdown rods out of the core and the core in its most reactive condition. Although neither fast nor automatic operation of this system is required, a reactivity decrease of about 1%/min is considered to be sufficient to prevent a hazardous condition. Because the use of this backup system is considered to be highly unlikely and a result of very abnormal circumstances, fast removal of the absorber is not a requirement.

c. Control of Equilibrium Xenon Effects

Design of the normal shutdown system is based on the reactivity addition associated with xenon decay being held by the addition of boron in the moderator. Calculations of the equilibrium core indicate that the reactivity decrease due to equilibrium xenon is 2.7%. The rate at which boron must be added or removed is fixed by xenon buildup and decay following a scram. Since over 30 hr will elapse before the xenon concentration decays to the full-power equilibrium value, the rate of boron addition following a reactor shutdown can be very slow.

Removal of the boron on a startup is fixed by the rate of xenon buildup. The minimum rate at which the boron poison is to be removed must be equivalent to the maximum rate of reactivity decrease due to the xenon buildup (0.2%/hr).

d. Control of Spatial Power Distribution Oscillations

The large size of this reactor makes it possible for local power perturbations in the core to cause flux distribution oscillations due to xenon buildup and decay. These oscillations are slow, generally of many hours in duration, but involve large segments of the core. In order to keep the power distribution changes to a minimum, a method is required for independent control of the local reactivity in several core volumes. Although the precise magnitude and frequency of spatial power oscillations are not known, data obtained indicate that the period

of the oscillations varies between many hours to one day and that a total reactivity of 0.1% to 0.2% is sufficient to regulate the oscillations. Therefore, the minimum requirements for control of spatial power oscillations are: (1) local control of flux distribution in 14 regions; (2) 0.1% total reactivity in local control elements; (3) ability to remove all control elements; (4) an instrumentation system to detect flux changes of about 1%, and (5) a control system to analyze the data obtained from the instrumentation system and provide data for suppression of the oscillations.

e. Power Level Control

Change in excess reactivity due to fuel burnup is compensated by continuous on-line refueling of the reactor. However, some variations occur in power level during startup, refueling, and steady-state power operation. Regulation of, or compensation for, these variations is to be with a power regulating control system. The maximum amount of reactivity which need be controlled is that associated with raising the reactor power from zero to full power; this amounts to about 0.3%.

3. Control System Designs

Three types of control are provided in accordance with the foregoing requirements. Normal shutdown control is accomplished by horizontal cylindrical control rods which move perpendicularly to the fuel channels; backup shutdown control and xenon decay control are accomplished by insertion and removal of a boron solution in the moderator; and power level and spatial power distribution oscillation regulation is accomplished by vertical movement of partial-length control rods. In-core instrumentation is provided to detect flux distribution changes due to xenon transients.

A schematic showing the location of the horizontal and vertical control rods and the location of the in-core detectors is shown in Figure II-45.

FIG II-45. Control Rod and In-Core Instrument Positioning Layout

a. Normal Shutdown System

Normally, the reactor will be shut down by the insertion of 84 hydraulically-actuated, hollow, cylindrical control rods. The control rods are stainless steel tubes containing boron-carbide, and are 2.5 in. OD x 0.094-in. -thick x 130-in. - long. As indicated in Figure II-45, the rods are placed in seven horizontal planes of six rods each, making a total of 42 rods on each of two opposing faces of the reactor. When inserted into the reactor, the rods are cantilevered between the vertically oriented calandria tubes. To minimize parasitics in the core, no guide tubes are used. The vertical deflection due to the weight of the rod is 0.40 in. Horizontal deflection due to a moderator velocity of 1 ft/sec, normal to the control rods, is 0.045 in.; the clearance between the OD of the vertical calandria tubes is 5.302 in. The total reactivity worth of all 84 rods is a minimum of 4%, and the insertion time for any one or for all control rods is 5 sec for 80% insertion.

Figure II-46 shows the horizontal penetrations and hydraulic actuator. The control rod actuator consists of a D₂O-operated hydraulic cylinder, with a spring-loaded return. The cylinder has a bore of 3.25 in. and a stroke of 130 in. The control rod is mechanically attached to the end of the cylinder piston rod and is supported by a bearing located at the moderator tank wall.

Sealing of the calandria tank, shield tank, and CO₂ cooling gas is accomplished by using a series of concentric sleeves extending from the various tanks to the area outside the biological shield. The tube diameters are stepped to prevent radiation streaming. All D₂O seals are static-gasket type to minimize leakage. Except for the moderator tank sleeve which is welded to the tank, all the components are removable for maintenance or replacement after the moderator has been drained below the level of the particular control rod.

The external hydraulic supply system for the shutdown rods is divided into four independent loops; each loop supplies 21 control rod actuators dispersed throughout the core. As indicated in Figure II-47, each loop consists essentially

FIG II-46. Horizontal Control Rod

FIG II-47. Horizontal Control Rod System Schematic

of a pump, piping to distribute the D_2O to the 21 cylinders, and a three-way solenoid valve to control the direction of flow at the rod end of each cylinder. The D_2O is obtained from the main storage tank, and the head-end of the cylinder is piped directly to the moderator tank to allow for fluid displacement during cylinder actuation.

Magnetic-reed switches mounted on the outside of the cylinder are used for control element in and out position indication. Energizing one or more of the solenoid control valves permits pressurized D_2O to enter the rod end of the cylinder, withdrawing the control rod from the core and compressing the return spring located in the head end of the cylinder. Complete withdrawal of all units can be accomplished in 30 sec, using a flow of 75 gpm at 100 psi in each loop. For the control rod to be held out of core requires that pressure be maintained in the rod end of the cylinder, but only leakage flow is supplied.

To produce a reactor shutdown or scram, the solenoid is de-energized, connecting the D_2O in the rod end of the cylinder directly to the moderator tank. The force of the compressed spring drives the element into the core. In the event of an electrical or pump failure, the solenoid valves, which are spring-loaded in one position, will automatically return to the dump position, initiating a reactor scram. The design of the scram return spring is such that a 200 lb force is available for rod insertion from the fully withdrawn rod position; in the fully inserted position a 40 lb force still remains to maintain the control rod inserted.

The shutdown rods are used in the fully inserted or fully withdrawn positions. Burnup of the boron is, therefore, negligible, and replacement of the rods will only be due to mechanical deterioration or system malfunction.

b. Backup Shutdown System

The backup shutdown system consists of a heavy-water boron solution which is injected into the D_2O moderator pumping loop. A concentration of 27.8 ppm B_{nat} has a reactivity worth of 10%, and is sufficient to maintain the reactor

subcritical under all conditions with all control rods out of the core. Injection of the boron solution to achieve a concentration of 27.8 ppm B_{nat} in the moderator can be accomplished in about four minutes.

Boron injection will occur when a valve is opened manually or by remote manual switch actuation. The boron backup system is used only if the reactor cannot be shut down by the normal system and when a hazardous reactor condition is anticipated.

c. Control of Equilibrium Xenon Effects

Compensation is made for the initial excess reactivity associated with equilibrium xenon, by the addition of a boron solution to the moderator. As xenon decays below the equilibrium concentration after about 34 hr, boron can be added to the moderator to maintain the shutdown margin. The boron solution is the same as that used for the backup shutdown system. However, only 6.3 ppm of B_{nat} in the D_2O moderator will be required for equilibrium xenon. Boron is removed at a rate approximately equal to the xenon grow-in rate. Since the maximum rate of xenon grow-in causes a reactivity decrease of about 0.2%/hr, the boron solution control system is capable of changing the boron concentration at a rate of 1 ppm/hr which is about twice the maximum rate of change required.

Boron not removed by the ion exchange system is burned out during operation with the reactivity being compensated by vertical control rods.

d. Control of Spatial Power Distribution Oscillations and Power Level

The core is divided into 18 regions comprising of one central region and 8 radial regions in each of two axial planes. Each of the 9 core regions contains a minimum of two partial-core-length absorber rods which are initially centered on the axial center of the core. Movement of either of the two partial-length control rods changes the local power distribution in the two axial planes.

Control of both spatial flux oscillations and small power level changes is by partial-length vertical absorber rods located in the core as shown in Figure II-45. Seventeen penetrations through the top of the moderator tank contain mechanical drive mechanisms which position any one of a cluster of four partial-length control rods in nine locations, and any one of a cluster of three partial-length control rods in eight locations. A total of 60 partial-length control rods is available for power and flux distribution control. As a minimum, 34 of these rods, 2 for each of 17 core positions, are used for controlling spatial flux distribution oscillations, and 26 of the rods are for power level control. The total reactivity held in the rods is about 0.3%, with between 0.1% to 0.2% being held by the 34 rods to be used for flux oscillation control.

In order to eliminate interference with the refueling machine, the drive mechanisms for the vertical control rods are located at the top refueling face between the top insulation blanket and the fuel tube coupling surface as shown on Figure II-48. Each drive mechanism is removable for servicing and to allow replacement of pressure tubes.

The drive mechanism (Figure II-49) consists of a 4-in. dia drum driven by a fractional-horsepower gear reducer AC motor, through a worm gear reducer. The absorber element consists of 1/2-in. OD borated stainless steel rod segments coupled with a stainless steel cable to form a flexible rod about 8-ft long. Rod flexibility is necessary to minimize interference of the rod with respect to the guide tube because of horizontal expansion of various structures above the calandria tank. The flexible rod is suspended within the guide tube in the moderator by a stainless steel tape 0.005-in. -thick x 0.250-in. -wide. This tape is attached to the drive take-up drum. Positioning of the drum is achieved by driving the drum with the AC motor. Position indication is obtained by a multiturn potentiometer driven directly from the tape drum. All components are designed for 100% relative humidity and 300°F temperature.

FIG II-48. Vertical Control Rod Positioning Layout

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FIG II-49. Vertical Control Rod Drive System

The lower section of the flexible-rod guide tubes for the 3-rod and 4-rod clusters consist of 0.563-in. OD x 0.020-in. -thick zircaloy tubes fastened together and perforated to allow moderator water to cool the rods. Stainless steel is used in the upper section of the guide tubes above the core by making a simple mechanical transition joint with the zircaloy tube. Details of the vertical control rod penetration, and mounting details are shown in Figure II-50.

All of the partial-length control rods can be completely removed from the core in order to make use of the reactivity tied up in the rods for power escalation or recovery from a power cut-back.

Because the guide tubes pass through the hot pigtail area of the upper face of the reactor, and because the drive mechanisms will be subjected to thermal radiation from the pressure tubes at the refueling face, light-water cooling coils are provided on the drive mechanism covers. A helium connection is also provided for each mechanism to purge the residual air and the tritium which collects at the top of the mechanisms. Figure II-51 is an isometric of a typical 4-rod cluster assembly showing the cooling coils and helium purge line.

The drive motor is designed to position the control rod at about 20 ft/min. Therefore, the maximum rate at which reactivity can be added is about 0.03%/sec. All rods can be completely withdrawn from the core in 20 sec to 60 sec, depending on the initial position in the core.

4. Reactor Core Monitoring System

Three-dimensional flux or local power data are obtained from the temperature reading of the outlet coolant from each fuel channel combined with the flux readings from 33 Hilborn* neutron flux detectors. Eleven Hilborn detectors are located radially on three axial planes, as shown on Figure II-51. A minimum of one detector is located in each of nine radial regions in two axial planes of the reactor.

*Reuter-Stokes Electronic Components, Inc.

FIG II-50. Vertical Control Rod Installation

FIG II-51. Vertical Control Rod Drive System Isometric

The three-dimensional flux data are automatically fed to a digital computer which is programmed to yield information on the magnitude and location of spatial flux changes. From this information, data are generated for positioning the appropriate vertical control rods to terminate and correct the xenon-induced change.

The computer output is used to indicate the movement of the vertical control rods which should be made manually.

III. COOLANT SYSTEMS

A. COOLANT

1. General

The organic coolant selected for the HWO CR is a mixture of terphenyl isomers. This material has a low vapor pressure and is non-corrosive; thus, it permits the use of relatively low pressure carbon steel piping and components. It does not present special handling problems and requires only normal industrial safety precautions. Induced activity due to radiation is low; therefore, shielding requirements are relatively slight and coolant systems are readily accessible for operation and maintenance.

2. Composition

Unirradiated or makeup coolant is a mixture of terphenyl marketed commercially as Santowax-OM*. The unirradiated material contains a small fraction of high molecular weight polymers, or high boilers (HB). Under reactor operating condition, the HB content increases (see Section A-4 below). An equilibrium operating HB concentration of 10% was selected to provide the optimum combination of physical and heat transfer properties and coolant decomposition rate (HB formation rate). The approximate compositions of the equilibrium irradiated coolant and of HB are presented in Table III-1.

3. Physical Properties

The physical properties of irradiated Santowax-OM have not been determined, but are expected to be very close to those of Santowax-OMP, which is used at the Piqua Nuclear Power Facility and on which most of the experimental work has been done. The estimated properties of the unirradiated and irradiated coolant as a function of HB content and temperature, are shown in Table III-2. The vapor pressure of the irradiated material may be increased by the presence of low boilers as well as dissolved gases and water, and therefore depends on the extent of degasification (see Section III.C. 1).

*Monsanto Company trade name

The vapor pressure of hydrocracked coolant (See Section III. C. 3) will be increased slightly because of the formation of biphenyl.

TABLE III-1
APPROXIMATE COMPOSITION OF COOLANT AND HB

<u>Approximate Composition of Santowax-OM plus 10% HB</u>	
<u>Constituent</u>	<u>Content(%)</u>
Low boilers	< 0.03
Biphenyl	2
Terphenyls	77
Intermediate boilers	11
High boilers	10
<u>Composition of HB - Molecular Weight Range</u>	
<u>Mol wt range</u>	<u>Content(%)</u>
226-268	6
269-344	6
345-420	10
421-496	73
497-572	1
573-648	< 1
> 648	3
<u>Composition of HB - Compound Distribution</u>	
<u>Constituent</u>	<u>Content(%)</u>
Polyphenyls	75
Triphenylene	15
Phenanthrenes	2
Olefins	3
Other types	5

TABLE III-2
PROPERTIES OF ORGANIC COOLANT

Property	HB Content (%)	Temperature (°F)			
		500	600	700	800
Density (gm/cc)	0	0.917	0.870	0.824	0.776
	10	0.930	0.885	0.839	0.794
	20	0.944	0.900	0.855	0.810
	30	0.958	0.915	0.871	0.829
Viscosity (centipoise)	0	0.54	0.37	0.26	0.20
	10	0.66	0.43	0.30	0.23
	20	0.79	0.51	0.35	0.26
	30	0.98	0.63	0.43	0.31
Specific Heat (Btu/lb-°F)	0 to 30*	0.534	0.566	0.599	0.631
Thermal Conductivity (Btu/hr-ft-°F)	0	0.069	0.066	0.062	0.059
	10	0.071	0.068	0.065	0.061
	20	0.073	0.070	0.067	0.064
	30	0.075	0.072	0.069	0.067
Vapor Pressure (psia)	0	2	6	16	40
	14†	-	7	20	50
	37†	-	17	39	89
Melting Point	10	178°F			

*Decrease at 30% HB is <2.0%.

†Estimated from OMRE coolant data.

4. Decomposition Rate

a. Radiolytic Decomposition

Radiolytic decomposition rates are calculated as functions of coolant composition and temperature. Calculated values for G_γ , G_n and total G are shown in Table III-3.* These calculations are based on the following reactor characteristics: (a) Thermal power: 3093 Mw; (b) Thermal energy deposited in coolant: 0.42%, (c) Energy deposition distribution: 77% neutrons, 23%

gammas; and the following coolant radiolysis properties, based on recent data interpretations (references 1, 2 and 3). (a) Activation energy for G_γ is about 1 kcal/mole; (b) Fast neutron effect (G_n/G_γ) is about 4.5 and essentially independent of temperature in the temperature range of interest; (c) Radiolysis reaction follows second order kinetics.

TABLE III-3
CALCULATED G^* VALUES FOR HWO CR COOLANT

Terphenyl Content (%)	Average Core Temperature								
	600°F			650°F			700°F		
	G_γ	G_n	G	G_γ	G_n	G	G_γ	G_n	G
100	0.19	0.83	0.68	0.19	0.86	0.71	0.20	0.90	0.74
90	0.15	0.68	0.56	0.16	0.70	0.58	0.16	0.73	0.60
80	0.12	0.53	0.44	0.12	0.55	0.45	0.13	0.58	0.48
70	0.091	0.41	0.34	0.094	0.42	0.35	0.098	0.44	0.36

*Based on $G = f_n G_n + f_\gamma G_\gamma$ where $f_n = 0.77$ and $f_\gamma = 0.23$.

At an average in-core coolant temperature of 670°F, with a coolant composition of 90% terphenyl, the calculated total radiolytic decomposition rate is 0.47 lb/Mwht (1450 lb/hr at full power).

b. Pyrolytic Decomposition

The calculated terphenyl pyrolysis rate based on published data** is

* G_γ = molecules of terphenyl decomposed per 100 ev energy absorbed from gammas.

G_n = molecules of terphenyl decomposed per 100 ev energy absorbed from fast neutrons.

G = molecules of terphenyl decomposed per 100 ev energy absorbed from the total radiation field.

** NAA-SR-6920; "Coolant Decomposition Rates and Make-up Costs for Organic Reactors"; R.H.J. Gercke and J.F. Zack, Jr.; June 15, 1964

approximately 30 lb/hr, which is negligible compared to radiolysis at full power.

5. Activation

Coolant radioactivity is due principally to activation of inorganic impurities (introduced in the make-up coolant or through corrosion) and release of recoil products from the cladding of the fuel elements. It is anticipated that under normal operating conditions the radiation level at the surface of the large coolant piping will be approximately 10 mr/hr. This low level will allow direct contact maintenance. Operation at PNPF has indicated similar levels. Coolant activity as a result of cladding failures is discussed in Section XI.

B. MAIN HEAT TRANSFER SYSTEM

The main organic coolant system transfers the thermal energy from the reactor core to: (1) the steam generating units, where superheated steam is produced for the turbine-generator; and (2) the reheaters, where steam from the turbine high pressure casing is reheated before it is returned to the low pressure casings.

Organic coolant is circulated at the rate of 110×10^6 lb/hr through the reactor core, with the outlet pressure controlled at 100 psia. At full power, coolant is heated in the core from 595°F to 750°F, absorbing 10×10^9 BTU/hr, 2921 Mwt, from the core. This heat is used to generate 9.07×10^6 lb/hr of 925 psig, 725°F superheated steam and to reheat this steam to 153 psig, 725°F conditions after it leaves the steam turbine high-pressure section.

This system is shown diagrammatically in Figure III-1. Design data are shown in Table III-4. The arrangement of the system in the plant is shown in Figures III-2, -3, and -4. The buildings shown in Figs. III-2, -3 and -4 are discussed in Section X.

FIG III-1. Organic Coolant Systems Flow Diagram

The main heat transfer system contains three coolant loops. In selecting the number of loops, factors considered were the loop costs, equipment availability, plant reliability, and economical use of building space. The loops are arranged to provide flexibility of piping, access for equipment maintenance and replacement, and economy in layout.

TABLE III-4
MAIN HEAT TRANSFER SYSTEM DESIGN DATA

Number of parallel coolant loops	3	
Thermal power to coolant (Mwt)	2,921	
Total reactor coolant flow (lb/hr)	110×10^6	
Reactor inlet coolant temperature (°F)	595	
Reactor outlet coolant temperature (°F)	750	
Reactor coolant average temperature (°F)	672	
Coolant temperature rise across reactor (°F)	155	
Pressure at reactor inlet header (psia)	284	
Total system pressure drop (psi)	284	
Reactor pressure drop (header to header) (psi)	184	
Main loop coolant velocity (ft/sec)	30	Maximum
Total steam generation rate (lb/hr)	9.07×10^6	
Reactor coolant volume (gal)	110,000	Includes mixing tanks
Surge tank coolant volume (gal) (0.8 full)	16,000	
Piping coolant volume (gal)	70,000	
Steam generation equipment coolant volume (gal)	70,000	
Auxiliaries	64,000	
Total system coolant inventory (gal)	330,000	

TABLE III-4 (Continued)

Number of pumps	3	One per loop
Flow rate each pump (gpm)	90,000	
Total pump head (ft)	800	
Coolant temperature at pump (° F)	750	
Shaft horsepower each pump (HP)	17,000	Steam turbine drive
Superheater thermal duty (Mwt)	407	Total - three loops
Evaporation thermal duty (Mwt)	2,117	Total - three loops
Reheater thermal duty (Mwt)	419	Total - three loops
Superheater surface area (ft ²)	97,500	Total - three loops
Evaporator surface area (ft ²)	202,000	Total - three loops
Reheater surface area (ft ²)	97,200	Total - three loops

In addition to the main heat transfer loops, provisions are included for system pressurization and over-pressure relief, system draining and venting, core cooling during loop shutdown, and coolant leakage recovery.

1. Main Loop Arrangement

The three main heat transfer loops are connected in parallel to the reactor inlet and outlet mixing tanks. Each piping loop contains a main coolant circulating pump, a steam generating unit consisting of an evaporator and separate superheater, reheater, blocking valves, relief valves, and appropriate instrumentation. On the organic coolant side, the superheater and reheater are connected in parallel upstream of the evaporator.

In each of the three loops, organic coolant is pumped at the rate of 90,000 gpm from the reactor core through the superheater and reheater, then through the evaporator and back to the core. Approximately 28% of the total flow in each loop flows through the reheater for reheating steam from the high pressure

FIG III-2. Reactor Building Plans and Elevations

FIG III-3. Reactor Building Plans and Elevations

FIG III-4. Auxiliary Buildings - Plan and Elevation

section of the turbine unit. Most of the total flow, 72%, is circulated through the superheater to superheat the steam leaving the evaporator. The organic streams leaving the superheater and reheater converge in a common pipe before passing to the evaporator inlet.

