JUL 11 1966
JUL 11 1966

AI-CE-Memo-6
Volume I of II

MASTER

HEAVY WATER ORGANIC COOLED REACTOR

HWOCR 1000 Mwe
Nuclear Power Plant
Preliminary Conceptual Design

VOLUME I
ECONOMIC ANALYSIS

RELEASED FOR ANNOUNCEMENT
IN NUCLEAR SCIENCE ABSTRACTS

COMBUSTION ENGINEERING, INC.
Nuclear Division

ATOMICS INTERNATIONAL

A Division of North American Aviation Inc.

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

RELEASED FOR ANALYSIS
IN NUCLEAR SCIENCE ABSTRACTS

AI-CE-Memo-6

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights, or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

HEAVY WATER ORGANIC COOLED REACTOR

1000 Mwe Nuclear Power Plant Preliminary Conceptual Design

H.C. \$ 2.00; MN .75

Volume I Economic Analysis

Contracts: AT(38-1)-383
AT(38-1)-386

FOR THE
U. S. ATOMIC ENERGY COMMISSION

Issued October 1, 1965

COMBUSTION ENGINEERING, INC.
Nuclear Division

ATOMICS INTERNATIONAL

A Division of North American Aviation Inc.

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)

TABLE OF CONTENTS

	<u>Page No.</u>
I. INTRODUCTION AND SUMMARY	I-1
II. PLANT DESCRIPTION SUMMARY.	II-1
A. Reactor	II-1
B. Moderator Systems	II-2
C. Organic Coolant Systems	II-3
1. Primary Coolant System	II-4
2. Coolant Process System	II-5
D. Controls and Instrumentation	II-5
E. Turbine and Steam Equipment.	II-6
F. Condenser and Feedwater System	II-7
G. Electrical Systems	II-7
H. Service Systems	II-8
I. Radioactive Waste Systems	II-8
J. Plant Arrangement and Structures	II-9
III. ECONOMIC ANALYSIS	III-1
A. Fixed Charges on Invested Capital	III-2
1. Plant Capital	III-2
2. Moderator and Coolant Investment	III-6
3. Fuel Investment	III-7
B. Operating Costs	III-9
1. Fuel Cycle	III-9
2. Operation and Maintenance.	III-18
3. Nuclear Liability Insurance	III-19
C. Energy Generation Cost	III-20

IV. FUEL UTILIZATION IV-1

APPENDIX A - PLANT CHARACTERISTICS

List of Tables

<u>Table No.</u>	<u>Title</u>	<u>Page No.</u>
I-1	1000 Mwe HWOCR Plant Energy Generation Cost Estimate Summary	I-6
III-1	Reference Economic Bases	III-1
III-2	1000 Mwe HWOCR Plant Estimated Total Capital Cost	III-3
III-3	1000 Mwe HWOCR Plant Estimate of Direct Construction Cost	III-4
III-4	Fixed Charges on Moderator and Coolant Investment	III-7
III-5	Fixed Charges on Fuel Investment	III-8
III-6	Present Value Factors	III-11
III-7	Reference Fuel Cost Bases	III-12
III-8	Initial Fuel Investment	III-13
III-9	Final Core Disposal	III-14
III-10	Approach to Equilibrium Fuel Cycle Cost	III-15
III-11	Equilibrium Fuel Cycle Cost	III-16
III-12	Levelized Annual Fuel Cost	III-17
III-13	Operation and Maintenance Summary Cost Estimate	III-18
IV-1	Comparison of Dynamic Fuel Utilization	IV-5

List of Figures

<u>Figure No.</u>	<u>Title</u>	<u>Page No.</u>
III-1	Energy Generation Cost vs Plant Factor	III-21
IV-1	Forecast of Nuclear Capacity Growth in the U. S. A.	IV-6

I. INTRODUCTION AND SUMMARY

The overall objective of the HWOOCR 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 can in principle be stretched to meet the demand comfortably, through the judicious use of high-utilization converters, such as the HWOOCR, and breeders.