The reactor and the reactor inlet and outlet coolant mixing tanks are located inside the reactor building. The coolant loops and associated equipment are located in the steam generator and pump building. A block valve is provided on each side of each loop penetration of the reactor building. These valves are used to isolate the loop from the reactor and the reactor building in the event of a pipe rupture, major release of fission products to the coolant, or equipment malfunction.

The mixing tanks serve as the coolant collection headers to connect the reactor piping complex with the main heat transfer system. Coolant returning from the three main coolant loops enters the reactor inlet mixing tank where it is distributed to the various reactor piping inlet headers located inside the biological shield. After passing through the reactor, the coolant is collected from the outlet headers by the reactor outlet mixing tank, and is then distributed back to the main coolant loops.

The outlet mixing tank also serves to provide a delay time for the coolant leaving the reactor. In the event of a major release of fission products to the coolant, the associated radioactivity is retained in the reactor building by closing the main loop isolation valves. The piping and mixing tank volume is sufficient to provide a total of 10 sec of coolant transport time at full flow between the time the coolant leaves the reactor core and the time it reaches the main loop isolation valves. This provides sufficient time to detect the fission products and isolate the loops before a

significant amount of fission product can leave the reactor building. The size of the outlet tank also provides a means for attenuating pressure waves resulting from rapid closure of the loop isolation valves.

2. Main Loop Piping and Valves

The main coolant piping system is fabricated from type ASTM A-212 Grade B carbon steel, and is designed in accordance with the latest American Standards Association Code for Pressure Piping. Design pressure and temperature are 400 psig and 750°F, respectively.

The main loop piping has been sized for a maximum coolant velocity of 30 ft/sec. Piping to and from the evaporator and superheater is 38-in. OD with 5/8-in. wall thickness. Piping to and from the reheaters is 20-in. OD with 3/8-in. wall thickness.

All other piping 2-in. through 12-in. diameter is Schedule 40, and all lines smaller than 2-in. are Schedule 80. All-welded construction is employed in the main coolant system, except where flanges are required for cleanout opening.

The main loop piping is arranged to provide the required flexibility. The double block valves provided in each inlet and outlet line to the reactor are provided with the necessary instrumentation and power operators for remote operation. They are cast carbon-steel gate valves with chromium-nickel alloy trim components. A back-seating feature is incorporated in the design to minimize valve stem leakage in the full-open position. These valves are furnished with thermal-isolating extension bonnets and packed stuffing boxes.

3. Steam Generating Equipment

Main steam for the turbine-generator is generated in three units, each consisting of a superheater and a natural circulation evaporator. Each of

the three main coolant loops is provided with one steam generating unit. Steam exhaust from the high-pressure casing of the turbine is reheated in three separate reheater units, one in each loop. The total steam-generating thermal duty for the plant at full power is 2524 Mwt or 8.6×10^9 Btu/hr. The total reheater thermal duty is 419 Mwt or 1.4×10^9 Btu/hr. The total heat removed by the steam generating equipment is 22 Mwt greater than the heat input by the core. This is due to the fact that the pumps add 34 Mwt of energy to the coolant and the heat losses are estimated at 12 Mwt.

Design data for each evaporator, superheater, and reheater are given in Table III-5.

Feedwater at 420°F is supplied to the shell of the evaporator. The feedwater temperature is raised to steam saturation temperature (540°F) in an economizer section, which is an integral part of the steam generator. The feedwater enters the economizer section and flows counter-current to the exiting organic. Feedwater at approximately saturation temperature emerges from the economizer section and mixes with the steam-water mixture in the boiling zone, where it is ultimately converted to steam. The steam that is generated flows through steam separation equipment contained within the steam generator shell, and then flows on to the superheater.

a. Superheaters

Each superheater is a heat exchanger consisting of a horizontal shell containing two U-tube bundles extending from a cylindrical tube sheet located at the center of the shell (Fig. III-5). Organic coolant flows in the shell and steam in the tubes. Each tube bundle has a circular cross section and the shell is close-fitting around the tube bundles. The central portion of the superheater shell is enlarged to form a plenum. This space serves as a collection header for organic entering and leaving the tube bundle.

TABLE III-5

STEAM GENERATING EQUIPMENT DESIGN DATA

<u>Evaporator</u>	
Thermal duty (Mw)	706
Organic flow (lb/hr)	36.7×10^6
Organic inlet temp (° F)	707
Organic outlet temp (° F)	595
Organic side pressure drop (psi)	35
Feedwater temp (° F)	420
Saturation outlet temp (° F)	540
Steam pressure (psig)	945
Steam flow (lb/hr)	3.02×10^6
<u>Superheater</u>	
Thermal duty (Mw)	136
Organic flow (lb/hr)	26.4×10^6
Organic inlet temp (° F)	750
Organic outlet temp (° F)	721
Organic side pressure drop (psi)	15
Steam inlet temp (° F)	540
Steam outlet temp (° F)	725
Steam outlet pressure (psig)	925
Steam side pressure drop (psi)	20
Steam flow (lb/hr)	3.02×10^6
<u>Reheater</u>	
Thermal duty (Mw)	140
Organic flow (lb/hr)	10.3×10^6
Organic inlet temp (° F)	725
Organic outlet temp (° F)	672
Organic side pressure drop (psi)	18
Steam inlet temp (° F)	390
Steam inlet pressure (psig)	165
Steam outlet temp (° F)	725
Steam outlet pressure (psig)	153
Steam side pressure drop (psi)	12
Steam flow (lb/hr)	2.63×10^6

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FIG III-5. Steam Superheater

The superheater is of counterflow design with organic in the shell flowing parallel to the tubes. A horizontal baffle occupying the full shell diameter extends from the U-bend of the smallest U-tube on one end to the same point on the opposite end. The baffle separates organic flowing down one leg of the U-tube from that flowing over the other leg. The central steam tube-sheet header is also divided by a full-diameter baffle to separate the steam entering one end of the U-tubes from that exiting from the other end.

Each superheater contains 5200 U-tubes, 5/8 in. OD x 0.049 in. wall-thickness and has a heat transfer surface area of 32,500 ft². The superheater overall heat transfer coefficient is 182 Btu/hr-°F-ft². The plane of the U-bends is vertical. All of the tubes enter the cylindrical tubesheet in a radial direction. All tubes except those on the longitudinal centerline of the unit contain a bend a small distance away from the tubesheet for radial-entry orientation into the tubesheet. The angle of the bend increases progressively for tubes located farther from the center of the tube bundle. The bend velocity of the steam from the tubes is 60 ft/sec.

The superheaters are of carbon steel, all-welded construction, and are radiographically and hydrostatically tested in accordance with ASME Boiler and Pressure Vessel Code requirements. The shell materials are A-212B and the tubes A-210. The tubes are rolled and welded into the tube sheet. Each unit weighs approximately 200,000 lb dry, and contains an additional 60,000 lb of organic when operating. Each unit is approximately 44-ft long and 10-ft in diameter at the central portion of the shell.

b. Evaporators

The evaporators are of the natural recirculation type. They are double

U-tube horizontal heat exchangers and are similar to the superheaters. The tube bundles and the central cylindrical tubesheet (Fig. III-6) are located in the bottom portion of the shell. The water level is maintained near the middle of the shell covering the tubes. Steam separation equipment is contained in the upper portion of the shell above the water level.

Organic coolant from the superheater and reheater enters the upper leg of the U-tubes through a pipe internal to and concentric with the cylindrical tubesheet. This pipe is connected to the inside of the cylindrical tubesheet, with a ring to separate organic entering the tubes from that leaving the tubes. Organic exiting from the tubes enters the annular region between the central pipe and the cylindrical tubesheet and leaves the evaporator through the outlet nozzle.

The economizer or preheating section, integral with the evaporator is formed by shrouding or encasing the necessary length of the outlet leg of the U-tubes. The tube supports serve as baffling inside the shrouded portion of the tubes. This arrangement separates the entering feedwater (except for a small amount of leakage) from the boiling mixture in the rest of the shell, until the feedwater has reached saturation temperature. The combined heat transfer area of the economizer and boiling zone is smaller than the heat transfer area required when the feedwater is added directly to the boiling mixture. This reduced area requirement is due to the higher log-mean temperature difference existing individually in the preheating and boiling zones, as compared to the log-mean temperature difference resulting when the feedwater is added to the boiling mixture. The savings in heat transfer area become more pronounced as the organic outlet temperature approaches the saturation temperature of the steam.

FIG III-6. Steam Evaporator

Each evaporator contains 10,700 U-tubes, 5/8 in. OD x 0.065 in. wall-thickness and has a heat transfer surface area of 67,300 ft². The overall heat transfer coefficient in the boiling zone is 400 Btu/hr-°F-ft², and 167 Btu/hr-°F-ft² in the preheating zone. The plane of the bend of the U-tubes is vertical. These tubes enter the cylindrical tubesheet as described for the superheater. The organic velocity in the tubes is 13.5 ft/sec.

The evaporator is of carbon steel, all-welded construction, and is radiographically and hydrostatically tested in accordance with ASME Boiler and Pressure Vessel Code requirements. Shells, heads, and similar components are A-212B material, and the tubes are A-210. The tubes are rolled and welded into the tube sheet. Each evaporator weighs approximately 500 tons dry, and contains an additional 75,000 lb of organic and 130,000 lb of water at operating conditions. Each unit is approximately 51-ft long and 13-ft diameter.

c. Reheaters

The reheaters are of counterflow U-tube design with steam in the shell and flowing parallel to organic in the tubes (Fig. III-7). The design utilizes a single U-tube bundle and a flat tubesheet. To separate hot entering organic from cooled organic leaving the unit, the organic header end is partitioned. The shell is close fitting around the tube bundle to confine the steam to the open paths between the tubes in the tube bundle. A dividing partition is used on the steam side, to separate steam flowing down one leg of the U-tube from that flowing over the other leg, thus giving the counterflow design. The partition extends from the tubesheet through the tube land formed between the legs of the U-tubes, to the U-bend of the smallest U-tube, and occupies the full diameter of the shell.

SIDE ELEVATION

HEAT TRANSFER
SURFACE AREA
32,400 FT²

FIG III-7. Steam Reheater

Each reheater contains 3370 tubes, 5/8 in. OD x 0.049 in. wall thickness. The heat transfer area per vessel is 32,400 ft². The reheater overall heat transfer coefficient is 138 Btu/hr-°F-ft². The organic velocity is 10 ft/sec. Parallel flow velocity of the steam in the shell is 116 ft/sec (average). The shell or steam side includes a distribution belt to enable the steam to be admitted and removed from the tube bundle over the entire circumference of the tube bundle.

Each reheater is of carbon steel, all-welded construction, and is radiographically and hydrostatically tested in accordance with ASME Boiler and Pressure Vessel Code requirements. All materials are A-212B, except the tubes which are A-210. The tubes are rolled and welded into the tubesheet. Each unit weighs approximately 160,000 lb dry, and contains an additional 26,000 lb of organic when operating. Each unit is approximately 38-ft long and 8-1/2-ft in diameter.

4. Main Coolant Pumps

The three main coolant pumps are horizontal single-stage centrifugal units with vertical 38-in. diameter suction and discharge nozzles. Each pump has a single 48-in. diameter impeller. Pump driving energy is provided by steam turbines through parallel-shaft reduction gears. The approximate overall dimensions of each pump and drive unit are 47-ft long, 14-ft wide, and 10-ft high. Figure III-8 shows the arrangement of the pump and drive.

Each pump is designed to deliver 90,000 gpm of 750°F reactor coolant against a total head of 800 ft. At these operating conditions, each pump requires 17,000 brake HP to drive the shaft at 1200 rpm. The pump casings are of the vertically-split design, which allows the rotating elements to be

MAIN COOLANT PUMP & DRIVE

FIG III-8. Coolant Pump and Drive

removed for repair without disturbing the piping or the drives. The casings are made of carbon steel. Stainless steel is used for the shafts and impellers. Shaft sealing is accomplished with face-type mechanical seals. Seal flushing and water jacketing are used to keep the seal chambers below 400°F. The pump shaft bearings are of the conventional sleeve type and are lubricated with cooled oil. The reduction gears are standard industrial units with a 4.6:1.00 ratio.

The steam turbines are condensing, dual-inlet units designed to operate under normal conditions with 145 psig, 725°F steam, and during plant startup, with 900 psig, 725°F superheated steam. At full load, the turbine shafts rotate at 5500 rpm.

The horizontal pump arrangement was selected because steam turbines and gears for this rating are readily available only with horizontal shafts. Reviews with a number of large pump manufacturers has indicated that main coolant pumps with the required capacities are feasible and within present manufacturing capabilities.

5. Surge Tank and Pressurization

A 20,000-gal surge tank is connected to the reactor outlet mixing tank by a single 8-in. line. The tank contains about 2100 SCF of nitrogen and 16,000 gal of coolant at 350°F and 75 psig. The tank serves as a gas cushion to dampen very rapid, but small, pressure variations, and provides a volume of coolant to keep the shutdown cooling system full in the event of isolation of the degasifier tank (see Section III C.1). A high-pressure nitrogen supply and vent is provided to permit remote adjustment of the coolant volume in the tank. In the event of a major coolant leak and subsequent pressure decrease, coolant in the surge tank is automatically forced out of the tank and into the coolant system by the nitrogen pressure.

The pressure in the main heat transfer system is maintained by a back-pressure control valve in the line from the reactor inlet mixing tank to the degasifier tank. Two parallel-connected full-capacity pressurizing pumps, which take suction from the degasifier tank, continually return coolant to the reactor inlet mixing tank. Each pressurizing pump has a rated capacity of 2000 gpm at a total head of 800 ft and is driven by a 450 HP motor. Pressurization system design data are presented in Table III-6.

TABLE III-6
DESIGN DATA FOR PRESSURIZATION & DEGASIFICATION SYSTEMS

<u>Item</u>	<u>Data</u>
Reactor Outlet Control Pressure (psia)	100
Coolant Flow Rate (gmp)	2000
Coolant Temperature (°F)	595
Water Removal Rate at 0.5 psig (lb/hr)	100
Decomposition Gas Removal Rate at 0.5 psig (SCFH)	1150

6. Organic Vent, Drain and Relief

This system provides the necessary connections, piping, and vessels to drain and fill the organic systems, and to handle the discharge from the pressure relief devices. In accordance with code requirements, relief valves are provided to protect all organic process systems equipment subject to over-pressure conditions. In both the reactor and auxiliary buildings, the outlets from these relief devices discharge into headers connected to an organic drain tank. The entrained liquid separates out in the drain tank, and the disengaged vapors vent to either the organic vent vapor trap or the relief scrubber tank, before venting to the plant stack.

A pressure rupture disc is installed in a line connecting the drain tank and the relief scrubber tank. This disc prevents normal organic vapors from contaminating the relief scrubber. In the event of a large pressure-relief discharge, such as opening of the main coolant system relief valves, the

disc will rupture, allowing the large volume of vapors to exhaust through the relief scrubber. The vapors are directed into the bottom of the tank and rise up through the trays and counterflow of water. The water condenses most of the steam and organic present, allowing the non-condensable vapors to exhaust up the plant vent stack.

Three organic drain tanks are provided with a total capacity to contain the coolant drained from one main coolant loop, and also to provide liquid-vapor separation in the event of an overpressure accident. Drain pumps are provided to transfer organic from the drain tank to the organic recovery system (see Section III. C.3). A filter is provided at each drain pump discharge to remove particulate matter. The three drain tanks have a total capacity of 100,000 gal. Two tanks are located in the reactor building and the third in the auxiliary building (see Section X). The drain transfer pumps each have a capacity of 200 gpm and are driven by 10 HP motors.

7. Shutdown Cooling

A continuous and reliable method of removing decay heat from the reactor during normal and emergency shutdowns is provided by an independent shutdown heat removal system. This is a single loop (Fig. III-1) and is connected directly across the reactor inlet and outlet mixing tanks, and includes two parallel-connector full-size two-speed pumps, a heat exchanger which removes the decay heat by generating steam, a condenser which condenses this steam, and connecting piping. The system is designed to maintain the fuel element cladding temperature at or below normal operating level if it should become necessary to shut the main coolant pumps down quickly and isolate the reactor building. The system is also used for normal shutdown cooling to permit isolation of all the main coolant loops for maintenance. All system components, except the condenser, are located in the reactor building.

The shutdown cooling system is designed to be completely automatic and operate under all adverse conditions. The motor drives for the organic shutdown cooling pumps and condenser cooling water pumps are connected to the emergency power supply. Each of the two shutdown cooling pumps is

sized to provide a flow rate of 15,000 gpm (~5% of full power flow). The shutdown cooling heat exchanger is an organic-to-water evaporator sized to remove ~2% of full reactor thermal power, at coolant inlet temperature of 750°F with 15,000 gpm coolant flow and 300 psig steam pressure. Two percent of thermal power represents the estimated decay heat load 2.5 min after reactor shutdown. In sizing the components, credit is taken for the amount of heat transferred to the heavy water moderator, since the moderator cooling system continues to function and removes heat transferred to the moderator by radiation and by conduction through the gas-filled space between the process tubes and calandria tubes. The shutdown cooling condenser returns the condensate to the shutdown cooling heat exchanger by gravity flow, and is sized to remove ~1% of full thermal power at a steam inlet pressure of 300 psig. The excess steam produced during the first hour after reactor shutdown is discharged to atmosphere.

a. Operation

During normal reactor plant operation, the coolant is bypassed around the shutdown cooling heat exchanger, except for sufficient flow to generate and provide steam for steam tracing and other process requirements. This operation at less than full capacity assures that the system is always ready for emergency service. For additional reliability, both shutdown cooling pumps are operated continuously, but at reduced speed to minimize the power load. Organic coolant circulated the shutdown loop is taken from the reactor inlet mixing tank through the shutdown loop is taken from the reactor inlet mixing tank through a by-pass line which is valved open during normal plant operation. The main shutdown cooling system inlet line from the reactor outlet mixing tank is isolated from the system by a check valve in the piping.

b. Operation During Reactor Shutdown

For normal reactor shutdown, decay heat is removed either by using the shutdown cooling system or by using one of the main coolant system loops. In the event an emergency condition requires isolation of the reactor building and the main coolant loops, the shutdown cooling system is put into full capacity operation automatically, and provides organic coolant flow through the reactor core to remove decay heat. The initiating signal automatically: (1) increases the speed of the shutdown cooling pumps to provide a total flow rate of 15,000 gpm, (2) closes the two series-connected valves in the shutdown cooling system bypass inlet line, which, (3) results in the opening of the check valve in the main inlet line, and (4) increases coolant flow through the shutdown cooling heat exchanger to full system capacity.

8. Coolant Leakage

This system automatically detects significant coolant leakage in the reactor building, and collects and returns this coolant to the shutdown cooling system, thus assuring maintenance of an adequate organic coolant supply to the shutdown cooling system.

If leakage occurs in either the refueling rooms or piping chases of the reactor building, the coolant spills into the area and flows to a low-point floor drain, then in open drain lines by gravity to a 25,000-gal drain tank. A drain tank level alarm is actuated to alert operating personnel. If the coolant level continues to rise, two 2000-gpm vertical sump pumps are started automatically, and the isolation valve in the pump discharge line opens. A level controller controls the level in the tank at approximately its midpoint. The coolant is returned into the shutdown cooling loop at the suction of the shutdown cooling pumps.

As an added precaution, should an insufficient amount of coolant be collected by the leakage drain tank, emergency makeup line is used to transfer coolant from the new coolant storage tanks to the drain tank, causing the drain pumps to start up. This new coolant is then pumped to the shutdown cooling system pumps.

C. COOLANT PROCESS SYSTEMS

During reactor operation, the organic coolant tends to experience compositional changes due to radiolytic and pyrolytic decomposition and a low rate of system corrosion. As a result, impurities such as high boilers, decomposition gases, and corrosion products are formed and circulate with the coolant stream. To maintain the coolant essentially at equilibrium and with the required composition for heat transfer, low decomposition rate, anti-fouling, safety, and other considerations, three process systems are provided: degasification, adsorption, and coolant recovery. One system of each type is provided. These systems are connected directly or indirectly to the reactor inlet and outlet coolant mixing tanks, and not to the three main heat transfer loops.

1. Degasification

The degasification system is designed to accomplish the following:

- a) Remove the hydrogen and light hydrocarbons generated by the decomposition of organic coolant.
- b) Remove excess water in the main loop coolant resulting from possible in-leakage from the steam system.
- c) Accommodate changes in system coolant volume resulting from variations in operating temperature.
- d) Remove particulate matter from the organic coolant by filtration.

Fig. III-1 includes a flow diagram of the degasification system. Table III-6 presents design data for this system. The degasifier tank is maintained at an operating pressure of approximately 0.5 psig. The flow of 595°F coolant from the reactor inlet mixing tank to the degasifier tank is varied by the pressure control valve which controls the pressure in the reactor outlet mixing tank. Before entering the degasifier tank, the coolant passes through a 3-micron glass spool filter to remove particulate matter. This location for the filter allows a portion of the pressure drop between the main coolant system and degasifier tank to be utilized for filtration. The filtered coolant then sprays into the degasifier tank, where the gaseous decomposition products and water vapor are released. The gaseous products pass through a series of condensers before entering the waste gas system (see Section V. G. 1). The degassed coolant is pumped from the degasifier tank back to the reactor inlet mixing tank by the pressurizing pumps.

The degasifier tank is a vertical vessel with an internal spray distributor; operating pressure is maintained at 0.5 psig. As the coolant sprays into the degasifier tank, approximately 0.5% of the influent organic is vaporized and released, along with the entrained gases and water vapor. The vapors leaving the degasifier tank pass into the degasifier condenser and are cooled to 450°F. Approximately 80% of the vaporized coolant and 40% of the water vapor are condensed and returned to the degasifier tank. The remaining vapors enter a degasifier after-condenser and are cooled to 320°F. At this point, an additional 20% of the coolant vapors, and 10% of the water vapor, are condensed and returned to the degasifier tank.

The normal coolant level in the degasifier tank is approximately at its midpoint. Under steady-state temperature conditions, the coolant flow rates

to and from the degasifier tank are equal. During normal operation, this flow rate is 2000 gpm. When the main coolant system is undergoing a temperature change, the degasifier tank acts as a coolant accumulator to accomplish the change in system volume resulting from the temperature variation.

2. Adsorption

The adsorption system is provided to remove impurities from the organic coolant so that film deposits on heat transfer surfaces are minimized. High-temperature organic is passed through adsorption columns containing Attapulugus Clay*. Impurities are selectively deposited on the clay; after saturation, the clay is regenerated by burning the adsorbed material on site. The process diagram of this system as shown in Figure III-9 and Table III-7 presents relevant design data.

TABLE III-7
DESIGN DATA – ADSORPTION SYSTEM

Item	Design Data
Coolant Processing Rate (gpm)	75
Coolant Inlet Temperature (°F)	750
Adsorber Material	Attapulugus Clay
Adsorber Operating Cycle (days)	7
Adsorbent Life Time	9 Regenerations

*Mineral & Chemicals Philipp Corp.,
Menlo Park, N. J.

LEGEND

1/2"	1/2" AIR SCREWER COUMNS
1/4"	PRIMARY FILTER
1/2"	FRULESS PIPING
1/2"	INSTRUMENT CILLICIL + THERMOUPLE LEADS
1/2"	INSTRUMENT CAPILLARY TUBING
1/2"	IN INSTRUMENT AIR LINE
1/2"	TEMPERATURE INDICATING CATHODE
1/2"	PRESSURE INDICATING
1/2"	DIFFERENTIAL PRESSURE INDICATING
1/2"	WINDMILL AT F.L.
1/2"	DIFFERENTIAL PRESSURE ALARM HIGH
1/2"	CLATE VALVE
1/2"	WINDMILL AT F.L. VALVE
1/2"	TRANSMITTER LOCALLY MOUNTED
1/2"	WINDMILL AT F.L. VALVE
1/2"	WINDMILL AT F.L. VALVE
1/2"	WINDMILL AT F.L. VALVE

NOTE

ALL UNIDENTIFIED NUMBERS ARE PIPING DIMENSIONS IN INCHES

FIG III-9. Organic Adsorption System Flow Diagram

The adsorption system takes coolant from the reactor outlet mixing tank and returns the processed coolant to the degasifier tank. This system is designed to treat coolant at such a rate that the combined flow of coolant to the adsorber and distillation column (see Sec. III. C. 3 below) results in approximately one coolant inventory being processed by the combination of these systems every three days.

Two of the three adsorption columns are on-stream normally while the third column is "down" for clay regeneration. The piping and valving are arranged so that coolant passes through the two operating columns in series. All columns feed into a common effluent line containing two 3-micron backup filters which remove any clay the coolant may have picked up from the columns.

By sampling and analysis, the impurity level in the coolant is determined where it enters the first adsorber, between the two columns, and as it leaves the second adsorber. When the impurity level in the effluent reaches that of the column influent, the first column is valved out and the third, or fresh, adsorber is valved into operation as the second of the two on-stream columns. Column life is expected to be of the order of one to two weeks.

Prior to initially processing organic coolant, the Attapulugus Clay adsorbent is activated in the kiln. Before being transferred to the adsorption columns, the activated clay is held in the adsorbent storage bin. The columns are charged by dumping in the adsorbent through a 12-in. port at the top.

Coolant in the spent adsorbent is allowed to drain from the column to a contaminated coolant tank. After draining, residual coolant in the column is recovered by displacement with HB. Approximately two column-volumes of HB are pumped through the bed. The HB also drains to the contaminated coolant tank. The coolant which accumulates in the contaminated coolant tank

is reprocessed in the coolant recovery system. After the HB is drained from the column, the bed is dried by purging with hot nitrogen. The spent clay is stored within the column for several days to allow for radioactive decay. The decayed spent clay is then dumped and regenerated by burning off the adsorbate in the kiln. It is expected that the clay will be regenerated nine times before disposal becomes necessary. After the adsorbent is regenerated, it is transferred to the clay storage bin. From the storage bin, the reactivated adsorbent is returned to the adsorption columns.

Spent clay is handled pneumatically within piping to prevent the release of contaminated dust in the process area. Flue gases from clay regeneration are filtered through a dust collector and absolute filter before release to the plant stack.

3. Coolant Recovery System

The coolant recovery system controls the high boiler (HB) content in the main coolant system at 10% by distillation and converts 90% of the high boilers resulting from organic decomposition back to usable reactor coolant by catalytic hydrocracking. Figure III-10 is a flow diagram of this system. Table III-8 presents design data.

A sidestream of 45 gpm of 750°F coolant containing 1480 lb/hr of HB to be converted is withdrawn from the main organic coolant system. This flow combines with 0.4 gpm of makeup coolant as feed to the coolant recovery system. Coolant makeup is required, since not all the high boilers are recovered as useful coolant. The incoming coolant enters a distillation column, which is maintained at pressures down to 1 psia by a mechanical vacuum pump. The flashed portion of the column feed passes to an overhead condenser, where the organic condenses and drains to a distillate receiver

LEGEND

- LOCALLY MOUNTED
- ⊖ BOARD MOUNTED
- PI PRESS. INDICATING
- LG LEVEL GLASS
- FR FLOW RECORDING
- TI TEMP. INDICATING
- LI LEVEL INDICATING
- TS TEMP SWITCH
- PRC PRESS RECORDING CONTROL
- LIC LEVEL INDICATING CONTROL
- FRC FLOW RECORDING CONTROL
- TIC TEMP INDICATING CONTROL
- TRC TEMP RECORDING CONTROL
- ⋈ GATE VALVE
- ⊗ TRANSMITTER LOCALLY MOUNTED
- ⊕ DIAPHRAGM OPERATED VALVE
- ⊖ ELECTRICALLY OPERATED VALVE
- ORIFICE
- INSTRUMENT AIR LINE
- PROCESS PIPING
- INSTRUMENT ELECTRIC AND THERMOCOUPLE

NOTE
ALL UNIDENTIFIED NUMBERS ARE PIPING
DIMENSIONS IN INCHES

FIG III-10. Coolant Recovery System Flow Diagram

TABLE III-8
DESIGN DATA — COOLANT RECOVERY SYSTEM

Item	Design Data
HB Conversion Rate (lb/hr)	1480
Coolant Processing Rate (gpm)	45
HB Concentration in Coolant (%)	10
Feed Temperature (°F)	750
Product Yield from Hydrocracker	
Useful Coolant (%)	90
Coke Material (%)	1.5
Waste Gases (%)	8.5
Hydrogen Requirements (SCFH)	2700
Catalyst	Co Mo O ₄ on Al ₂ O ₃
Operating Cycle	Regenerate weekly
Operating Life	1 year

tank. This distillate is then pumped back to the main organic coolant system. The unflashed portion of the coolant (containing the HB) feed is pumped directly from the column to the hydrocracking reactors feed tank, or is circulated through the reboiler heater back to the reboiler section of the column by a bottoms pump. The level in the reboiler section is controlled by diverting a portion of the circulating bottoms to the hydrocracking reactors feed tank.

The feed stream to the catalytic hydrocracking reactors is controlled at 40 to 100% HB,* and is drawn from the feed tank by the feed pumps. The feed then mixes with a hydrogen stream and passes through an economizer which is heated by coolant after it leaves a hydrocracking reactor. An electric auxiliary

*IDO-16877 May 1963, "Catalytic Hydrocracking of High Boiler in Nuclear Reactor Coolant", L. E. Gardner

feed heater is provided to supply heat to the feed stream during startup. The combined organic-hydrogen feed then enters one of the two parallel catalytic hydrocracking reactors at 900°F and 950 psig. As the organic-hydrogen mixture passes over the catalyst, about 30% of the HB is converted back to usable coolant. The conversion of the HB consumes 2700 SCFH of hydrogen. The effluent passes through the feed economizer and enters a gas-liquid separator. Here an unreacted 100,000 SCFH of hydrogen is separated from the stream for recycling. A hydrogen recycle cooler reduces the temperature of the recycle hydrogen before the hydrogen is compressed and returned to a high-pressure hydrogen tank. The organic stream flows into a hydrogen degasifier which is maintained at atmospheric pressure for further hydrogen removal. Hydrogen thus liberated is vented to the coolant degasifier tank. The organic flows to the distillation column to join with other incoming feed, where it is fractionated into usable coolant and unreacted high boilers which are recycled back to the hydrocracking reactor. This recycling results in an overall conversion of 90% of the HB to usable coolant.

Hydrogen and light ends not condensed by the overhead condenser after leaving the distillation column are collected in the vapor space of the distillate receiver. From there, the gases are drawn off through vapor traps to remove the more readily condensed components, and are pumped into a waste gas collection tank. High-hydrogen-content waste gas from the degasifier is also received by the waste-gas collection tank. The combined flow to the waste gas collection tank goes to the hydrogen recovery system which has a palladium diffuser to recover the hydrogen from the organic waste gases. The recovered hydrogen flows into a high pressure hydrogen tank, and the remaining gases are vented to the waste gas system (see Sec. V. G.1). Each catalytic reactor contains 6000 lb of catalyst. The active portion of the catalyst is cobalt molybdate on an alumina carrier. The spent catalyst is regenerated by passing hot compressed air over the bed to burn off the carbon waste deposits.

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IV. MODERATOR SYSTEMS

A. GENERAL

1. Design Basis

Figures IV-1 and IV-2 are flow diagrams of the heavy water moderator systems. The moderator cooling system removes the heat generated in the heavy water within the calandria during normal and emergency conditions. Other moderator process systems provide the following services:

- a) Calandria pressure control and inert-gas blanketing of the systems
- b) Maintenance of heavy water purity
- c) Storage of heavy water inventory
- d) Process requirements for the hydraulically-actuated reactor control system
- e) Soluble poison for nuclear control.

Normal purity level of the heavy water moderator is 99.75% D₂O. This level will be maintained by the moderator purification system, by normal makeup, and by the addition of high-grade heavy water as required.

The moderator cooling system is designed to remove 162 Mwt of heat, which is 5.5% of the reactor thermal power to the coolant. Most of this heat (156 Mwt) is recovered in the steam feedwater cycle, with the heat being transferred in the lowest-temperature feedwater heaters.

2. Construction Materials

The out-of-core portions of the heavy water moderator systems, including heat exchangers and piping, are constructed of stainless steel. The calandria vessel is fabricated of stainless steel with Zircaloy-2 tubes.

FIG IV-1. Moderator Cooling System Flow Diagram

LEGEND

- (FR) FLOW RECORDER
- (CR) CONDUCTIVITY RECORDER
- (PDI) DIFFERENTIAL PRESSURE INDICATOR
- (PRC) PRESSURE RECORDING CONTROL
- (MD) MOISTURE DETECTOR
- (FRC) FLOW RECORDING CONTROL
- (IRC) CURRENT RECORDING CONTROL
- (LI) LEVEL INDICATOR
- (LAH) LEVEL ALARM HIGH
- (LAL) LEVEL ALARM LOW
- (LAX) LEVEL ALARM
- | T ORIFICE
- | GATE VALVE
- | DIAPHRAGM OPERATED VALVE
- | SOLENOID OPERATED VALVE
- PROCESS PIPING
- INSTRUMENTATION AIR LINE
- ⊗ TRANSMITTER LOCALLY MOUNTED
- LOCALLY MOUNTED
- BOARD MOUNTED

FIG IV-2. Moderator Auxiliary Systems Flow Diagram

3. Heavy-Water Losses

The following design features are responsible for limiting HWO CR heavy water losses: (a) the use of a completely all-welded system, (b) provisions for recovering heavy water from the atmosphere in the main heavy equipment areas and from all vented cover gas, (c) provisions for recovering heavy water from spent ion exchange resins, and (d) use of a leak collection system to recover possible leakage from pump seals and large valve stems.

Since the HWO CR design utilizes a low pressure, low temperature heavy water system, the loss rate will normally be lower than higher pressure and higher temperature systems. The rate of heavy-water loss for a 1000-Mwe HWO CR has been estimated to be 10 lb/day which is less than 1% of the total inventory per year.

B. MODERATOR COOLING SYSTEM

Design data for this system are presented in Table IV-1.

TABLE IV-1

DESIGN DATA - MODERATOR COOLING SYSTEM

Item	Design Data	Remarks
Moderator Cooling System		
Heat Generated in Moderator	162 Mwt	
Heat Transferred to BFW*	156 Mwt	
Heat Removed in Spray Cooler	6 Mwt	Normal Operation
Design Heat Load for Spray Cooler	22 Mwt	Emergency Operation
Calandria Inlet Temperature	140°F	
Calandria Outlet Temperature	200°F	

* BFW = Boiler (Evaporator) Feedwater

TABLE IV-1

DESIGN DATA - MODERATOR COOLING SYSTEM (Continued)

Item	Design Data	Remarks
Average Temperature in Calandria	190°F	
Materials of Construction	Stainless Steel	
System Design Pressure	150 psig	Excluding Calandria
Main Moderator Circulating Pumps	3 Required	
Capacity (Each)	5500 gpm	
Differential Pressure	100 psi	
Type	Horizontal Centrifugal	
Driver	450 hp	Electric Motor
Seal Type	Mechanical	Gas seal backup with leak-off between seals
Main Moderator Heat Exchangers (BFW Heating)		3 Required Straight tube, single pass on shell and tube side - single tube sheet
Surface Area (Each)	10,000 ft ²	

The moderator cooling system is designed to remove 162 Mwt of heat from the heavy water moderator. Of the total, approximately 156 Mwt is transferred to main feedwater and approximately 6 Mwt is rejected to cooling water in the spray cooler system.

Moderator leaves the calandria vessel at 200°F through an 18-in. header and flows to the suction of three one-third size moderator circulating pumps. Each pump is rated at 5500 gpm against a total head of 240 ft and is driven by a 450-hp motor through a variable-speed magnetic coupling. Each pump discharges directly to a moderator heat exchanger in which heat is transferred to main feedwater. The D₂O leaving the heat exchangers is collected in a 14-in. header and returned to the calandria at a temperature of 140°F.

The moderator cooling system pressure is controlled to maintain approximately 2.5 psig at the top of the calandria.

Calandria vessel moderator inlet and outlet temperatures are maintained constant during all normal operating conditions. The moderator inlet temperature is controlled by varying the flow of feedwater to the heat exchangers, and the outlet temperature is controlled by varying the speed of the moderator circulating pumps. The calandria vessel is full at all times. Excess flow into the system discharges into an overflow tank. This tank drains to one of the heavy-water storage tanks which serves as the expansion tank for the system.

A spray header is provided to cool the calandria tubes in the event of a major leak or rupture in the main heavy water cooling loop. During emergency cooling by means of the spray system, a drain line from the bottom of the calandria to the storage tank is opened to provide a continuous supply of heavy water, through the storage tank, to two full-size, two speed spray header pumps. During such emergency cooling, the heavy water flow rate to the spray header is 2500 gpm. However, to maintain them in constant readiness for emergency operation, the spray header and pumps are utilized continuously, but at a reduced flow rate (750 gpm), during normal operation.

C. MODERATOR AUXILIARY SYSTEMS

1. Purification

A moderator purification system is included in the design to provide for removal of ionic and particulate impurities from the heavy water. During reactor operation, the system continuously purifies a 50 gpm side-stream of heavy water withdrawn from, and returned to, the moderator cooling system. Particulate matter is removed by a 50 μ filter and ionic impurities are removed by ion-exchangers. A cation and a mixed-bed ion-exchanger are used in series; the cation and anion resins are in the D and OD form. The heavy water is at neutral pD.

The ion exchange columns are permanent, shielded items. Fresh resins are deuterized and spent resins are de-deuterized in a separate column. The resins are sluiced using D₂O as the carrier fluid to and from the ion-exchange columns. Deuterizing and de-deuterizing of the resins is done by D₂O/H₂O displacement. The effluent is collected in varying D₂O purity ranges and stored for shipment to an off-site upgrading facility. Purification system data are given in Table IV-2.

TABLE IV-2

DESIGN DATA - MODERATOR PURIFICATION SYSTEM

Item	Design Data	Remarks
Purification System		
Purification Flow Rate	50 gpm	Normal Operation
Purification Method	Ion Exchange	
D ₂ O pD	7.0	
D ₂ O Resistivity	1 x 10 ⁶ ohm-cm	

2. Cover Gas

The cover gas for the heavy water moderator is helium. The purpose of the cover gas system is to provide: (a) a means for controlling the pressure within the calandria; (b) an inert medium to transport deuterium and oxygen decomposition gases to a catalytic recombiner; (c) an inert cover gas for all moderator systems to protect the heavy water from air contamination and prevent isotopic down grading; and (d) an inert gas for purging, drying, and draining the moderator systems.

The gas supply consists of a standard tube-trailer of 40,000 scf capacity as an operating supply, and a reserve storage unit of 20,000 scf. Pressure control of the calandria vessel is provided by maintaining the cover gas pressure on the overflow tank at 0.5 psig during reactor operation. The storage tank, into which the overflow tank drains, is also maintained at 0.5 psig by means of a pressure equalizing line. The overflow tank is located above the calandria, to maintain a total static pressure of 2.5 psig at the top of the calandria. Excess pressure is vented through a back pressure control valve to the plant stack. All cover gases vented from the heavy water systems are dried to recover heavy water.

During reactor operation, cover gas circulates continuously from the heavy water storage tank, through a catalytic recombiner and the overflow tank, before returning to the storage tank. Circulation of approximately 100 scfm is provided by two full-size, non-lubricated, liquid-sealed compressors (one is a spare). Palladium on alumina pellets is used as the catalyst. Electric heaters on the recombiner prevent condensation on the pellets as condensation would poison the catalyst. The gas stream is analyzed continuously. Oxygen is supplied to the gas stream if the deuterium reaches high levels.

3. Fill, Drain, and Storage

Heavy water is received at the site in 500-lb helium-blanketed drums. Heavy-water drums are received, stored, and unloaded in a service building adjacent to the reactor building. Heavy water inventory data are presented in Table IV-3.

TABLE IV-3

MODERATOR INVENTORY

Item	Design Data
Calandria	588,000 lb
Moderator Cooling System	40,000 lb
Auxiliary Systems	17,000 lb
Reserve	9,000 lb
Total Inventory	654,000 lb

Two 50,000-gal storage tanks are provided to contain the entire inventory of the heavy water. These tanks are located in the reactor building below the calandria. Initially, the storage tanks are filled from the shipping drums by gravity flow or small transfer pumps.

The calandria vessel and most of the moderator system piping and components are gravity-drained to the storage tanks. A small transfer tank is used to empty components located below the storage tanks. During reactor operation, the transfer tank is used to collect leakage from pump and valve seals, and to receive the heavy water which is added for makeup. Periodically, the heavy water is pumped from the transfer tank to the storage tanks by the transfer pumps. The transfer pumps also take suction from the main storage tanks and are used for system filling. One of the storage tanks is partitioned to provide a small internal tank which is used as a thermal expansion tank for the moderator during system startup and initial operation.

4. Soluble Poison Injection

A poison-injection system is provided to inject a heavy water solution of boric acid into the moderator. The system is used for emergency reactor shutdown only in the event of failure of the normal shutdown system. Approximately 400 gal of a 150°F saturated boric acid solution is maintained in a tank, under a pressure of 50 psig. The maximum required boron content is 25×10^{-6} gm B_{nat}/cc D₂O. Shutoff valves are provided in the tank outlet line, which is sized to permit total injection of the poison within two minutes after the actuating signal.

During reactor operation, boric acid may also be added to the moderator slowly to compensate for relatively gradual reactivity changes. A boric acid solution supply tank and metering pump are provided to inject the solution at the required rate.

Boron is removed from the moderator in the moderator purification system. A deborating ion-exchange column, containing anion resins, is provided for use when the removal rate required is greater than that normally available.

5. Hydraulic Operation of Shutdown Rods

Normal shutdown of the reactor is accomplished by 84 shutdown neutron poison rods inserted horizontally through the side of the calandria, each driven by the action of a spring on a driving piston. During reactor operation, the rods are held out of the calandria by the force of pressurized heavy water acting on pistons to compress the springs. Continuously operating pumps are provided to maintain a pressure of 100 psig for this purpose. These pumps take suction from the heavy water in the storage tank, and discharge to the hydraulic cylinders of the shutdown rods.

On a reactor scram, the pressurized water in the cylinders is relieved to the storage tank to allow the springs to drive the rods into the calandria. Bypass flow from the pump discharge back to the storage tank is provided when the pumps are not pressurizing the cylinders.

6. Recovery

Provisions are included for the recovery of heavy water from four general sources: (a) leakage from pump and valve seals, (b) accidental spills, (c) airborne heavy water vapor from the atmosphere within the heavy water equipment areas, and (d) deuterizing and de-deuterizing resins used in the purification system ion exchangers.

Leakage from pump and valve seals is collected on an individual-leak basis, and drained to the transfer tank, from which the heavy water is returned to the storage tanks.

Spilled heavy water is collected in sumps and pumped to a holdup tank. The heavy water is sampled and analyzed to determine the purity level and, if recoverable, is then transferred to a contaminated-D₂O tank for subsequent shipment to an upgrading facility. A cleanup system including a filter and ion exchanger is provided to remove impurities and reduce contamination, as required, prior to shipment.

Airborne heavy water vapor is removed from vented off-gases and from the atmosphere within the heavy water equipment areas by gas drying units. This moisture is also collected for subsequent shipment to an upgrading facility.

Heavy water is recovered from ion exchange resins by displacing the heavy water with light water before the resin is discarded. The effluent displacement from this operation is collected and, if it contains at least 2% heavy water, is shipped to an upgrading facility.