The steps planned toward the accomplishment of the broad purpose include the design of an HWOOCR 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 HWOOCR program objective and to provide 1000-Mwe HWOOCR 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 D_2O 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 damages the material, requiring continuous make-up.

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 make-up 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 reduced markedly. 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 HWO CR 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.

A number of HWO CR 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 the 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.

The energy generation cost estimates for both investor-owned and publicly-owned HWO CR plants are summarized in Table I-1. The details of the costs are discussed in Section III of this volume.

TABLE I-1
1000 Mwe HWOCR PLANT
ENERGY GENERATION COST ESTIMATE
SUMMARY

Basis: Net Output = 1076 Mwe Plant Factor = 0.8		Investor- Owned	Publicly- Owned	
<u>Investment</u>				
<u>(10⁶ \$)</u>				
Plant		121	117	
D ₂ O (\$20/lb) and Coolant (12¢/lb)		13.4	13.4	
Initial Fuel		9.7	9.5	
<u>(\$/net kw)</u>				
Plant		112	109	
D ₂ O, Coolant, Land & Working Cap.		13	13	
Initial Fuel		9	8.8	
<u>Energy Generation Cost</u>				
Fixed Charges (%/yr), (mills/kwh)				
Plant	12	1.92	7	1.09
D ₂ O, Coolant, Land & Working Cap.	10	0.18	5	0.09
Initial Fuel	10.9	0.14	6.3	0.08
Operating Costs (10 ⁶ \$/yr), (mills/kwh)				
Fuel Cycle - LAFC	5.34	0.71	5.30	0.70
Operation and Maintenance	1.73	0.23	1.73	0.23
D ₂ O and Coolant Make-up & Nuclear Liability Insurance	0.55	<u>0.07</u>	0.55	<u>0.07</u>
TOTAL, mills/kwh		3.25	2.26	

II. PLANT DESCRIPTION SUMMARY

The HWO CR power plant generates a gross electrical output of 1088 Mw, utilizing a 3093 Mwt reactor. Using turbine-driven pumps, the net electrical output is 1076 Mw. Operating with an organic coolant temperature of 750°F at the reactor outlet, superheated steam at 900 psig and 725°F is delivered to the turbine. A nuclear reheat steam cycle is employed yielding a net plant efficiency of 34.8%.

The primary loop components are carbon steel. Low induced-activity in the coolant minimizes the shielding requirements.

Advantage is taken of the separate fuel channels to utilize bi-directional refueling and coolant flow through the reactor in order to produce a more efficient nuclear and thermal-hydraulic design. On-power refueling yields a potential for attaining high plant factors in addition to minimizing thermal cycling of the plant. The absence of heavy water in the primary coolant loop minimizes the plant D₂O inventory, while the reactor achieves the excellent fuel utilization characteristics of heavy-water-moderated systems. Since the organic coolant in the core is present only in the process tubes, coolant make-up costs due to radiation damage are reduced considerably below those for a typical organic-moderated and -cooled reactor.

A summary of the reactor and plant characteristics is given in Appendix A.

A. REACTOR

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. The core is designed for one coolant pass utilizing bi-directional flow and refueling. Fuel is fed through the reactor in opposite directions in adjacent process tubes. The coolant flows in the same direction as the fuel feed within each tube.

The calandria is a vertical cylindrical stainless steel tank, 20-ft-high and 25-ft-dia, with vertical Zircaloy-2 tubes which surround the SAP* process tubes. Cylindrical steel shield tanks containing water and steel shot are located above and below the reactor calandria. The shield tanks are also calandrias through which the flow tubes pass.

A radial thermal shield of steel and water is around the calandria. Surrounding the entire complex is a concrete biological shield which is also the supporting structure.