7. Upgrading Facility

Permanent on-site heavy water upgrading facilities are not provided. With all-welded heavy-water systems, and with all components of the systems operating at slight positive pressure, downgrading by the in-leakage of light water will be negligible. In addition, all heavy water-to-light water heat exchangers are operated with higher pressure on the heavy water side to insure that leakage is out of rather than into the heavy water side. Downgraded heavy water will be shipped in 50-gal drums to an off-site upgrading facility.

Purity of the heavy water will be maintained by normal makeup and with additional high grade heavy water as required.

V. REACTOR SERVICE SYSTEMS

A. SPENT-FUEL POOL COOLING

The spent-fuel pool cooling system is designed to remove .125% of the rated reactor thermal power, which amounts to a heat duty of 13.5×10^6 Btu/hr. This heat duty is approximately equivalent to the decay heat from a full core loading after 30 days decay in the reactor, or one-half of a core loading after 7 days decay. The preceding criteria provide more than adequate heat removal capacity for the normal mode of continuous on-line refueling.

The system is filled with demineralized water. Circulation pumps take suction from the fuel storage pool, and recirculate the pool water through heat exchangers to remove the decay heat. Two half-size pumps and heat exchangers are provided. Each pump is rated at 450 gpm at total head of 150 ft and is driven by a 30-hp motor. A side stream from the discharge of the heat exchangers is bypassed through a filter to remove impurities. The system is fabricated from stainless steel. Water chemistry is controlled to ensure minimum attack on the fuel cladding.

B. COMPONENT HIGH-TEMPERATURE COOLING WATER

The component high-temperature cooling water system is used to provide 250°F pressurized cooling water to organic vapor condensers and hydrogen coolers in the coolant recovery and degasification systems, to the flue gas cooler in the waste gas system (see Section V. G. 1), and to the heat exchangers on the refueling machine. The system pumps take suction from a surge tank and pump the water through one of two full-size heat exchangers, where the pressurized water is cooled to 250°F by service cooling water (see Section IX A). The water is then circulated through the stated heat loads and returned to the surge tank. Provisions are included for passing a side stream of the cooled (250°F) water through a filter and ion-exchanger, as well as for the addition of

a corrosion inhibitor. Each pump (one is a spare) is sized for 175 gpm at a total head of 100 ft. The heat duty for the system is 9×10^6 Btu/hr.

C. COMPONENT LOW-TEMPERATURE COOLING WATER

The component low-temperature cooling water system is used to provide 80°F treated cooling water to reactor plant components. The system consists of a surge tank, two full-capacity 4500 gpm, 175-hp pumps, four 1/4 capacity heat exchangers, side stream filters and demineralizers, and a corrosion control charge tank. Water from the discharge of the pumps passes through the shell side of the heat exchangers and is cooled by the service cooling water system (see Section IX. A) to 80° F. The cooling water is then distributed to cool the main coolant pumps, coolant pressurizing pumps, shutdown cooling pumps, fuel storage pool coolers, reactor shield coolers, moderator spray coolers, various organic cold traps, and sample coolers throughout the plant. The system is designed for total heat duty of 60×10^6 Btu/hr of which approximately one-quarter is contributed by the fuel storage pool when it contains a full core loading. Use of 1/4-capacity exchangers enables one unit to be out of service except when the full heat duty must be removed from the fuel storage pool simultaneously with the normal plant load. Corrosion inhibitor is added to the water by circulating a side stream through a corrosion control charge tank located on the discharge side of the pumps.

D. NITROGEN SUPPLY

The nitrogen supply system is used to provide: (1) a pressurized inert gas in the reactor surge tank, (2) an inert cover gas in vessels containing organic coolant, (3) an inert gas for purging organic vessels and equipment, (4) an inert gas atmosphere for draining organic systems, and (5) refueling machine requirements. The system consists of two liquid nitrogen supply tanks, each capable of supplying 25,000 SCF, connected in parallel to a common header maintained at 200 psig.

Nitrogen is supplied to the reactor surge tank at main header pressure. A pressure reducing valve is located in the main header to supply nitrogen at 30 psig to the organic process systems. A connection is provided in the main header to tie into an auxiliary nitrogen supply for purging the plant systems prior to initial plant startup.

E. CARBON DIOXIDE

Carbon dioxide gas is used as the insulating gas between the process tubes and the calandria tank. The carbon dioxide gas fills the annulus between the process tube and calandria tank. The gas is removed and sampled periodically to determine if heavy water or organic has leaked into the annulus. Approximately 300 cc/min of carbon dioxide is withdrawn from the annulus by a gas blower, passed through a process gas chromatograph and a charcoal adsorption column, and returned to a carbon dioxide plenum common to all process tubes. The chromatograph is adjusted to monitor for heavy water and organic gases. The presence of either heavy water or organic indicates the possibility of a leak. The charcoal adsorber is a purifier for the carbon dioxide system.

All sampling connections and lines are stainless steel. Carbon dioxide is added to the system as required to maintain a positive pressure of 2-in. of water and to prevent air in-leakage.

F. REACTOR-PLANT STARTUP STEAM

Auxiliary steam for system preheat is obtained from an auxiliary steam generator (see Section IX. 1.) or from the shutdown cooling heat exchanger by utilizing decay heat energy. During startup, one main coolant pump is operated by the steam from the auxiliary steam generator or shutdown cooling heat exchanger to raise the main coolant temperature to 540°F. This coolant flow, together with the shutdown cooling system flow, is sufficient to bring the reactor to low power (~30 Mwt) operation. Steam generated by nuclear heat, 50,000

lb/hr at 900 psig, is then fed to the turbine-drive high-pressure admission nozzles of the second main coolant pump. Similarly, as reactor power is increased further, steam from this loop is utilized to initiate operation of the third coolant loop. Reactor power, coolant flow, and steam production will then be increased to enable the plant to "bootstrap" itself up to full-flow conditions on all three coolant loops. An auxiliary motor-driven feedwater pump is used during startup to provide feedwater to the steam generators.

G. RADIOACTIVE WASTE DISPOSAL

1. Waste Gas Disposal (Figure V-1)

The waste gas handling system is designed to provide for the controlled release and dispersion of radioactive waste gases to the atmosphere. After leaving the coolant recovery and degasification systems, the waste gases are compressed to 400 psig and heated to 700° F, then passed through a palladium diffuser. The hydrogen in the waste gases diffuses through the diffusion barrier and passes to the hydrogen supply in the coolant recovery system. Under normal conditions, the remaining gases are reduced in pressure and cooled to 100° F in a water-cooled heat exchanger. After being depressurized and cooled, the gases flow through one of three charcoal adsorbers to remove traces of iodine. Storage tanks are provided in which the gases may be stored, if required, to allow the radioactive components to decay to acceptable levels prior to dilution with building heating and ventilation system air and release through the plant stack.

In the event that fission product activity in the waste gas exceeds prescribed limits, the flow of gases to the charcoal adsorbers is stopped. The gas pressure then builds up and the gas stream collects in one of the three 2000 gal decay-storage tanks. The entire waste gas flow resulting from 24 hours of full power operation can be accumulated in the storage tanks before the design pressure of the tanks is reached. The gas in the storage tanks is diluted and

released to the atmosphere at a controlled rate such that the activity in the plant stack is always within the allowable limits. By continually bleeding the storage tanks as the gaseous fission product activity decays, tank capacity may be extended well beyond the 24-hr period.

Flue gases from the adsorber kiln and the coolant recovery catalyst regeneration processes are combined and passed through a cooler, where the gas temperature is lowered from 1000°F to 400°F. The cooled gases pass through a dust collector, a high efficiency filter, and a condenser. If the activity level of this stream allows, these gases are diluted with heating and ventilating system air and released through the plant stack. If the flue gas stream leaving the condenser contains an unacceptable level of radioactivity, it is diverted to the above-indicated storage tanks, and subsequently released in the manner described.

2. Aqueous Waste Disposal

The aqueous waste system collects and monitors all potentially-contaminated aqueous wastes and reduces the activity to acceptable levels before the waste stream is discharged from the plant. Aqueous wastes from the auxiliary building are collected from contaminated areas and drained by gravity to a sump. Similarly, aqueous wastes from the reactor area are collected in a sump located within the reactor building. These wastes are periodically pumped from the sumps to a settling tank in the auxiliary building to facilitate the separation of organic material from the water. The water phase is then pumped through a filter and adsorber to a compartmented waste holdup tank. The water is sampled, and if the activity is below the allowable concentration, it is diluted with the plant non-radioactive effluent water and discharged from the plant to the river. Provisions are also included to pass the waste water through ion exchange columns for removal of radioactive constituents if required by the activity level.

3. Solid and Liquid Waste Disposal

Plant liquid wastes consist mainly of analyzed organic samples, organic liquid removed periodically from the aqueous waste system settling basin, and contaminated vacuum-pump oil. These liquids are mixed with a dry adsorbent, placed in 55-gal drums, and shipped to a disposal site.

Solid wastes consist of combustible materials, ventilation system filters, discarded pipe and other metallic components, spent Attapulugus Clay from the coolant adsorption system, and spent catalyst beds from the coolant recovery system. Low-activity wastes such as paper, rags, clothing, and ventilation filters normally are packaged in unshielded containers for shipment to a disposal site.

Attapulugus Clay from the adsorption system normally is placed in unshielded drums. If the activity associated with the clay prevents this manner of handling, concrete is added to the drums to provide the necessary shielding.

The spent catalyst from the coolant recovery system is removed from the system, complete with the pressure vessel containing the catalyst. The pipe connections on the vessel are sealed, and the entire unit is shipped off-site for disposal after an appropriate decay period.

H. REFUELING MACHINE SERVICES

The refueling machines require a supply of reactor coolant for fuel cooling during in-core fuel transfer operations. A 50 gpm organic coolant stream is provided to each of the two refueling machines. This coolant flow is obtained from the discharge of the pressurizing pumps and, after passing through the refueling machines, is returned to the coolant degasifier tank.

I. NEW-COOLANT HANDLING

The new-coolant handling system transfers the bulk shipments of organic coolant from an insulated tank car to a 50,000 gal steam-heated storage tank.

The storage tank is steam heated to ensure that the coolant is maintained in a liquid state and is always available for use as makeup.

Coolant is pumped to the coolant recovery system during the initial filling of the main coolant system and during normal coolant makeup operation. One 100-gpm centrifugal pump is provided for unloading the tank car and for initial system filling. Two 2-gpm gear pumps are provided for coolant makeup flow to the coolant recovery system.

FIG V-1. Waste Gas System Flow Diagram

VI. CONTROL AND INSTRUMENTATION

A. REACTOR AND TURBINE PLANT CONTROL SYSTEM

The control systems for the HWOCR concept reactor and turbine plants are designed for a primarily base-loaded plant with minimum required dynamic response capability. A digital computer system will log plant operating data and will print-out information either automatically or on command. This computer will also monitor various system component actions, safety devices, and protective elements, with the capability of initiating action and/or alerting the operator in the event of an off-normal condition. The computer will have sufficient capacity to permit programming for control of steady state operation and power level changes, and for plant monitoring.

In general, the automatic control systems for normal operation will be solid-state analog-type or pneumatic systems.

1. Design Criteria

Specifically, the design criteria for the HWOCR plant control system provide the following:

- a) Manual operation from 0% to 100% rated power.
- b) Automatic regulation from 20% to 100% rated power at constant load levels with capability for matching minor demand fluctuations.
- c) Dynamic testing to satisfy safety and regulatory requirements.
- d) Interlocks with the plant protective system.
- e) Maintenance of satisfactory flux distribution throughout the core, including suppression of local xenon-induced variations.
- f) Programmed distribution of power between coolant loops.
- g) Constant steam pressure and temperature (900 psig and 725°F) at the turbine throttle.

h) Constant feedwater level for the natural recirculating steam generator.

i) Constant steam temperature (725°F) at the reheater outlet.

2. Plant Control Computer and Instrument Functions

Figure VI-1 shows the primary reactor plant controls. The following subsections describe the functions of the various control components.

a. Outlet-Temperature Controller

Reactor organic-coolant outlet temperature is maintained constant by the action of the outlet-temperature controller. Coolant outlet temperature measurements from thermocouples at three different points are averaged. This averaged outlet temperature is compared with the temperature setpoint, to produce a temperature-error power-trim output to the power demand computer.

b. Power Demand Computer

Reactor demand power level is established in the power demand computer section. The power level for base-load operation is manually set at the power demand setpoint station. In the case of load-following operation, measured coolant flow and coolant ΔT are multiplied in the power demand computer to determine the demand power requirement. Coolant flow is adjusted to satisfy steam demand requirements in another portion of the control system.

In either the base-load or load-following mode, the power demand is trimmed with coolant outlet temperature error to produce a power setpoint input to the power controller.

c. Power Controller

The power controller compares power setpoint with measured flux to produce an output which schedules the rod position controller to position the control rods.

FIG VI-1. Plant Control System Schematic

d. Three-Element Feedwater Control System

Feedwater flow is scheduled to match any change in steam flow, through the action of a conventional three-element feedwater control system:

For each steam generator, steam flow is compared with feedwater flow in the flow computer which produces a change in the feedwater demand signal to the level computer. The feedwater demand signal is trimmed by feedwater level in the level computer which produces an output to position the feedwater control valve to each of the steam generators.

e. Steam Pressure Controller

Steam pressure is compared against the steam pressure setpoint in the pressure controller to produce a pressure error output to the pressure computer. This error is summed with a turbine first-stage steam pressure anticipation signal to produce a pressure computer output, which is a power-demand load-index.

f. Main Coolant Pump Load Computer

The power demand load index acts through the main coolant pump load computer to set main coolant flow in the reactor and steam generators by scheduling steam flow to the main coolant pumps turbine drives.

g. Feedwater Pump Load Computer

The feedwater pump load computer schedules steam flow to the feedwater pump driver turbines to maintain constant discharge pressure. A measured pressure feeds back to the computer where it is compared to setpoint. An error between setpoint and measured feedwater-pressure is modified by an anticipation signal from the steam-pressure controller and then effects the required pump speed adjustment.

h. Reheater Temperature Controller

The reheater temperature controller compares steam temperature setpoint with reheater outlet steam temperature to produce an output which positions the coolant control valve, to determine the coolant flow split between the reheater and the superheater.

i. Turbine Bypass Control

In case of a turbine trip, the turbine inlet steam will be dumped to the condenser by the action of three back-pressure control valves.

j. Coolant Process Instrumentation

The thermocouples used to measure the reactor organic coolant inlet and outlet temperatures are iron constantan, high-speed, stainless steel assemblies, located in the mixing tanks. Dual iron-constantan thermocouples are also installed in the outlet line from each fuel tube. One thermocouple from each tube is connected for readout; the other is an unconnected spare.

Diaphragm-seal, force-balance type, pressure transmitters are used to measure coolant pressure. These transmitters are located on the discharge of the main coolant pumps and pressurizing pumps.

The flow transmitters are of the internal steam traced, free balance type, and are located at the organic coolant outlet piping from the steam generators.

B. NUCLEAR INSTRUMENTATION SYSTEM

The objectives of the nuclear instrumentation system are as follows:

- 1) To provide continuous monitoring of reactor level from shutdown to 150% of rated core power output.
- 2) To provide power level and period signals to the plant protective system for alarm, setback and scram purposes.
- 3) To provide power level signals to the plant control system for automatic regulation of reactor power level.

The nuclear instrumentation system provides continuous indication of reactor thermal power level by monitoring neutron flux leakage from the reactor. Leakage flux is a function of fission rate and is, therefore, proportional to reactor power level. The neutron flux from source level to full reactor power varies over a span greater than 10 decades. Although negligible power is developed in the lower and intermediate portions of the range, and operation in this region is transitory, it is important from the standpoint of safe operation that the instrumentation be capable of monitoring the entire range of neutron flux. Since no single instrument can satisfactorily cover the

entire flux range, the system is divided into three ranges: source, intermediate, and power. Each range covers a specific portion of the neutron flux span with positive overlapping between successive ranges.

The nuclear instrumentation system consists of sixteen separate and complete instrumentation channels, as shown on Figure VI-2. Both the source and intermediate ranges have four identical channels, and the power range has eight channels which provide signals to the reactor flux control system and the protective system. Four channels located on a 90° radial spacing are used in each of the startup ranges to provide adequate safety and reliability of power level indication. Four additional channels are provided in the power range, to obtain a linear flux level signal for power regulation.

The neutron detectors are housed in instrument thimbles located in the biological shield around the reactor core tank. The thimbles are adequately cooled to protect the detectors from high temperatures, and contain the necessary gamma shielding and neutron moderator material to obtain optimum detector performance.

1. Source Range Channels(I through IV)

The source range instruments, which comprise four independent channels, monitor the neutron flux from shutdown (or source level) to five decades above this level. Each channel consists of an adjustable-voltage power supply, and a pulse-rate and period computer which receives output pulses from the neutron detector. This unit shapes the pulses, eliminates gamma and noise signals and computes the logarithm of the pulse rate. The pulse rate is proportional to the neutron flux at the detector and, hence, is an indication of reactor power level. Logarithmic signals are utilized to provide full-range indication without scale switching. The period circuitry differentiates and amplifies a signal from the pulse rate computer, thereby obtaining a signal that is inversely proportional to the reactor period. This signal, when displayed on meters containing hyperbolic scales, provides indication of reactor period in seconds. Due to statistical fluctuations of neutron pulses, the period signal from the source channels

FIG VI-2. Nuclear Instrumentation System Block Diagram

is of an erratic nature and employed only as an operational aid. No automatic corrective action is taken from this signal, because these fluctuations would result in numerous erroneous setbacks.

2. Intermediate Range Channels (V through VIII)

The intermediate range instruments, comprised of four independent channels, monitor neutron flux in the intermediate portion of the flux range. These channels provide coverage for six decades of power level, and overlap the upper region of the source range and lower portion of the power range. A logarithmic system is used to permit continuous coverage of the entire channel span without range switching. During the transition through the intermediate range, reactor power level increases approximately exponentially; hence, the reactor period is of paramount importance. In the event of a startup accident, a fast automatic shutdown is required to limit the rise of power before plant parameters exceed design values. Period circuitry is used to initiate this fast shutdown. When reactor power is above a predetermined value (adjustable from 2% to 20% of rated power) a period cutout circuit is actuated. This circuit prevents the period signal from actuating the Protective System. Bypassing the period signal will not impair the safety of the reactor, since the plant is adequately protected by other signals during operation in the power range. It does, however, improve the overall plant reliability by eliminating false power range setbacks resulting from the period circuitry.

Each intermediate range channel consists of the following components:

a) A compensated ionization chamber (electrical gamma compensation is provided to minimize the sensitivity of the detector to gamma radiation, thereby extending the range of operation)

b) An adjustable voltage power supply

c) A log current and period computer which converts the current from the ionization chamber to a voltage that is proportional to the logarithm of the current. Differentiation of this voltage provides a signal inversely proportional to reactor period. The four channels are connected in a two-of-four logic for automatic power setback.

3. Power Range Channels (IX through XII)

The four power channels monitor the neutron flux from 1% to 150% of full reactor power. In addition to providing power level indication, these channels provide signals for protective action. Signals to the protective system are used to setback and scram the reactor when the reactor power level in any two of the four channels exceeds predetermined safe limits.

Each channel consists of an uncompensated ionization chamber and an adjustable voltage power supply. A linear current generates a signal proportional to the detector thermal flux. The amplifier will have sufficient power to provide signals for the power level recorder, alarms, the protective system, neutron flux control system and the period trip signal cutout circuit.

4. Linear Channels (XIII through XVI)

The linear channel provides accurate linear power level indication over a range from rated power to 6 decades below rated power. This range span is achieved by employing a wide-range dc amplifier, and range switching.

These channels each contain a compensated ionization chamber, an adjustable-voltage power supply, and a linear micromicroammeter with range switching. The ammeter amplifies the output of the ionization chamber and produces a voltage to drive the linear level recorder. The signal from one of these channels is used to automatically regulate the core power level during power operation.

C. REACTOR PROTECTIVE SYSTEM (Figure VI-3)

The reactor protective system is designed to protect the reactor, main heat system components, and auxiliary systems components from damage during all modes of operation. This system monitors pertinent plant parameters and automatically reduces reactor power when such parameters exceed pre-set limiting values. Depending upon the severity of the condition, the action initiated by the protective system will be alarm, setback (rapid reactivity withdrawal), or scram.

FIG VI-3. Protective System Block Diagram

1. Interlocks

Electrical and mechanical interlocks are provided to prevent automatic or manual operation of components out of proper sequence during startup, power operation, or shutdown. Manual misoperation of components will be overridden by the interlocks and result in visual and audible alarms.

2. Scram Circuit

Input for the scram circuit is provided by the output from 12 scram coincidence units and from two noncoincidence scram circuits. The coincidence scrams are:

- a) High power level
- b) Short intermediate-range period.
- c) High fuel element outlet temperature
- d) Low coolant flow
- e) High system pressure
- f) Low system pressure
- g) Low degasifier
- h) High coolant activity (gross fuel rupture or fuel melting)
- i) High moderator pressure
- j) Low moderator level in moderator storage tank
- k) Earthquake

The non-coincidence scrams are:

- a) Manual
- b) Turbine trip.

The reactor scram circuit performs the following functions:

- a) Deenergizes the reactivity insertion system
- b) Deactivates the neutron flux controller
- c) Energizes the alarm and annunciator
- d) Reduces the D_2O circulating pump motor speed
- e) Initiates turbine plant shutdown program.

3. Setback Circuit

The setback circuit is activated from five coincidence circuits and one non-coincidence circuit. The coincidence setbacks are:

- a) High power level
- b) High fuel element outlet temperatures
- c) High moderator outlet temperature
- d) Low moderator flow
- e) Short intermediate-range period.

The noncoincidence setback is "Manual".

Upon receipt of a setback signal from one or more sources, the setback circuit initiates reactivity withdrawal, deactivates the neutron flux controller, and energizes the annunciator. The setback action ceases when the cause of setback no longer exists.

4. Loop Shutdown Circuit

The loop shutdown circuit is activated by one of the following:

- a) Detection of very high radioactivity in reactor outlet coolant mixing tank (coincident with scram)
- b) Diagnosis of major coolant leak in a main coolant loop (post-scram)
- c) Complete loss of flow in one loop (isolates that loop)

Main loop isolation action consists of activating the fast-closing reactor block valves and shutting down the main coolant pump turbine drives.

5. Leak Detection

a. Coolant Leak Detection Circuit

Detection of small leaks in the main coolant loops and reactor complex will be provided by thermocouples suitably mounted under or around the piping and sump systems or by smoke detectors. To prevent unnecessary shutdown from spurious signals, the thermocouple and smoke detector leak sensors will provide only alarm protection. Low system pressure and degasifier tank low level signals will be symptomatic of major leaks and will automatically actuate the coolant leak location and isolation circuits.

b. Coolant Leak Location and Isolation Circuit

This circuit is activated by signals from the low system-pressure and degasifier tank low level subsystems. The circuit is a logic circuit which interrogates the shutdown cooling system, the pressurization system, and the main cooling loops to identify and isolate the defective systems. Systems found free of leaks are left in service to assure decay heat removal capability.

c. Moderator Leak Detection Circuit

Small leaks in the moderator system will be detected by moisture detectors, analyzers and thermocouples suitably mounted under or around the piping, and appropriate level indications in sump areas. In addition, flow, pressure and level instruments will be used to detect a large moderator loss. After detection and location of a leak, manual or automatic isolation of the leak will be initiated, depending on the circumstances involved.

d. Pressure Tube and Calandria Tube Leak Detection Circuit

Gas samples taken from the annulus between the pressure tubes and calandria tubes are analyzed to detect organic or heavy water leaks.

D. FAILED FUEL ELEMENT DETECTION SYSTEM

A failed fuel element detection system is provided to meet the following criteria:

- 1) Detect immediately any gross fuel-cladding failure which could contaminate the main organic system, and initiate action to isolate the reactor building.
- 2) Determine the exact location of a failed fuel element in minimum time.

The high coolant-velocity in the reactor piping requires a transport delay in the system to provide sufficient time to detect a cladding failure and isolate the main coolant systems before gross contamination can occur. Isolation is necessary only in the case of gross fission product release from a large or multiple failure. An arrangement of gamma detectors is provided at the coolant outlet headers and the reactor outlet mixing tank. Power-operated quick-closing valves are provided in each main coolant line to permit complete isolation of the reactor from the piping outside the reactor building. By measuring the difference in activity between the outlet of the reactor outlet mixing tank and the reactor outlet headers, a detection capability is obtained. A difference-signal from these detectors, greater than the preset value, will immediately activate the scram circuitry and the fast-closing isolation valves in all three main coolant loops.

The system for locating individual failed fuel elements is based on detecting delayed neutrons from fission products following failure of the fuel element cladding. Following detection of the neutrons, discrimination may, if necessary, be further enhanced by controlled slow pressure changes or power cycling. Upon receiving indication of a cladding failure, a scanning of all fuel channels for delayed neutrons will be required.

in sets of pipes past individual gamma detectors. After the background activity has died down, the individual channels in the set may be examined for the exact failure location.

E. RADIATION MONITORING

1. Stack Monitoring

Stack effluent will be monitored by separate gaseous and particulate monitors.

2. Liquid Monitoring

Gamma activity of the main reactor headers is monitored for major fuel-cladding ruptures with GM units. The health physics room contains a heavy-water sampling station in which samples are collected from various areas for tritium monitoring. These heavy-water samples and operating personnel urine samples are analyzed for tritium in a multichannel analyzer. A separate counting room contains the additional counting and monitoring equipment required in normal health physics duties. Tritium area monitors also function as heavy-water system leak detectors.

3. Area Monitoring

All areas where fission products might be present, or where direct radiation might be received, are monitored. Detectors are wall-mounted GM units. A three-decade sensitivity range may be selected within an overall range of 0.01 mr/hr to 10^6 R/hr. For general purpose monitoring, the normal range is 0.1 mr/hr to 100 mr/hr. Tritium monitors with sensitivities of 10^{-6} /m are used in those areas where tritium could be released. Radiation intensity of each station is recorded on a multipoint recorder. In addition to the stationary monitors, portable GM, tritium and particulate monitors are available at pre-selected locations.

VII. TURBINE PLANT

A. BASIC DESIGN AND ARRANGEMENT

The reference HWO CR plant has a net electrical output of 1076 Mw and utilizes a single-shaft turbine-generator operating in a reheat regenerative feedwater cycle as shown in Figure VII-1. The steam flow diagram is shown in Figure VII-2.

The turbine is a tandem- compound six-flow, 1800 rpm, four-casing unit, provided with 52-in. last-stage buckets. Steam at 900 psig, and 725°F from the superheaters flows through four stop valves and four control valves located within two steam chests, into the 100% (full arc) admission, double-flow, high pressure casing. Extraction steam is taken from this casing for the first feedwater heater, and from the crossover pipes for the second feedwater heater. Steam leaving the first casing flows to the reheaters where it is reheated from 390°F to 725°F. A portion (approximately 6%) of the steam leaving the reheaters is extracted for turbine drives for the three main coolant pumps and the three main feedwater pumps. The remaining steam from the reheaters flows through intercept valves to the three double-flow low pressure section of the turbine, where it expands to the three corresponding surface condensers at a pressure of 1.5 in. Hg abs. Intercept valves are provided between the inlets to the low-pressure sections, to provide turbine overspeed protection from the energy stored in the reheaters and piping.

Extraction steam is taken from the low pressure casings of the turbine for the third and fourth feedwater heaters. By reheating the steam after it leaves the high pressure casings, the moisture removal problem is eliminated, resulting in an end-point moisture content of approximately 9%.

Steam for the low pressure shaft packing, shaft packing exhausters, and condenser air ejectors is obtained from the main steam header, high pressure shaft packing, and valve leakoffs, and from the crossover pipes. A portion of the energy in this steam is reclaimed for feedwater heating in the air ejector and packing exhausters condensers.

FIG VII-1. Steam & Feedwater System Heat Balance

[illegible]

FIG VII-2. Steam Flow Diagram

Heat generated in the heavy water moderator of the reactor is rejected in the fifth feedwater heater, thus providing a thermodynamic improvement. Feedwater pressure in the heavy water heat exchangers is maintained below that of the moderator, to prevent degradation of the heavy water in case of leakage. This is accomplished by controlling the condensate pumps discharge pressure to maintain a constant differential between the two systems. Intermediate condensate booster pumps are used to circulate the feedwater from the fifth heater to the deaerator.

The three main feedwater pumps and the three main reactor coolant pumps are driven by dual-inlet, condensing steam turbines. At plant loads exceeding approximately 60%, the turbines receive low pressure superheated steam from the reheaters. At lower plant loads, high pressure steam from the main steam header is admitted to satisfy the pumping requirements. Three auxiliary condensers are used, each providing the condensing requirements for one coolant and one feedwater pump drive turbine. The feedwater pumps circulate the feedwater from the deaerator to the steam generator through the first and second heaters. Use of steam reheat (after the first casing) and of the pump drive turbines in the cycle provides an improvement in the net plant heat rate which results in an economic advantage over a no-reheat cycle using large electric pump drive motors.

The generator is rated at 1280 mva, with a hydrogen pressure of 60 psig, 0.85 pf, 24 kv, 3 phase, 60 cycle.

The turbine plant arrangement is shown in Figures VII-3, -4, and -5. The ground floor of the turbine plant is at Grade 45; the main turbine operating floor is at Grade 87, an elevation of 42 feet above the ground floor. A mezzanine level is provided at Grade 65, below the operating floor, for miscellaneous equipment. All heavy rotating equipment, except the turbine generator unit, is on the ground floor, thus minimizing foundation and structural costs. The main feedwater pumps, reactor coolant pumps, coolant pump drive turbines and corresponding condensers are on the ground floor of the steam generator and pump building, adjacent to the turbine building.

SEE FIG VII-5 FOR SECTION X-X

FIG VII-3. Turbine Building Plan - Above Operating Floor

SEE FIG VII-5 FOR SECTION X-X

FIG VII-4. Turbine Building Plan - Mezzanine and Ground Floor

VII-7

SECTION X-X
SEE FIG VII-4

FIG VII-5. Turbine Building - Longitudinal Section

Under the design load conditions defined in the heat balance, Figure VII-1, the plant power generation, thermal requirements, and efficiency are given in Table VII-1.

TABLE VII-1
TURBINE PLANT DESIGN SUMMARY

Reactor Thermal Output (including moderator and Shield) (Mwt)	3093
Reactor Thermal Power to Coolant (Mwt)	2921
Evaporator and Superheater Thermal Power (Mwt)	2524
Reheater Thermal Power (Mwt)	419
Gross Generator Electrical Output (0.85 pf) (Mwe)	1088
Plant Auxiliary Electrical Power (Mwe)	12.0
Plant Net Electrical Output (Mwe)	1076
Plant Net Heat Rate (Btu/kwh)	9800
Plant Net Thermal Efficiency (%)	34.8

B. TURBINE-GENERATOR

Detail design data for the turbine-generator are listed in Table VII-2.

TABLE VII-2

TURBINE-GENERATOR DESIGN DATA

Turbine arrangement	TC6F-52 in. LSB**
Throttle pressure (psia)	915
Throttle temperature (°F)	725
Throttle enthalpy (Btu/lb)	1345.9
Throttle flow (lb/hr)	9.05×10^6
Reheat pressure (psia)	180
Reheat temperature (°F)	725
Reheat enthalpy (Btu/lb)	1388.0
Reheat flow (lb/hr)	7.893×10^6
Condenser pressure (in. Hg)	1.5
Turbine exhaust flow (lb/hr) (Total)	6.437×10^6
Turbine exhaust enthalpy (Btu/lb) (UEEP*)	1011.7
Duty (Btu/hr) (Total)	606×10^9
Generator rating (kva)	1,280,000
Generator terminal voltage (kv)	24
Generator power factor	0.85
Generator hydrogen pressure (psig)	60
Feedwater temperature (°F) (Final)	420
Feedwater enthalpy (Btu/lb)	397.5
Shaft-driven auxiliaries	None
Steam-driven auxiliaries - hot reheat	Main feedwater and main coolant pumps

* Used-energy end-point

** Last stage buckets

Rupture diaphragms are provided to protect the exhaust casings from excessive pressures. A low-speed turning gear is provided to minimize shaft deformation during the cooling cycle. Valve stem and shaft packing leakoff steam is used for feedwater heating or in the steam seal regulator and gland packing exhausters. The turbine is lagged and encased for conventional indoor installation.

The conductor-cooled generator has a liquid-cooled stator and gas-cooled rotor, and is rated at 1280 mva at 60 psig hydrogen pressure, 0.85 pf, 0.58 SCR, 24 kv, 3 phase, and 60 cycles. A separate motor-driven exciter is provided.

1. Moisture Separation

At the design inlet pressure, the 185°F superheat available from the superheaters and the 335°F superheat from the reheaters eliminate the need for special moisture removal features. The end point moisture is approximately 9%.

2. Control

Due to the problems associated with partial admission on large diameter control stages, and the anticipated base load operation, throttling control with 100% or full arc admission is used. Four control valves operating in parallel, two in each of two steam chests, are used for throttling control. Four stop valves are used for unit shutdown and overspeed protection. Three reheat intercept valves, one for each low pressure casing, are also used to protect against overspeeding during a generator tripout.

The turbine is provided with a pressure controller which positions the control valves to hold the steam pressure essentially constant. On excess pressure, the turbine by-pass valves open to dump the excess steam to the condenser.

3. Oil System

The turbine oil system consists of a high pressure hydraulic control system and a low pressure lubrication system. The high pressure system is supplied by the main oil pump on the turbine shaft. Lubricating oil is discharged from the main oil pump through one of two parallel oil coolers to the main bearing system, thrust bearing, and turning gear. Oil is returned from the bearings to the reservoir by gravity. An auxiliary motor-driven oil pump on the reservoir supplies the oil requirements during turbine starting and stopping and acts as a backup for the main oil pump.

Two motor-driven oil pumps, one of which has a direct current motor driver operated from the station battery, are also mounted on the oil reservoir for emergency lubrication of the turbine bearings.

The oil purification system consists of a continuous-bypass type turbine oil conditioner, complete with circulating pumps and a 500 gph centrifugal oil separator. Two 18,000-gal horizontal oil tanks are provided, one for fresh oil and one for spent turbine oil, for the 15,000-gal system requirements.

Lubricating oil is used to seal the generator glands to prevent hydrogen leakage. This system consists of motor-driven seal oil pumps to supply oil to the generator glands, defoaming tanks, vacuum pump, and cooler.

C. PUMP DRIVE TURBINES

Steam turbines are used for driving the reactor coolant pumps and the main feedwater pumps. The turbines are dual-inlet condensing units. A double-flow exhaust is used to minimize last-stage losses. Each turbine is provided with control equipment, and an oil tank and pump which provide the reduction gear lubricating oil requirements.

The low pressure inlet is connected to the reheater outlet and operates at 145 psig-725°F during rated plant load. The high pressure inlet, which

operates at light plant loads, receives steam at 900 psig-725°F from the main steam header. Each of three condensers, operating at 1.5 in. of Hg absolute, receives the exhaust steam from one coolant and one feedwater pump turbine.

Each coolant pump turbine is rated at 17,000 shaft horsepower at 5500 rpm, and drives its corresponding pump through a 4.6 ratio reduction gear. The rated steam flow is 125,000 lb/hr when operating with 145 psig-725°F steam.

Each feedwater pump turbine is rated at 5100 shaft horsepower at 5400 rpm, and drives its corresponding pump through a 1.5 ratio reduction gear. The rated steam flow is 39,000 lb/hr when operating with 145 psig-725°F steam.

D. MAIN CONDENSERS

Design data for the main condensers are listed in Table VII-3.

TABLE VII-3

MAIN CONDENSERS - DESIGN DATA

Number of cooling-water pumps	6
Flow rate (gpm-each)	108,000
Head (ft)	30
Drive rating (hp)	1000
Condenser type	Single Pass
Number of units	3
Tube wall (BWG)	18
Material	Admiralty
Size (in.)	1
Length (ft)	50
Design heat transfer surface (ft ² -each)	160,000
Design cooling-water temperature (°F)	57
Design saturation temperature (°F)	91.7
Cooling-water flow (gpm-each condenser)	200,000

Each of the three low pressure turbine elements requires a 160,000 sq ft main condenser to provide a back pressure of 1.5 in. Hg, with a condensing load of 2.06×10^9 Btu/hr, when supplied with 200,000 gpm of 57°F cooling water. The condensers are single-pass with divided water box construction. Each condenser is equipped with 12,220 (1-in. OD No. 18 BWG admiralty metal) tubes, 50-ft long and rolled at both ends into silicon bronze tube sheets. The condensers are designed for 85% clean lines, 7 ft/sec water velocity, and an oxygen content of less than 0.01 cc per liter.

The three condenser hot-wells are cross connected to equalize the levels in the condensers. Use of a divided water box allows either half of the condenser to be in operation while the other half is out of service. Each condenser is provided with two 78-in. inlet and two 78-in. outlet connections for the circulating water piping. The condensers are located with the tubes at right angles to the turbine shaft and are rigidly supported on the grade foundation. An expansion joint is installed between each turbine exhaust flange and condenser neck. Each condenser hot-well is divided vertically along the axis of the tubes, and is compartmented to facilitate the detection and location of tube leaks. Total hot well storage capacity is two minutes. Under steam-dump conditions, when a fault or malfunction trips the turbine generator, all three condensers are used to attenuate and condense 10% of full-throttle turbine-bypass steam flow.

Condensate level is maintained in the condenser by action of level controllers mounted on the hot-well. A low water level condition in the condenser causes the controller to open a control valve which allows make-up water to flow (by vacuum drag) from the condensate storage tank to the condenser hot-well. High water level causes a control valve at the condensate pump discharge to open and pass excess condensate into the condensate storage tank.

E. AIR REMOVAL

Each of the three main condensers is serviced by one steam-jet air ejector which is used for normal air removal requirements. Each unit consists of one

twin element 2-stage steam air ejector with common inter- and after-condensers. The jets are installed in parallel with one element providing the capacity for the associated condenser. Main steam is supplied to the jets under automatic pressure control. Each element is rated at 1000 lb/hr of air and water-mixture saturated at 1 in. Hg suction pressure and 72°F. The non-condensable gases from this operation are discharged directly to the atmosphere. The three condensers are also serviced by two motor-driven, hogging, mechanical vacuum pumps. Each pump has a capacity of 6000 cfm at 15 in. Hg vacuum, and is used for evacuating the condenser during startup.

F. AUXILIARY CONDENSERS

Three auxiliary condensers are provided to receive the exhaust from the pump turbines. Each condenser receives the exhaust from one coolant and one feedwater pump turbine, and contains 15,000 sq ft of heat transfer surface to provide a back pressure of 1.5 in. Hg, with a condensing load of 162×10^6 Btu/hr. Each condenser is supplied with 15,000 gpm of 57°F cooling water by the main condenser cooling water pumps.

The air removal and cooling water systems are common with the main condenser systems. Condensate is pumped to the main condensers by auxiliary condensate pumps. The condensers are two-pass, with divided water box construction. Each condenser is equipped with 2960 (7/8-in. OD No. 18 BWG admiralty metal) tubes each of which has a 22-ft effective-tube length.

Two full-size, vertical, auxiliary condensate pumps (one a spare) are provided to pump the condensate from the auxiliary condensers to the main condensers during normal operation. If during startup the auxiliary steam generator is supplying the steam for the steam turbine drives, the condensate is returned to this unit on level control. An independent high and low condensate level control is provided for the three auxiliary condensers. Each condensate pump is rated at 1000 gpm at a total dynamic head of 150 ft, and is driven by a 50-hp motor.

G. CONDENSATE AND FEEDWATER SYSTEM

The condensate and feedwater stream is divided into three parallel trains of closed heaters with a common single full-capacity deaerating heater. Each train is arranged and hydraulically balanced so that, in the event of failure of a component, the train or component may be bypassed and the failure corrected while the other trains remain in operation. The cycle is based on four extraction stages of feedwater heating and the use of moderator coolers for heating low temperature condensate. The heater drain system is based on full cascading of the drains, with a drain by-passing system to the condenser for start-up and heater-outage conditions. The condensate path from the condenser hot-well to the steam generator is as follows: condensate hot-well pumps, air ejector condensers, gland seal condenser, moderator coolers, condensate booster pumps, low pressure heaters with integral drain cooler, open deaerating heater, main feedwater pumps, and two high pressure heaters with integral drain cooler. The extraction-flows from the turbine casings consist of slightly superheated steam for all heaters. The first-point high pressure heater drains to the second-point high pressure heater, and the combined drains cascade to the deaerating heater. The drain from the low pressure heater cascades directly to the condenser hot-well. Feedwater system design data are presented in Table VII-4.

1. Condensate Pumps

Pump suction and discharge headers with isolation valves are used for both the condensate and condensate booster pumps to permit operation of the plant at reduced load should one of these pumps need to be shutdown for repair. The condensate from the hot-well is pumped by three vertical turbine pumps. Each pump has a capacity of 5000 gpm at 160 ft total dynamic head, and is driven by

TABLE VII-4

FEEDWATER SYSTEM - DESIGN DATA

Feedwater demineralizing	None
Deaeration	Yes
Feedwater heaters (total number)	13
Extraction closed	9
Extraction open	1
Moderator heat recovery	3
Number of banks	3
Drains	Cascade
Number of main feedwater pumps	3
Flow (gpm-each)	6600
Feedwater temperature (°F)	304.8
Total dynamic head (ft)	2700
Driver type	Auxiliary steam turbine
Driver power (hp)	6500
Number of auxiliary feedwater pumps	1
Flow (gpm)	500
Total dynamic head (ft)	2500
Driver type	Motor
Driver power (hp)	400

Tables VII-5, -6, and -7 present detailed feedwater heater, and steam jet ejector and shaft-packing exhauster condenser data.

TABLE VII-5

FEEDWATER HEATER DATA

Extraction Point (Heater)	No. 1	No. 2	No. 4	No. 5
Number of units	3	3	3	3
Terminal difference				
Feedwater outlet (°F)	2	5	5	(heavy water)
Drain cooling (°F)	10	10	10	-
Feedwater flow (lb/hr)	3,032,750	3,032,750	2,471,836	2,471,836
Feedwater inlet temp. (°F)	364.7	307.0	167.9	93.3
Feedwater inlet enthalpy (Btu/lb)	338.2	278.8	135.8	61.3
Feedwater outlet temp. (°F)	420.0	364.7	229.0	167.9
Feedwater outlet enthalpy (Btu/lb)	397.5	338.2	197.2	135.8
Feedwater pressure (psia)	1125	1145	140	35
Feedwater pressure drop (psi)	15	15	15	15
Extraction steam flow (lb/hr)	195,584	182,852	143,153	3.07×10^6 (D ₂ O)
Extraction steam emthalpy (Btu/lb)	1257.0	1206.7	1206.0	135.8
Extraction steam pressure (psia)	315.5	172.6	22.4	50.0
Leakoff flow (lb/hr)	2020	-	-	-
Leakoff flow enthalpy (Btu/lb)	1345.9	-	-	-

TABLE VII-5

FEEDWATER HEATER DATA

Extraction Point (Heater)	No. 1	No. 2	No. 4	No. 5
Drain flow rate from higher heater (lb/hr)	-	197,604	-	-
Drain flow from higher heater, temp. ($^{\circ}\text{F}$)	-	374.7	-	-
Drain flow from higher heater enthalpy (Btu/lb)	-	347.8	-	-
Heater drain flow (lb/hr)	197,604	380,456	143,153	3.07×10^6 (D_2O)
Heater drain temp ($^{\circ}\text{F}$)	374.7	317.0	177.9	140
Heater drain enthalpy (Btu/lb)	347.8	287.1	145.8	75.8
Total heat transfer (million Btu/hr)	177.8	168.2	151.8	184.1

TABLE VII-6

FEEDWATER DEAERATOR HEATER (NO. 3) DATA

Number of units	1
Inlet feedwater flow (lb/hr)	7,415,509
Inlet feedwater temp (°F)	229.0
Inlet feedwater enthalpy (Btu/lb)	197.2
Outlet feedwater flow (lb/hr)	9,098,250
Outlet feedwater temp (°F)	304.8
Outlet feedwater enthalpy (Btu/lb)	274.6
Extraction steam flow (lb/hr)	534.841
Extraction steam enthalpy (Btu/lb)	1310
Extraction steam pressure (psia)	72.0
Blowdown or leakoff flow (lb/hr)	6529
Blowdown or leakoff enthalpy (Btu/lb)	1,181.1
Drain flow rate from higher heater (lb/hr)	1,141,371
Drain flow from higher heater, temp (°F)	317.0
Drain flow from higher heater, enthalpy (Btu/lb)	287.1
Total heat transfer (million Btu/hr)	574.0

TABLE VII-7

STEAM JET AIR EJECTOR CONDENSER AND SHAFT PACKING
EXHAUSTER CONDENSER DATA

	SJAEC	SPEC
Number of units	3	1
Feedwater flow (lb/hr)	2,471,836	7,415,509
Feedwater inlet temp (°F)	91.7	92.1
Feedwater inlet enthalpy (Btu/lb)	59.7	60.1
Feedwater outlet temp (°F)	92.1	93.3
Feedwater outlet enthalpy (Btu/lb)	60.1	61.3
Steam flow (lb/hr)	1,000	9,000
Total heat transfer (million Btu/hr)	1.0	9.0

a 250 hp, 4160 volt, vertical drip-proof induction motor. The condensate discharges into a common header, through the three parallel air ejector condensers and turbine gland seal condenser, to the heavy water moderator coolers located in the reactor building. Instrumentation is provided in the main condensate stream to detect increases in conductivity and chloride contamination caused by condenser tube leakage.

2. Heavy Water Moderator Coolers

To minimize the heavy water inventory, the heavy water moderator coolers are located in the reactor building, adjacent to the reactor. The condensate stream passes out of the turbine building in a single line and connects to the inlet header of the moderator coolers in the reactor building. The condensate flow is divided into three parallel streams through the shell side of three moderator coolers. The moderator coolers are vertical single-pass heat exchangers designed to heat the full condensate stream of 7.41×10^6 lb/hr from 93°F to 160°F. The condensate leaving the moderator coolers is collected into a common header and passes in a single line back to the condensate booster pumps suction header in the turbine building. The moderator coolers are operated at low pressure on the condensate side to assure that any leakage that might occur is from the heavy water tube-side to the condensate shell side; leakage of condensate into the heavy water would downgrade the heavy water. The condensate pressure at the moderator cooler inlet is maintained about 20 psi for this purpose. Quick-closing valves are provided in both the inlet and outlet lines of the moderator coolers, to isolate a cooler in the event of leakage. The condensate outlet from each cooler is monitored continuously for heavy water leakage. Two temperature control valves, one in the supply and one in

the bypass, regulate the flow of condensate to the coolers as demanded by the moderator temperature controller. A recirculating line to the condenser provides for cooling the moderator during times of low condensate demand loads, and for removal of decay heat from the moderator after the reactor is shut down.

3. Condensate Booster Pumps

Three horizontal centrifugal condensate booster pumps are provided to pump the condensate from the pump suction header through the three parallel low pressure heaters to the deaerator. Each pump has a rated capacity of 500 gpm at a total dynamic head of 280 ft, and is driven by a 450 hp, 4160 volt, drip-proof, horizontal-induction motor.

4. Deaerator

A single deaerator is used in the feedwater cycle to provide for high pressure deaeration and to reduce the non-condensable gases in the condensate feed to a minimum. The deaerator is of the spray-tray type with a separate 50,000-gal condensate storage tank to provide approximately two minutes supply at rated load. The deaerator is designed to reduce the maximum residual oxygen to 0.005 cc per liter and the carbon dioxide to zero. The deaerating heater is located on top of the turbine building to provide suction head for the main feedwater pump. Two level control valves are provided in the condensate supply line to control level in the deaerator storage tank. The deaerator is operated at 72 psia at turbine rated load. The deaerator pressure will remain above atmospheric pressure during low load operation.

5. Main Feedwater Pumps

Three horizontal, multistage, barrel type, centrifugal main feedwater pumps are provided to supply the three steam generators in the reactor plant. Each pump has a rated capacity of 6600 gpm of 305°F water at a total dynamic head of 2700 ft. Each pump is driven by a 5100 hp, 5400 rpm steam turbine through a reduction gear. Each pump takes suction directly from the deaerator, and

discharges the feedwater through one of three parallel trains of two high-pressure heaters. The three feedwater streams leaving the No. 1 high pressure heaters are connected to a single equalizing header. From this header the stream divides into three separate lines to supply feedwater to each of the three steam generators. Each line to the steam generators is provided with a flow meter and feedwater control valve which maintains proper water level in the steam generator. Each main feedwater pump is protected from overheating by an automatic minimum-flow recirculation by-pass valve which opens and discharges feedwater to the deaerator when the feedwater flow through each pump is less than the minimum required. Each feed pump is provided with a check valve to prevent reverse flow through an idle pump. Also, a motor-operated valve is provided at the outlet of the No. 1 high pressure heater which is electrically interlocked with the pump turbine controls to protect against pump damage in the event the check valve sticks open.

During startup and at low steaming rates, an auxiliary motor-driven main feed pump is furnished for temporary use to provide feedwater to the steam generators. This pump has a capacity of 500 gpm (2.5% of full load) at a differential head of 2500 ft and is driven by a 400 hp, horizontal, induction motor.

6. Feedwater Heaters

Three trains of three closed feedwater heaters are provided to make a total of nine closed heaters. The high pressure train which follows the main feedwater pumps consists of heaters No. 1 and No. 2, and the low pressure train which precedes the deaerator is the No. 4 heater extraction point. The open deaerating heater is the No. 3 heater extraction point. All the closed feedwater heaters have integral drain coolers. All the closed heaters are conventional, horizontal, two-pass, U-tube, removable shell units sized for 1/3 capacity in each shell. The heaters have carbon steel shells, 70/30 cupro-nickel tubes for the No. 1 and 2 high pressure heaters, and admiralty tubes for the No. 4 low pressure heaters.

The low pressure heaters are located on the turbine operating floor, and the high pressure heaters are located below the operating floor on the mezzanine level. Use of the heavy water moderator coolers for low temperature feedwater heating makes it impossible to locate the low pressure heaters in the condenser necks.

7. Feedwater Heater Controls

Proper water level is maintained in each heater shell by regulating the flow from the heater. Normally the sub-cooled drains cascade to the next lower related heater, with the normal level control valves passing full flow. A second high level control valve is also furnished for each heater to pass additional flow directly to the condenser on extreme high level or if the normal drain valve fails to function or is out of service. High level alarms are provided on each of the feedwater heaters.

The heater shells in each train are vented to the next lowest heater, with the No. 2 heater being vented to the deaerator and the No. 4 heater being vented to the condenser. Normally heaters are operated in trains, with a complete train being removed from service in the event of component failure.

8. Extraction Lines

Extraction steam piping is provided from the four extraction points on the turbine to the feedwater heaters. Two extraction lines are provided for each low pressure heater shell and three for the deaerator. One extraction line is provided for each of the high pressure heater shells. To protect the turbine from damage, all extraction lines are furnished with non-return valves which are actuated by: (a) the turbine overspeed relay dump valve, or (b) high water level in the related heater. In addition, extraction steam by-pass valves are provided on the high pressure feedwater heaters and the deaerator, to pass steam directly to the condenser. These by-pass valves open when the non-return valves close.

H. STEAM AND FEEDWATER SYSTEM PIPING

The main steam, reheat steam, and feedwater piping is shown in Figure VII-3. The three main steam lines leaving the superheater and the three reheater supply and return lines are carried overhead from the steam generator building on a pipe bridge to the roof of the turbine plant. The lines drop down the north wall to enter the turbine area just below the operating floor. The three main steam lines connect to an equalizing header located upstream of the four turbine throttle valves. Each steam line leaving the superheater is provided with a non-return valve and steam flowmeter. Twelve code safety valves are provided in the piping between the steam generator and superheater. These valves are sized to relieve full-steam generator flow. The turbine steam bypass line to the main condenser is provided with a pressure regulating valve that opens to discharge steam to the condenser in the event of a turbine trip, and for removal of decay heat from the main coolant system. If the condenser or turbine plant is out of service, decay heat removal is provided by a manually-operated valve discharging directly to the atmosphere.

Exhaust from the high pressure turbine is manifolded in an equalizing header. Exhaust steam is carried in three reheat steam lines, one going to each of the three reheater units. Isolating valves are provided in each line. The reheat steam lines from the reheater units connect to an equalizing header ahead of the low pressure sections. The three intercept valves are located in the lines ahead of this header, to permit isolation of a reheater unit for maintenance. Code safety valves are provided as required in the reheat steam lines.

The feedwater control valve station is located on the mezzanine level in the turbine building. A feedwater control valve is provided for each of the three evaporators. The three lines leaving the turbine plant are routed with the main steam lines to the steam generator and pump building.

I. CONDENSER COOLING WATER SYSTEM

The condenser cooling water pumps are located in a concrete structure west of the turbine building (see Section X. L.). Six vertical, motor-driven, pumps are provided, each with a capacity of 108,000 gpm at a total head of 30 ft. Each pump is driven by a 1000 hp, 4160 volt, vertical induction motor.

One 78-in. pipe connects each pump discharge to an associated condenser inlet water box. Each condenser outlet water box discharges to a flume through a 78-in. pipe. The flume discharges over a concrete weir in the discharge canal. The weir sets the seal pit elevation to maintain syphon recovery in the circulating water. With this piping arrangement, no valves are required in the cooling water piping, as a half-condenser may be dewatered after shutting down its pump. Expansion joints are provided at each pump and at the water box connections. To remove entrained air during operation, a vacuum priming system consisting of two pumps and vacuum tank is provided. Vacuum connections are provided on each water box.

VIII. ELECTRICAL SYSTEMS

A. MAIN GENERATOR

The station generator is a single unit, hydrogen inner-cooled conductor, 1800 rpm, 3 phase, 60 cycle, 24 kv, 1280 mva, 1088 mw, 0.85 pf, 0.58 SCR at 60 psi hydrogen pressure. Generator neutral is grounded through a grounding transformer and resistor combination.

The main exciter consists of two 4500 hp induction motors, each coupled to a 3000 kw dc generator, for a total exciter rating of 6000 kw.

B. MAIN TRANSFORMERS

Two main transformers connected in parallel are provided. Each transformer is rated at 600 mva, 3 phase, 60 cycle, 24-161 kv, delta-wye, FOA, 750 kv BIL, and with no-load tap changer for four 2.5% HV taps, liquid level gauge, dial type liquid thermometer, vacuum pressure gauge, tank pressure relief device, 6 bushing CT's, sudden pressure relay, winding temperature relay, and three HV lightning arrestors.

C. MAIN UNIT SWITCHING AND PROTECTIVE EQUIPMENT

The 161 kv switchyard equipment consists of oil circuit breakers and the necessary current transformers and potential transformers to provide adequate relaying protection to the main transformers and the main generator. The generator is protected by differential, overcurrent, reverse current, and ground relaying. These relays act to isolate the generator in the event of a fault, by tripping the 161 kv circuit breakers and actuating the steam valves to shut down the turbine.

The main transformer is protected by differential relaying and a sudden-pressure relay. Protective action is the same as with the generator relaying.

D. PLANT AUXILIARY POWER SOURCES (Figure VIII-1)

1. Startup AC Power

Startup power is provided by the common station service transformer, which is a 30 mva, 161-4.16 kv, 65°C rise, FOA, 3 phase transformer connected to the 161 kv main bus. In addition to providing startup power, this transformer provides reserve capacity in the event of an outage of the unit station service transformer during normal plant operation. This transformer is equipped with a no-load tap changer with four 2.5% H. V. taps, a liquid level gauge, a dial type liquid thermometer, vacuum pressure gauge, tank pressure relief device, sudden pressure relay, winding temperature relay, and 6 bushing type current transformers.

2. Normal AC Power

Normal plant auxiliary power is provided by the unit station service transformer, which is a 30 mva, 24-4.16 kv, 65°C rise, FOA, 3 phase transformer connected directly to the 24 kv main generator leads. This transformer is equipped with a no-load tap changer with four 2.5% HV taps, a liquid level gauge, dial type liquid thermometer, vacuum pressure gauge, tank pressure relief device, sudden pressure relay, winding temperature relay, and 6 bushing type current transformers.

3. Emergency AC Power

In the event of the loss of normal plant auxiliary power, emergency 480 volt power is provided by a 1000 kw, 480 volt, 3 phase, 60 cycle, 0.8 pf diesel-generator. The diesel unit is started automatically by an undervoltage relay on the plant 480 volt bus, upon loss of normal power. This relay has inverse characteristics which prevent a diesel start on a transient voltage dip. The diesel-generator is capable of attaining normal speed, with a stabilized voltage output, in 6 to 10 seconds.

An interruption of normal power scrams the reactor. Electrical equipment which must be returned to service immediately following a reactor scram is started automatically when the diesel-generator reaches normal speed. Other

diesel-generator supported equipment is brought back into service manually as required.

4. DC Power

A 250 volt DC system is provided to supply power to those DC items which cannot tolerate a power interruption. During normal operation, static-type rectifiers supply this DC power from normal plant AC power. When a power outage occurs, a 250-volt battery, which "floats" on the system during normal operation, assumes the load. The battery is of the lead-acid Plante positive plate type and has a 1500 amp-hr rating at an 8-hr discharge rate.

The rectifiers are also used to maintain the batteries fully charged. Two fully-rated rectifiers are provided, each capable of supplying all of the DC system power requirements.

5. 120/208 Volt Uninterrupted Power

Two motor-generator sets are provided to furnish uninterrupted AC power to plant protective and control instruments. Each generator is rated at 7.5 kva, 120/208 volt, 3 phase, 60 cycle. Each of the M-G sets is capable of assuming the full load.

Normal driving power is provided by a synchronous motor, which keeps the M-G set output in synchronism with plant power. This drive motor has emergency diesel-generator back-up. In addition, the M-G set is coupled to a DC drive motor through a small flywheel. The DC motor provides driving power to the M-G set upon loss of normal AC power until the diesel-generator assumes the load. To prevent excessive wear of the DC motor brushes and commutator, a mechanism is provided to lift the brushes automatically when the M-G set is operating on AC power. The flywheel helps the set maintain proper speed during the time between loss of normal power and the lowering of the brushes on the DC motor.

6. Regulated and Noise-Controlled Power

Each of the plant monitoring and control circuits that require electrical power of the highest quality are supplied by a combination of isolating-regulating

transformers and voltage regulating power supplies from the 120/208 volt un-interrupted bus. Each of these units is sized to match the individual loads and is in the 500-to-750 watt range.

7. 120/208 Volt Momentarily-Interruptable Power

A momentarily-interruptable 120/208 volt bus is provided for loads such as emergency lighting. This bus is normally supplied from the 480 volt bus. On loss of normal power, the bus is transferred by an automatic transfer switch to a silicon controlled rectifier inverter which supplies backup power from the station battery. The inverter is energized at all times, but delivers power only when normal power is lost. Because of the high reliability factor of these solid state units, no stand-by inverter is provided.

E. POWER DISTRIBUTION EQUIPMENT

1. Isolated Phase Buses

Isolated phase, metal-clad buses are used to transmit power from the main generator to the main transformers and the unit station service transformer. The buses are rated at 24 kv, 60 cycle, 3 phase, 110 kv BIL. The buses to each of the two main transformers are forced-air cooled, and are rated at 18,000 amp. The bus to the unit station service transformer is self-cooled and rated at 500 amp.

2. 4.16 kv Switchgear

The 4.16 kv switchgear is of the indoor metal-clad type, and has draw-out type air circuit breakers. The switchgear bus sections are rated at 1000 amp and the circuit breakers have a 500 mva interrupting capacity. All motor feeder switchgear sections include the necessary protective relaying, metering, and control equipment.

3. 480 volt Switchgear

The 480 volt switchgear is of the metal-clad type and is arranged in a double-ended unit substation with selective primary feed configuration. The

buses fed by 1500 kva transformers have 75,000 amp I. C. main breakers and 50,000 amp I. C. feeder breakers. The buses fed by 1000 kva transformers have 50,000 amp I. C. main breakers and 25,000 amp I. C. feeder breakers.

4. Motor Control Centers

The motor control centers are rated at 480 volt, Class II, type B. Each center is located as near as possible to the associated load. All motor starters are combination type, with circuit breakers.

F. MOTORS

Electric motors 250 hp and larger are rated at 4160 volts, 60 cycles, 3 phase. Motors 1/3 hp and smaller are rated at 115 volts, 60 cycles, single phase. Those between 1/3 and 250 hp, and all motors connected to the emergency bus, are rated at 480 volts, 3 phase, 60 cycles.

Outdoor motors are provided with either weather-protected or totally-enclosed fan-cooled enclosures. Most of the indoor motors have drip-proof enclosures. In areas with special environmental requirements, appropriate enclosures are provided.

G. LIGHTING

Lighting is in accordance with the latest recommendations of the IES. Mercury vapor lighting is provided in the high-bay areas. Fluorescent lighting is installed in the control room, offices, laboratories, and similar areas. Incandescent lighting is used in general operating areas. Emergency lighting circuits are supplied from the 120/208 volt momentarily-interruptable bus.

H. COMMUNICATIONS

A public address system consisting of telephone-type handset stations and loudspeaker assemblies is provided. The system has two channels, one for paging and one for party line service. Simultaneous conversations may be

conducted on each channel without interference. There is also a conduit system provided for hook-up to the local telephone company.

Tone oscillator equipment is installed to sound emergency alarms over the paging system. Emergency alarms are controlled from the control room.

I. GROUNDING

A one-ohm (max.) grounding system is installed at the plant. All structural steel and electrical equipment frames are solidly grounded. "Cadweld" type ground connections are made whenever possible.

J. RACEWAYS AND WIRING

Cables for 4160 volt service are single-conductor, 5 kv, shielded, with butyl insulation and neoprene or PVC jacket. Wiring for all power circuits is minimum No. 12 AWG, 600 volt with type TW insulation. Type AF fixture wire is used on lighting fixtures.

Within the plant, cables are run either in rigid steel conduit or in cable trays. 4160 volt cables routed through cable trays are generally three-conductor, with interlocked armor.

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IX. PLANT SERVICE SYSTEMS

A. REACTOR PLANT COOLING WATER

Three vertical pumps, each capable of pumping half of this system's flow requirements, are located at the intake structure (see Figure X-1) to supply river water to the shutdown cooling condenser, and to the heat exchangers in the component high-temperature and low-temperature cooling water systems. Each pump has a rated capacity of 5000 gpm at a total dynamic head of 200 ft, and is driven by a 350 hp, 4160 volt, drip-proof, solid-shaft induction motor. These pumps are of standard cast iron, bronze-fitted construction. The return water from the condenser and heat exchangers is discharged via the tunnel to the river.

B. TURBINE PLANT COOLING WATER

Three vertical pumps, each capable of pumping half of this system's flow requirements, are located at the intake structure to supply cooling water to turbine plant equipment. Each pump has a rated capacity of 7000 gpm at a total dynamic head of 200 ft, and is driven by 400 hp, 4160 volt, drip-proof, solid-shaft, induction motor. These pumps are standard cast iron, bronze-fitted construction. These pumps supply cooling water to the following equipment:

- 1) Main generator hydrogen coolers
- 2) Hydrogen seal oil coolers
- 3) Stator water coolers
- 4) Main turbine lube oil coolers
- 5) Auxiliary turbine (main coolant and feedwater pump drives) lube oil coolers
- 6) Mechanical vacuum pumps

- 7) Main condenser cooling water pumps
- 8) Vacuum priming pump oil coolers
- 9) Air compressors and aftercoolers
- 10) Condensate booster pump oil coolers

The turbine plant cooling water pumps are also used to back up the fire protection system.

Return water from this system is discharged via the tunnel to the river.

C. MAKEUP WATER TREATMENT

Makeup feedwater treatment is based on using raw water from a deep well system. The well system supplies the domestic water requirements as well as water for makeup feedwater. Makeup requirements are provided for 3% of the rated turbine throttle flow at nameplate rating. The quality of the sub-surface water is considered to be average constituent quality; consequently, the use of coagulation and filter beds is not considered necessary. Two 1200 gpm, 50 hp, vertical, deep-well pumps discharge well water into a 60,000-gal raw water storage tank. The makeup requirements are provided by pumping 650 gpm of raw water from the storage tank through a filter, cation exchanger, degasifier, anion exchanger, and a mixed-bed ion exchanger for a final polish. Three filter-ion exchanger systems are provided. The systems are arranged for fully automatic operation.

Treated makeup water is stored in a 75,000-gal aluminum tank. Two 650 gpm, 50 hp, centrifugal pumps transfer treated water from the storage tank to the condensate storage tank (see below) and other turbine and reactor plant services.

D. CONDENSATE STORAGE

The condensate storage system, consisting of a storage tank, piping, and control equipment, supplies the condensate needs for both the reactor and tur-

bine plants. Makeup water to the system is supplied from the makeup water storage tank. A 250,000-gal aluminum condensate storage tank is located next to the turbine building. On a sudden drop in electrical load, the excess condensate from the condensers is dumped through level control valves to the condensate storage tank. On a sudden increase in electrical load, the condensate is drawn into the condenser hotwells through low level control valves.

E. DOMESTIC WATER

Domestic water is supplied by two 150 gpm, 15 hp centrifugal pumps (one is a spare). These pumps draw water from the raw water storage tank and pump water through a hypochlorinator to the sanitary system, shower, and wash facilities.

F. FIRE PROTECTION

Normally, fire main pressure is maintained by the turbine plant cooling water pumps through a cross connection line to the fire mains. Backup water for fire protection service is provided by two 3000 gpm, 300-hp, vertical, centrifugal pumps which are mounted on the intake structure and take suction from the river. One pump is electric-motor driven and the other pump is diesel-engine driven. On low pressure in the fire main, the motor-driven fire pump starts automatically; if that pump fails to start or maintain pressure, the diesel-driven pump starts automatically. Electrical power to the electrically-driven fire pump is supplied from two sources for added reliability.

Fire main water is distributed through a buried pipe loop to hydrants located at various places in the plant yard. Five main loops take off the main loop and cover the turbine building, pump building, reactor building, and reactor auxiliary building.

The organic piping and equipment areas of the buildings are protected by a dry pipe sprinkler system. A dry pipe deluge system is provided for protecting the outside coolant storage areas.

High temperature in any of these areas is detected by means of strategically-located, pneumatic, heat-actuated devices (HAD's) which operate both on rate-of-rise and fixed temperature principles. The plant is divided into alarm zones. In the event of a sudden high temperature in any one of the zones, the HAD's activate an alarm throughout the plant and an annunciator signal in the control room designates the zone affected. In the event of a fire or a major organic spill, the temperature rise within the affected area is detected by the HAD's and the sprinkler valve is opened, allowing water to flow to all nozzles. Fire heat melts the fusible elements in the sprinkler heads and water is sprayed into the area. The water cools and condenses the organic vapors, and cools down and freezes the organic coolant.

In the turbine plant, automatically-actuated water spray systems are provided for the oil-filled main and station service transformers. Water spray nozzles attached to fixed dry-pipe systems provide protection for the turbine oil reservoir, piping, and hydrogen seal unit. These nozzles are actuated manually by deluge control valves, upon alarm signal. Underfloor turbine oil piping is protected by a wet-pipe sprinkler system with fusible-plug type spray nozzles.

Hose stations and portable dry chemical-type and CO₂ fire extinguishers are distributed throughout the plant to supplement the main systems.

G. COMPRESSED AIR

Two separate compressed air systems are provided, one for the air requirements for controls and instrumentation and the other for general plant services. Compressed air for controls and instrumentation is supplied by two (one a spare) 275 scfm, 125 psig dry-type, two-stage, reciprocating, motor-driven (75 hp) compressors. Each compressor discharges through an aftercooler and moisture separator into a compressed-air receiver. Air passes from each receiver through a regenerative air dryer and filter before entering a header which feeds air to the individual controllers and instruments. The air piping includes cross-

connections on the discharge side of the compressors and on the outlet of the receivers, to permit maximum flexibility of operation. The compressors are arranged for dual control with automatic loading and unloading control. The spare compressor starts up automatically if the instrument air pressure drops below 80 psig.

The compressed air for general services (for which the purity and dryness of control and instrument air are not required) is supplied by one 600 cfm, 100 psig, motor-driven (125 hp), reciprocating, compressor. Air leaving the compressor passes through an aftercooler and moisture separator before entering a service air receiver. Cross connections are provided between the control and instrument air and service air systems for emergency backup to each system. Service air piping is tied in to the control and instrument air piping upstream of the instrument air dryers to improve the quality of the service air when required for control and instrument air. Each air system includes safety valves and auxiliary equipment.

All compressor equipment is located on the ground floor of the turbine building.

H. VENTILATION AND AIR CONDITIONING

1. Reactor Building

All areas of this structure, except those required to have an inert atmosphere, are provided with means for supplying, heating, cooling, dehumidifying, and exhausting the environmental atmosphere. Normal atmosphere control is by means of recirculating atmosphere conditioning system containing high efficiency particulate and air filters, cooling and heating coils, desiccant dryers, circulating fans, associated ductwork, and all controls necessary to maintain required maximum and minimum temperatures and pressure. Those areas containing heavy water process equipment are served by separate recirculating

which contain dehumidifiers for heavy-water recovery from the atmosphere. A purge air system is provided to work in conjunction with the recirculating systems. This system supplies dilution air as required to limit the buildup of contaminants, compensates for varying internal and external atmospheric pressure changes, and provides minimum outside air during occupancy. The components of this system are the same as for the recirculating systems, with the addition of exhaust fans. All air leaving the reactor buildup is discharged to the facility stack.

2. Fuel Handling and Organic Process Buildings

The ventilation and air conditioning facilities provided for these buildings are similar to those in the reactor building. The exhaust air is released through the facility stack. Normally, a slightly negative pressure is maintained in these buildings so that the release of building air to the atmosphere via openings in the exterior walls is minimized.

3. Heavy Water Service Building

This building is ventilated and air-conditioned the same manner as the organic process buildings. Heavy water recovery equipment is provided for the atmosphere within this building.

4. Turbine Building

Heat removal in the turbine-generator area is effected by natural ventilation, the air being supplied through wall louvers and exhausted through heat valves on the roof. Unit heaters are used in this area during shutdown. Heating and ventilation in the other areas is by means of unit conditioners.

5. Administration Building

The atmosphere in this building is regulated by an air conditioning system consisting of filters, heating coils, refrigerated cooling coils, fans, associated ductwork, and all controls necessary to maintain room temperatures.

The control room unit provides a space temperature most suitable to instrumentation reliability and personnel comfort.

I. AUXILIARY STEAM

Startup auxiliary steam requirements for the pump driver turbines, tracing, coils, and unit heaters are supplied by a station auxiliary, package-type, steam generator. This unit is furnished complete with draft fans, combustion and feedwater controls, deaerator, and condensate return pump. The steam generator is rated at 150,000 lb/hr of saturated steam at 200 psig.

To meet plant service requirements, 200 psig auxiliary steam headers are provided to various buildings. During normal operation, the auxiliary steam generator is shut down and the steam supply to the 200 psig headers is taken from the shutdown cooling heat exchanger or the main steam line.

Steam at 200 psig is used for tank heating and steam tracing. Each steam traced circuit is provided with a strainer, steam trap, and blocking valves. The steam pressure is reduced to 15 psig for use in space and domestic-water heating equipment. Condensate is recovered whenever possible and returned to the condensate system.

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X. SITE AND STRUCTURES

A. SITE DEVELOPMENT

The plant site is located on the east bank of the North River, 35 miles north of Middletown, the nearest large city.* Access to a state highway is provided by an existing secondary road which is in good condition and needs no improvements. Railroad access is provided by a 5 mile spur to a main line railroad.

The plot plan, Figure X-1, and the isometric layout, Figure X-2, show the general layout and building arrangement of the facility. Several of the buildings are also illustrated in Figures III-2, -3, and -4.

Facilities are available for performing all necessary work to prepare the site and yard for the nuclear power plant.

B. BUILDING ARRANGEMENT

Buildings for the nuclear facility are arranged around the reactor building in a manner designed to minimize pumping power, piping runs, and construction costs. This arrangement also provides convenient access from the administration building, which contains the general offices and control room, to the remaining plant buildings: steam generator and pump building, reactor auxiliary building, and service building.

C. REACTOR BUILDING

The reactor building houses the reactor, moderator cooling system, and refueling machines. It is a leak-tight, vertical cylindrical structure, 140 ft diameter x 187 ft high (above grade), with a hemispherical head and a concave base. The building is of all-welded carbon steel plate construction, rests on a reinforced concrete base, and its shell and head are lined with concrete as re-

* Hypothetical site in New England, as described in TID-7025, "Guide to Nuclear Power Cost Evaluation."

FIG X-1. Facility Plot Plan

1. REACTOR BLDG.
2. STEAM-GEN & PUMP BLDG.
3. TURBINE BLDG.
4. SERVICE BLDG.
5. AUXILIARY BLDG.
6. ADMINISTRATION BLDG.
7. D₂O SERVICE BLDG.
8. FUEL HANDLING AND STORAGE BLDG.

FIG X-2. Isometric Layout of Plant Buildings

quired for shielding. Concrete shielding is also provided as required around the reactor and the heavy water system. Building access is provided through personnel equipment airlocks. Vertical access to the various levels within the building is by stairways and an equipment elevator. The building is designed for an internal pressure of 15 psig at 165°F.

D. ADMINISTRATION BUILDING

The administration building houses the general offices, control room, laboratory, conference rooms, hot change areas, and air conditioning equipment. The building is three stories high and is located directly adjacent to the reactor auxiliary building through which access to the remainder of the plant is available.

E. STEAM GENERATOR AND PUMP BUILDING

The steam generator and pump building houses the steam generating equipment, main coolant circulating pumps, feedwater pumps, and associated steam turbine drives. The building is located at grade, adjacent to the reactor building. The steam generating equipment is in the high bay area of the building. The main coolant and feedwater pumps are in the low bay area at ground level. The pump turbine-drive condensers are located adjacent to the turbines at grade. Crane coverage is provided for pump and turbine maintenance and removal.

F. REACTOR AUXILIARY BUILDING

The reactor auxiliary building contains the auxiliary process systems associated with the organic systems. These systems include organic adsorption, coolant recovery, waste gas handling, aqueous waste, the main heating and ventilation system for the facility, and a radioactive maintenance and repair area. The building is located at grade and is between the administration and reactor buildings. Access between the auxiliary and reactor buildings is through a personnel-equipment airlock. The equipment space within the process area is

open-type construction with shadow shields provided around equipment for radiation attenuation where required.

G. HEAVY-WATER SERVICE BUILDING

The heavy-water service building is located adjacent to the reactor building and contains the heavy water purification system, heavy water recovery system, ion-exchange resin handling equipment, and heavy water storage tanks. Shielding is provided around the components where required. Equipment handling facilities are provided within the building. Facilities for shipping and receiving by truck or railroad are available in the adjoining fuel handling building.

H. FUEL HANDLING BUILDING

The fuel handling building is located adjacent to the heavy water service and reactor buildings. This building is at grade and contains an elevated spent fuel storage pool, devices for fuel handling, a crane for fuel cask handling, and a new fuel receiving and inspection area. A railroad spur and truck access are provided into the building. Access into the reactor building is by a personnel-equipment airlock.

I. TURBINE BUILDING

The turbine building is located adjacent to the steam generator and pump building and contains the turbine-generator, main condensers, feedwater heaters, and related auxiliary equipment. This building is located above ground except at the condenser hot wells, which are located approximately 4 feet below grade. Reduction of noise and vibration is effected by complete isolation of the turbine-generator pedestals from the building. A bridge crane spans the width and runs the entire length of the turbine room. The crane has a main and an auxiliary hoist and is sized to handle the generator rotors. A machine shop area is located at one end of the building.

J. SERVICE BUILDING

The service building is located at grade adjacent to the machine shop area of the turbine-generator building. The building serves as the shipping-receiving and warehouse area for the facility.

K. BUILDING CONSTRUCTION

Reinforced concrete construction is used extensively throughout the facility, because of favorable cost and radiation shielding properties. The reactor building is of concrete-lined welded steel plate construction. To give light weight, low maintenance, and a pleasing appearance, structural steel and aluminum wall panels are used for the turbine-generator building. The administration building is a conventional office structure. The remaining buildings are of tilt-up reinforced concrete construction.

Concrete block construction is used for curtain walls and partitions. Functional design, neat appearance, and low maintenance requirements are stressed in the building designs.

L. INTAKE STRUCTURE

A concrete river water intake structure is located between the cluster of plant buildings and the river. The following pumps are installed in this structure: 6 main condenser cooling water pumps, 3 reactor service water pumps, 3 turbine plant service water pumps, 2 fire water pumps, and 2 screen wash pumps. The intake structure is provided with 8 travelling screens with bar racks and stop logs. The screens are washed by the screen wash pumps into a trash trench, and the trash is washed to the river.

The intake structure is also provided with automatically controlled chlorinators to control algae and bacterial slime in all water entering the station.

XI. PLANT SAFEGUARDS

A. INTRODUCTION

Design of the 1000 Mwe HWOCR plant incorporates safety principles which assure that plant operation will not endanger the health and safety of the public or of plant operating personnel. The conceptual design features of the facility are sufficiently formulated to permit a general delineation of potential hazards and to recommend safeguards which will provide adequate protection against these hazards.

B. DESIGN CRITERIA

The HWOCR design incorporates engineering features which provide for a very low accident probability. Safety criteria are met through: (1) design performance limits, (2) engineered safeguards, and (3) inherent safety characteristics of the reactor.

Design performance limits ensure normal plant operation with an adequate margin of safety. Normal operating limitations include: (1) maximum fuel cladding surface temperature of 850°F, (2) minimum burnout heat flux ratio of 2, and (3) a prescribed operating limit on maximum coolant activity to allow normal maintenance activities.

Preliminary safeguards evaluations and safeguards analyses of previous organic reactors and heavy water moderated organic-cooled reactors have indicated the following as conservative requirements for safe HWOCR plant operation:

- 1) Double isolation valves on all main coolant lines penetrating the reactor building.
- 2) Pressure relief valves in the main coolant and moderator systems for internal over-pressure protection.

3) Capability of manual isolation of all piping connected to the main loop, including instrumentation lines, without excessive radiation exposure to personnel.

4) Design of the reactivity insertion system to limit the maximum insertion rate to a safe prescribed value.

5) Provision of an adequate and highly reliable reactivity shutdown system.

6) Provision of an emergency cooling system to ensure shutdown decay heat removal from the reactor.

7) Design of an automatic protection system to monitor all pertinent plant parameters and initiate corrective action in event of an unsafe condition.

Inherent safety features of the reactor design include the limited amount of excess reactivity required for plant operation and the negative prompt power coefficient of reactivity. On-line refueling permits a reduction in the excess reactivity requirement which, in turn, limits the magnitude of potential nuclear excursions.

The total power coefficient of reactivity is positive; however, the prompt power coefficient is negative, thus ensuring safe operation of the reactor. Main constituents of the total power coefficient are: (1) negative contributions resulting from fuel temperature changes, and (2) a positive contribution resulting from coolant temperature changes. The important aspect of the partial temperature coefficients is the time constant associated with temperature change of reactor components. The coolant temperature change follows power level change with a time lag that is several orders of magnitude longer than that associated with fuel temperature changes. Hence, initial power level responses to rapid reactivity inputs will be controlled primarily by the negative prompt power coefficient which results from changes in fuel temperature. The regulating system which controls power level will compensate for the positive coefficient resulting from temperature changes occurring on the longer time base.

C. COOLANT ACTIVITY

Radioactivity of the circulating organic coolant arises from the following sources:

- 1) Activation of impurities introduced into the system with makeup coolant. This is very low, because makeup coolant is distilled as it enters the system.
- 2) Activation of coolant system corrosion products.
- 3) Recoil products from the fuel cladding.
- 4) Fission products from uranium impurities in the fuel cladding.
- 5) Gaseous fission products leaking through defective fuel cladding.

Activity from the first four sources was estimated by using observed PNPf activity and accounting for the differences in the physical system, flux level, and fraction of coolant inventory in the core. The dose rate expected at the surface of the main loop piping from these sources is 10 mr/hr after steady-state conditions have been attained.

Activity from the fifth source depends on the number of defective fuel rods present in the core. The defect to be considered is a pinhole or crack in the cladding, such as might result from an imperfect weld during fabrication. By using the failed-fuel-element detection system the defective rods can be located and removed from the core by the fuel handling machine. Thus, the number of defective rods in the core at any one time is subject to administrative control.

In determining the coolant activity per defective rod, the following assumptions were made:

- 1) Maximum fuel temperature of 2200°F, which results in the release of approximately 0.3% of all gaseous fission products.
- 2) The fuel temperature profile limits release to those isotopes which are gaseous at 1500°F (viz., xenon, krypton and iodine).

3) No delay time of fission products in the fuel. This is conservative because available information indicates a delay time on the order of days. This phenomenon is currently being evaluated for possible application to the activity analysis.

4) 90% iodine retention in coolant, 10% removal in degasifier.

5) Average fuel power of 30 kw per rod.

On this basis, the specific coolant activity from defective rods is estimated to be $0.027 \mu\text{c}/\text{cm}^3$ per defective rod. This activity level will contribute approximately 7 mr/hr to the dose rate at the main coolant piping surface.

D. MATERIALS COMPATIBILITY

The HWO CR concept has an unusually low potential for material interactions, especially those of a violent nature. This is due primarily to the relatively inert behavior of the organic coolant. In general, the conditions which conceivably could result in chemical reactions with large energy release exist only in highly unlikely accident situations.* Specific interactions are discussed below.

1. Organic-UC

Experiments have demonstrated that no significant reaction occurs between uranium carbide and organic coolants. Before these materials can even come into contact a loss of cladding integrity must occur.

2. Organic-Metal

The main coolant system is composed of carbon steel, SAP and a small amount of stainless steel. Compatibility between these materials and the organic coolant has been demonstrated in the operations of OMRE and PNPf.

*Silverman, L., "The High Temperature Chemical Reactivities of the Uranium Carbides," NAA-SR-Memo-4269 (Rev. 1), Aug. 19, 1959.

3. D₂O-UC

The reaction between D₂O and UC is expected to be less than that between H₂O and UC, because of the deuterium isotope effect.* The lesser reaction is due primarily to the difference in zero-point energy between a bond to hydrogen and a corresponding bond to deuterium. This has been demonstrated by lower reaction rates between D₂O and other metals, such as lithium, sodium, aluminum, and iron, than with H₂O. When H₂O contacts UC, a rapid, but not violent, evolution of hydrogen and gaseous hydrocarbons takes place with subsequent oxidation of UC to UO₂ which slows and finally ends the reaction.

It should be noted that in this reactor three independent metal barriers must be breached in order to put D₂O and UC into contact, viz., (a) fuel cladding, (b) process tube, and (c) calandria wall. Therefore, such contact is unlikely.

4. D₂O-Metal

The D₂O system is constructed from stainless steel and a zirconium alloy. In a reaction with D₂O, which converts these metals to the associated oxides, considerable energy could be released. However, the conditions necessary for such a reaction to occur are quite severe†§ and are unlikely to ever be present in the reactor systems. For example, a violent chemical reaction could take place only under high temperature conditions where the metal is molten and certain limited mass ratios exist. Again, any D₂O reaction is expected to be less severe than a corresponding H₂O reaction.

5. Metal-UC

The compatibility of UC with the cladding material has been adequately demonstrated. UC is expected never to escape the cladding. However, it has also been found compatible with other construction materials used, and, thus, poses no serious reaction threat if contact should occur.

*Wilberg, K. B., "The Deuterium Isotope Effect," Chem. Rev. 55, 713-43 (1955)

†Epstein, Leo F., Metal-Water Reactions: VII Reactor Safety Aspects of Metal-Water Reactions (January 31, 1960) GEAP-3335.

§Higgins, H. M., and Schultz, R. O., "The Reaction of Metals with Water and Oxidizing Gases at High Temperature," (April 30, 1957), IDO-28000.

E. ACCIDENTS

A preliminary identification and evaluation of various types of potential accidents was undertaken. It was found that adequate engineering safeguards could be designed into the plant to ensure a safe and reliable facility. Conceivable accidents are generally divided into two categories: reactivity accident and mechanical accidents.

F. REACTIVITY ACCIDENTS

Several means are provided to protect against reactivity accidents. Of primary importance are the inherent safety features of the HWOCR concept; i. e., limited excess reactivity as a result of on-line refueling, along with a negative prompt power coefficient. Independently, these features generally will not prevent hazardous conditions, but the combined effects will reduce the severity of reactivity accidents.

Other means of protection against reactivity accidents are afforded by a number of automatic safeguards in plant control and protective systems. The short period, high flux level, and high temperature monitoring features of the plant protective system will terminate any nuclear excursion before the reactor power level and temperature can exceed safe values.

The reactor may be scrammed manually at any time. The limitation on the rate of reactivity insertion affords adequate time for manual corrective action.

G. MECHANICAL ACCIDENTS

Of several conceivable mechanical accidents, the major-loss-of-coolant accident is considered the most severe. Loss of coolant due to small-size pipe breaks, such as an instrumentation connection line, can be compensated for by the pressurizing system; thus, in these situations the reactor could be shut down in a normal controlled manner. A large-sized break would result in scramming the reactor by activation of a low-pressure, low-flow, or low degasifier tank coolant level circuit.

A piping rupture in a main heat transfer loop in the steam generator and pump building would result in automatic immediate shutdown of the reactor and isolation of the loop from the reactor building by closure of the block valves. The shutdown cooling system would provide decay heat removal and maintain core temperature within acceptable limits.

Coolant leakage from a pigtail rupture (assumed-credible reactor building pipe break) is drained to a drain collecting tank located on the lowest grade of the reactor building. This coolant is then pumped from the tank to the shutdown cooling tank for return to the main coolant system. In the event of a pigtail rupture, the reactor would be scrammed and isolated from the main heat transfer loops by closure of the block valves. The decay heat generated would be removed by the shutdown cooling system. Fuel in the failed channel would be cooled by the flow of organic coolant past the fuel element to the failed end of the channel.

H. ACCIDENT ANALYSIS

A preliminary radiological hazards analysis of plant systems containing organic coolant has been completed. The systems were analyzed from the point of view of determining the maximum potential radiological release for a major rupture occurring within the system. Isolation of the malfunctioning system was assumed to occur within one minute.

The analysis of the main coolant system considered a major pipe rupture and coolant spill, estimated to be 50,000 gal, followed by a fire in which all the spilled coolant was burned. The activity released depends on the specific activity of the coolant, which is a function of the number of defective fuel rods in the core. Therefore, the analysis was performed for various numbers of defective rods. All the activity contained in the spilled coolant was assumed to be released to the building atmosphere. A conventional building with two volume changes of air per hour was assumed. All the noble gases and 50% of the iodines were assumed to be released from the building.

Downwind doses over a 2-hr period, as a function of the number of defective fuel rods in the core, were then determined for this accident. Doses were determined for ground release and 90-meter stack release under Pasquil Type F

meteorological conditions. The resulting doses were applied to a hypothetical 160-acre reactor site (0.5 mile x 0.5 mile). A central plant location was assumed, so that the 2-hr dose at a distance of 0.25 mile provided an indication of the acceptability of the exclusion distance provided by this site. The dose computed at 0.25 mile was converted to fraction of maximum permissible emergency dose (MPED), which was taken as 25 rem for the whole body and 300 rem for the thyroid. Table XI-1 summarizes the results of this analysis. The results show that under ground-release conditions, approximately 500 defective rods could be tolerated before reaching the MPED at 0.25 miles. For a stack release the dose is significantly less.

Activity released from the various other coolant system considered was small compared to that from the main coolant. This is due primarily to the smaller system size and coolant throughput.

TABLE XI-1
50,000-GAL MAIN HEAT TRANSFER SYSTEM COOLANT SPILL AND FIRE

Number of Defective fuel rods	Coolant Activity* ($\mu\text{c}/\text{cm}^3$)	Dose Rate at Pipe Surface† (mr/hr)	Total Activity Release (curies)	Fraction of MPED received in 2 hr at 0.25 miles	
				Ground Release	90-m Stack Release
1	0.027	17	5	0.002	<0.001
10	0.27	80	54	0.02	<0.001
37	1.0	260	200	0.10	<0.001
100	2.7	680	540	0.21	<0.001
200	5.5	1300	1100	0.4	<0.001
500	13.7	3400	2700	1.0	<0.001
1000	27.3	6700	5400	2.1	0.001

*Includes activity from fission gases only

†Pipe is 36-in. dia, 9/16-in. wall; dose rate includes 10 mr/hr from non-fission gas sources.

I. CONTAINMENT

The analysis of coolant activity has indicated that very large amounts of coolant can be spilled in the steam generator and pump building without significant radiological problems. In Table XI-1, it was indicated that, under conservative assumptions made with respect to gas holdup in the fuel, a total of 500 defective fuel element rods can be tolerated without exceeding the MPED for ground release. Should such a spill occur, the total activity would not be released to the environment unless a fire occurred and consumed all of the coolant. If the ventilation system continued to function, the fumes would be released through the stack and the maximum offsite dose would be less than 0.1% of MPED. The release of this amount of activity as a result of coolant spill is not considered credible. Therefore, it is clear that radiological accidents from main heat transfer system coolant spills are not limiting and this system does not require containment. The main heat transfer loops have therefore been located external to the reactor building.

The fission product activity in the plant is associated with the fuel. Should an accident occur in the core (such as a meltdown of fuel) to release large amounts of activity to the coolant, this activity will be detected and a system will be automatically activated to (a) scram the reactor, (b) close the double isolation valves on all 3 main loops, and (c) switch the shutdown cooling system into the decay heat removal mode. The shutdown cooling system is located within the reactor building so that the circulation of radioactive coolant can be accomplished without endangering those outside the plant. The two emergency shutdown cooling pumps are each capable of handling the full flow and, furthermore, both pumps are always normally in operation to provide steam for auxiliary services.

The reactor building, which contains the reactor and fuel handling complex, is designed to contain all accidents occurring within the building. Several potential accidents have been examined on a preliminary basis to determine the pressure design requirements of the structure. These accidents include the possibility of large organic spills and fires with coincident use of a water sprinkler system. Other accidents studied include partial and complete meltdown of the reactor core. Based on conservative analysis, the maximum pressure buildup resulting from these accidents is approximately 15 psig. The building is designed for 15 psig, thus it can be concluded from studies conducted to date that the containment building will adequately protect the public from any undue hazard, and that the release of fission products to the surroundings can be controlled in such a manner as to assure that doses at critical points will be well within acceptable levels.

APPENDIX A

TABLE A-1

1000 Mwe HWO CR PLANT CHARACTERISTICS

A. GENERAL

1. <u>Reactor Type</u>	Heavy-water moderated; organic cooled; vertical fuel channels; one coolant pass; bi- directional refueling and coolant flow.
2. <u>Steam Cycle</u>	Superheat with single reheat, four-stage regenerative plus moderator heat recovery to condensate.
3. <u>Power</u>	
a. Total Fission Power, Including Moderator and Shield Heat Loss (Mwt)	3093
b. Net Reactor Power Transferred to Coolant (Mwt)	2921
c. Power Deposited in Moderator (Mwt)	162
d. Net Pumping Power to Coolant (Mwt)	22
e. Power Deposited in Shielding, etc. (Mwt)	10
f. Gross Electric Power Generation (Mwe)	1088
g. Net Plant Power Output (Mwe)	1076
h. Plant Auxiliary Load (Mwe)	12
i. Net Plant Efficiency (%)	34.8
j. Net Plant Heat Rate (Btu/kw-hr)	9800
4. <u>Moderator</u>	
a. Heat Rejection Method	Steam Cycle Feedwater Heating

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b. Duty (Mwt)	162
c. Number of Pumps	3
d. Flow Rate (gpm)	5500 each
e. Calandria Inlet Temperature (°F)	140
f. Calandria Outlet Temperature (°F)	200
g. Purification Method	Ion Exchange
h. Total Inventory (lb)	654, 000 (558, 000 in the reactor)
i. Cover Gas	Helium

B. REACTOR

1. Calandria

a. Material	Stainless Steel
b. Height (ft)	20.0
c. Outside Diameter (ft)	25.0
d. Wall Thickness (in.)	1.0
e. Upper Tube Sheet (in.)	1.5
f. Lower Tube Sheet (in.)	1.75
g. Average Moderator Temperature (°F)	190
h. Reflector Thickness (ft)	
Radial	1
Axial	1

2. Process and Calandria Tubes

a. Number	492
b. Lattice Arrangement	Square
c. Lattice Pitch (in.)	10.5
d. Gas between Calandria and Process Tubes	CO ₂

	<u>Process Tube</u>	<u>Calandria Tube</u>
e. Material	SAP 895	Zr-2
f. Thickness (in.)	0.116*	0.052
g. Inside Diameter (in.)	4.32	5.094

*Including 0.005 in. wear and corrosion allowance.

3. Fuel Elements

a. Type	Finned Rods	
	<u>Large Rod</u>	<u>Small Rod</u>
b. Number per Assembly	31	6
c. OD Excluding Fins, hot/cold (in.)	0.521/0.517	0.324/0.321
d. Fuel Diameter, hot/cold (in.)	0.476/0.472	0.277/0.275
e. Cladding Thickness, Excluding fins (in.)	0.020	0.020
f. Number of Fins per Rod	12	6 and 2
g. Fin Height, nominal (in.)	0.080	0.060 and 0.128
h. Fin Thickness, nominal (in.)	0.030	0.030 and 0.040

4. Fuel Assemblies

a. Type of Fuel	UC (nom. 5 wt.% carbon)
b. Type of Cladding	SAP
c. Number of Assemblies per Channel	5
d. Active Fuel Length per Assembly (in.)	41.52
e. Total Active Fuel Length (ft)	17.3
f. Total Column Length including End Plates (ft)	18
g. Fuel Assembly OD (in.)	4.260 (hot)
h. Fuel Assembly Radial Clearance, between outside of fins and channel (in.)	0.030 (hot)
i. Maximum Heat Release Rating (kw-ft)	33.0
j. Cross Section Area of Fuel in Assembly (in. ²)	5.85
k. Fuel per Assembly (kgU)	50
l. Fuel per Channel (kgU)	250
m. Total Core Loading (metric tons U)	123

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5. Fuel Inventory and Life

a.	Uranium Loading, Total (metric tons)	123
b.	Specific Power (kw/kg)	24.8
c.	Feed Enrichment (wt % U ²³⁵)	1.16
d.	Discharge Exposure* (Mwd/metric ton U)	15,000
e.	Discharge Enrichment* (wt % U ²³⁵)	0.21
f.	Discharge Fissile Plutonium (g/kgU initial)*	0.316
g.	Fuel Assembly In-Core Life (yr) (Plant Factor = 0.8)	
	Average	2.05
	Minimum	1.57
	Maximum	3.85

6. Nuclear Design

<u>Nuclear Design</u>	<u>Hot</u>	<u>Cold</u>
a. D ₂ O/UC (volume ratio) [†]	15.2	15.4
b. Organic/UC (volume ratio) [†]	1.11	1.12
c. D/U*, New Fuel (atom ratio)	30.3	
d. Organic Volume Fraction	0.446	0.448
e. Power Peaking Factors		
Basic Radial		1.17
Basic Axial		1.33
Local Radial--fresh fuel		1.30
Local Axial--fresh fuel [‡]		1.175
Local Flux Tilt		1.05
f. Neutron Average Lifetime, Equilibrium Core (sec)		5.7 x 10 ⁻⁴
g. Effective Delayed Neutron Fraction, Equilibrium Core		0.0049

*Weighted by throughput per region.

†Characteristic value in an active fuel segment of a fuel assembly based on 0.472/0.275 in fuel diameters in the cold condition.

‡For outer fuel element in the assembly.

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h. Reactivity Changes (mk)*		
1) Cold to Zero Power [†]		
Moderator, 68° to 190°F;		
Fuel and Coolant at 190°F		0.6
Fuel and Coolant from		
190° to 534°F		13.4
2) Zero to Full Power (no decay heat)		
Fuel from 534°F to 1000°F		-3.3
Coolant from 534°F to 675°F		+6.3
3) Zero to Full Power (decay heat present)		
Fuel from 595° to 1000°F		-2.9
Coolant from 595°F to 695°F		+3.7
4) Zero to Equilibrium Xenon		-27.0
5) Zero to Equilibrium Samarium		-7.0
i. Excess Reactivity (mk)		
Hot, Full Power, Equilibrium Xenon		
and Samarium		2
Zero Power, Fuel and Coolant at 190°F,		
Moderator at 68°F, No Xenon, with		
Equilibrium Samarium		10
j. Reactivity Worth of Control System (mk)		
Dissolved Boron		
Equilibrium Xenon		27
Emergency Shutdown		63
Vertical Control Elements		3
Horizontal Control Elements		40
k. Reactivity Coefficients [§]		

*mk=milli-k

[†]No xenon, with equilibrium samarium.

[§]At full power operating conditions.

Fuel Temperature	$-0.48 \times 10^{-5} \Delta k/k/^{\circ}F$
Coolant Temperature	$+0.53 \times 10^{-4} \Delta k/k/^{\circ}F$
Moderator Temperature	$+0.44 \times 10^{-5} \Delta k/k/^{\circ}F$
Moderator Purity	$-1.6\% \Delta k/k/\%H_2O$
Coolant Void	$+0.011\% \Delta k/k/\% \text{ void}$
Power	$+0.22 \times 10^{-2}\% \Delta k/k/\% \text{ power increase}$

7. Thermal-Hydraulic Design

a. Maximum Fuel Element Surface Temperature ($^{\circ}F$)	850
b. Heat Flux (Btu/hr-ft ²)	134,100
c. Heat Release, maximum (kw/ft)	26.7
d. Pressure Drop (psi)	
Header-to-header	184
Fuel Section	142
e. Coolant Velocity, maximum (ft/sec)	30
f. Pressure at Reactor Discharge Header (psia)	100
g. Pigtail Pipe ID (in.)	3.25
h. Mixing in Fuel Assembly (%)	64
i. Maximum Power per Fuel Channel, capability (Mwt)	7.30
j. Maximum Power per Fuel Channel, nominal (Mwt)	6.95
k. Average Power per Fuel Channel, nominal (Mwt)	5.93
l. Engineering Hot Channel Factors	
$F_{\Delta T}$	1.09*
F_{Θ}	1.21*
F_{ϕ}	1.12

*Does not include factors relating to flow distributions within the bundle as these are included explicitly in the three-dimensional calculations of the thermal-hydraulic performance.

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8. Reactivity Control System

a. Shutdown Rods

1) Number of Rods	84
2) Type and Description	Horizontal hydraulic cylinders with pressurized D ₂ O for removal; spring loaded for insertion.
3) Absorber	
Outside Diameter (in.)	2.5
Inside Diameter (in.)	2.31
Length (ft)	12.5
4) Position During Power Operation	Full Out
5) Maximum Temperature (°F)	200
6) Burnout Rate	Essentially zero
7) D ₂ O System Requirements	
Number of Pumps	8 (4 stand-by)
Pump Discharge Pressure (psi)	100
Pump Capacity for Removal of 21 Cylinders within 30 sec (gal)	36
Cylinder and Pipe Line Inventory (gal/drive)	8
8) Electrical Requirements	
Cable	12 No. 14 conductors/cable/drive
Power	115v, 60 cps, 1 ϕ , 25 w/drive
9) Mounting Space for Drive Package	
Beyond Biological Shield-minimum (ft)	18 high } centered on 22 wide } center line 18 long } of reactor

b. Xenon and Power Control

1) Number	9, 4-rod clusters 8, 3-rod clusters
2) Type	Stainless steel tape supported rods

3) Absorber	Boron carbide
4) Clad	Stainless steel, Type 304L
5) Absorber Dimensions	
Outside Diameter (in.)	0.5
Length (ft)	8
6) Drive Mechanism Space Requirements (in.)	3 x 6 x 10
7) Position During Power Operation	34 fully inserted 26 fully withdrawn
8) Electrical Requirements	
Cable	12 No. 14 conductors/ cable/drive
Power	115v, 3 ϕ , 60 cps, 25 w/drive
9) Cooling Requirements	
Light Water	1 gpm/drive
Helium Gas	Piping for bleed and purge
c. Soluble Poison Control	
1) Type	D ₂ O-Boron solution
2) No. of Systems	2
3) Concentration in Moderator (g G _{nat} /cm ³ D ₂ O)	25 x 10 ⁻⁶
4) Insertion Rate	
Emergency (g B _{nat} /cm ³ D ₂ O - min)	12.5 x 10 ⁻⁶
Control (g B _{nat} /cm ³ D ₂ O - hr)	1.3 x 10 ⁻⁶
5) Removal Rate	
After Emergency Injection	Complete removal
For Control with a Factor of 2 margin (g B _{nat} /cm ³ D ₂ O-hr)	1.3 x 10 ⁻⁶

6) Frequency Total Boron Removal	Once per year
d. On-Power Refueling Machine	
1) Type	Bi-directional push through refueling
2) No. of Refueling Machine Heads	2 active 4 spare
3) Refueling Cycle Time for Six Fuel Bundles (hr)	4.5
4) Oxygen Content in Atmosphere of Refueling Areas (%)	5
5) R-Motion	
Fast Speed (ft/min)	10
Slow Speed (ft/min)	0.5
6) Θ -Motion	
Fast Speed (rad/min)	1
Slow Speed (rad/min)	10^{-2}
7) Z-Motion	
Speed (ft/sec)	variable - zero to 0.1
Maximum Travel (in.)	8
8) Fuel Ram	
Speed (ft/sec)	variable - zero to 1
Maximum Force Capability (lb)	variable - zero to 3000
Maximum Net Force Addition to any Fuel Bundle (lb)	200
Maximum Travel (in.)	340
9) Magazine	
Speed (sec/position)	10
Fuel Assemblies (positions)	6
Spacer-Shield Assembly (positions)	2

Fuel Channel Seal Plug (positions)	2
Machine Closure Plug (positions)	2
Ram (positions)	1
Spare (positions)	2

10) End Shields

Outside Diameter (ft)	30
Tank Thickness (in.)	1
Calandria Side Tubesheet Thickness (in.)	2
External Side Tubesheet Thickness (in.)	2
Intermediate Tubesheet Thickness (in.)	1
Depth of Balls and Water Mixture (in.)	15 (ball volume %= 67)
Shield Cooling Water Flow (gpm)	1000

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C. PRIMARY COOLANT SYSTEM

1. Coolant	Santowax-OM + 10% High Boilers
2. Reactor Inlet Temperature ($^{\circ}\text{F}$)	595
3. Reactor Outlet Temperature ($^{\circ}\text{F}$)	750
4. Temperature Rise through Reactor ($^{\circ}\text{F}$)	155
5. Total Coolant Flow (lb/hr)	110×10^6
6. Primary Coolant Pipe Velocity (ft/sec)	30 (max)
7. Total System Pressure Drop (psi)	284
8. Reactor Pressure Drop-header-to-header (psi)	184
9. Reactor Core Outlet Pressure (psia)	100
10. Total Steam Generation Rate (lb/hr)	9.07×10^6
11. Number of Loops	3
12. Total Coolant Inventory (gal)	330,000

D. TURBINE-GENERATOR

1. Designation	TC 6F-52
2. Number of Casings	4
3. Speed (rpm)	1800
4. Makeup (%)	0.5
5. Number of Heater Stages	4 Extraction and 1 Moderator Heat Recovery
6. Steam Conditions at Turbine Throttle (psig/ $^{\circ}\text{F}$)	900/725
7. Feedwater Temperature, Final ($^{\circ}\text{F}$)	420

E. PRIMARY SYSTEM HEAT TRANSFER EQUIPMENT

1. <u>Coolant Pump</u>	
a. Number of Units	3
b. Location	Reactor outlet
c. Capacity (gpm)	90,000

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d.	Suction Pressure (psig)	75
e.	Discharge Pressure (psig)	359
f.	Total Dynamic Head (ft)	800
g.	Type	Horizontal Double Suction
h.	Seal	Mechanical
i.	Driver	
	Type	Dual-Inlet Condensing Steam Turbine
	Size (hp)	17,000
	Speed (rpm)	1200

2. Evaporator

a.	Number of Units	3
b.	Type	Horizontal - Natural Circ. - Integral Steam Drum and Economizer Organic on the Tube Side
c.	Duty (Btu/hr)	2410×10^6
d.	Surface (ft ²)	67,300
e.	Steam Generation Rate (lb/hr)	3.02×10^6
f.	Organic Coolant, Flow (lb/hr)	36.7×10^6
g.	Feedwater Inlet Temperature (°F)	420
h.	Steam Outlet Pressure (psig)	945
i.	Steam Temperature (°F)	539.7, saturated
j.	Organic Inlet Temperature (°F)	707
k.	Organic Outlet Temperature (°F)	595
l.	Organic Pressure Drop (psi)	35
m.	Design Conditions	
	Steam Side - shell (psig/°F)	1050/650
	Steam Side - tubes (psig/°F)	1050/750
	Organic Side (psig/°F)	400/750
n.	Dimensions (ft)	14 dia x 51 long
o.	Weight (tons)	500

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3. Superheater

a. Number of Units	3
b. Type	Horizontal - Organic on Shell Side
c. Duty (Btu/hr)	462×10^6
d. Steam Flow (lb/hr)	3.02×10^6
e. Organic Flow (lb/hr)	26.4×10^6
f. Surface (ft ²)	32,500
g. Steam Inlet Temperature (°F)	539.7
h. Steam Outlet Temperature (°F)	725
i. Organic Inlet Temperature (°F)	750
j. Organic Outlet Temperature (°F)	721
k. Steam Outlet Pressure (psig)	925
l. Steam Pressure Drop through Superheater (psi)	20
m. Organic Pressure Drop (psi)	15
n. Steam Side Design Conditions (psig/°F)	1050/750
o. Organic Side Design Conditions (psig/°F)	400/750
p. Dimensions (ft)	10 dia x 36 long
q. Weight (tons)	100

4. Reheater

a. Number of Units	3
b. Type	Shell and U Tube - Organic on the Tube Side
c. Duty (Btu/hr)	475×10^6
d. Surface (ft ²)	32,400
e. Steam Flow (lb/hr)	2.63×10^6
f. Steam Pressure Drop (psi)	12
g. Steam Inlet Temperature (°F)	390
h. Steam Outlet Temperature (°F)	725

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i.	Organic Flow (lb/hr)	10.3 x 10 ⁶
j.	Organic Pressure Drop (psi)	18
k.	Organic Inlet Temperature (°F)	750
l.	Organic Outlet Temperature (°F)	672.5
m.	Steam Side Design Conditions (psig/°F)	300/750
n.	Organic Side Design Conditions (psig/°F)	400/750
o.	Dimensions (ft)	8 1/2 dia x 38 long
p.	Weight (tons)	80
5.	<u>Primary Coolant Piping</u>	
a.	Nominal OD (in.)	38
b.	Nominal Wall Thickness (in.)	5/8
c.	Design Pressure (psig)	400
d.	Design Temperature (°F)	750
e.	Relief Valve Setting (psig)	400
f.	Pipe Material	Carbon Steel A212 Gr B
g.	Velocity in Main Piping (ft/sec)	30
h.	Main Coolant Isolation Valves	12 (4 per loop)
6.	<u>SURGE TANK</u>	
	Number and Type	1 vertical
	Capacity (gal)	20,000
	Design Conditions (psi/°F)	400/750
	Cover Gas	Nitrogen

F. AUXILIARY SYSTEMS

1.	<u>Shutdown Cooling System</u>	
a.	Type	Independent Heat Exchanger with 2 Motor Driven Pumps
b.	Duty (Mwt)	60 (2% full power)
c.	Number of Pumps	2
d.	Flow Rate, each (gpm)	15,000 (5% full flow)

2. Degasification System

a. Type	Atmospheric Pressure Spray Degasifier
b. Water Inleakage (lb/hr)	100
c. Water Concentration (ppm)	200
d. Flow Rate (gpm)	2000

3. Coolant Recovery System

a. Type	Catalytic Hydrocracker
b. Yield (%)	90
c. Coolant Decomposition (lb/hr)	1480
d. New Coolant Makeup (lb/hr)	148

4. Coolant Purification

a. Type	Adsorption - Attapulugus Clay
b. Flow Rate (gpm)	75

G. REACTOR BUILDING

Type of Construction	Steel-lined Concrete Cylinder with Hemispherical Head and Concave Base
Outside Diameter (ft)	140
Total Height above Grade (ft)	187
Total Volume, Net (ft ³)	1.5 x 10 ⁶
Maximum Pressure (psig)	15