Each fuel assembly consists of 37 uranium carbide fuel rods clad in SAP tubes. The cladding is 0.020-in. -thick and is finned. Thirty-one rods 0.521-in. dia, and six rods, 0.324-in. -dia, are clustered to form an assembly 4.260-in. -dia. Each fuel assembly has an overall length of 44 in. Five fuel assemblies are installed in each process tube.

Reactivity shutdown control is provided by 84 horizontal neutron-absorbing rods which pass through the reactor core between the calandria tubes. The poison elements are held outside of the active core region by heavy-water hydraulic pressure against a spring-loaded piston in a cylinder at the end of each rod. Release of this pressure allows the spring to drive the poison element into the core region. Xenon oscillation and power control is provided by vertical, stainless-steel-tape-supported rods at 17 locations between the fuel channels. Control during startup and backup shutdown system is provided by boron dissolved in the moderator.

B. MODERATOR SYSTEMS

The D₂O moderator systems remove the heat deposited in the heavy water within the calandria; maintain the required degree of purity; provide for storage

* SAP refers to Sintered Aluminum Product, a sintered mixture of aluminum powder and 7-to-10% aluminum oxide powder.

of the D_2O ; provide an inert gas blanket and control pressure within the calandria; and provide the flow required for the hydraulically-actuated reactor-shutdown system and the soluble-poison shutdown system.

The moderator cooling system is designed to remove 162 Mw of heat from the heavy-water moderator. D_2O leaves the calandria at a temperature of $200^{\circ}F$ and is returned at $140^{\circ}F$. The cooling medium is the main turbine condensate; thus, the moderator heat is not rejected, but is utilized in the low-pressure feedwater heater.

Particulate matter is removed from the heavy water by filtration, and ionic impurities by ion exchangers containing deuterated resins.

A helium cover gas protects the moderator from isotopic downgrading due to air contamination, and provides means for controlling the pressure within the calandria. During reactor operation, the cover gas is circulated continuously through the moderator system to sweep out the deuterium and oxygen decomposition gases. These gases are reunited in a catalytic recombiner and returned to the heavy water inventory.

The moderator is used in two ways to effect reactor shutdown: (1) spring-loaded poison rods, held out of the core by heavy-water pressure, shut the reactor down when the pressure is released; and, (2) soluble poison is injected into the moderator to shut the reactor down if the poison rods fail.

C. ORGANIC COOLANT SYSTEMS

The organic coolant selected for the HWOCR is a mixture of terphenyl isomers having the properties of an organic material which is marketed commercially as Santowax-OM. This material is inexpensive ($\sim 12¢/lb$ in large quantities), has a low vapor pressure, and is noncorrosive; thus, a relatively low pressure, 400 psig, carbon steel system is used. Induced activity due to radiation is low; therefore, shielding requirements are minimized and coolant systems are readily accessible for operation and maintenance.

1. Primary Coolant System

The primary coolant system transfers the thermal energy from the reactor core to steam generating units where 9.05×10^6 lb/hr of 940 psia, 725°F , superheated steam are produced for the turbine-generator; and to steam-reheat units where steam exhausted from the high pressure turbine is reheated to 725°F before entering the low pressure turbine. The total primary coolant flow rate is 110×10^6 lb/hr, with core inlet and outlet temperatures of 595°F and 750°F , respectively, during full power operation. The core outlet pressure is controlled at 100 psia.

The primary coolant system consists of three coolant loops, each with an evaporator, superheater, reheater, a coolant circulating pump, isolation valves, and interconnecting piping. The coolant piping is 38 in. OD with a 5/8 in. -wall-thickness. Coolant velocity in this piping is 30 fps; the total system pressure drop is 280 psi. The loops are connected across reactor inlet and outlet mixing tanks which serve as coolant collection headers on each side of the reactor piping complex. The outlet mixing tank also serves to provide a time delay for the coolant leaving the reactor. In the event of a fuel element cladding break, this delay is sufficient to enable detection of fission products in the core outlet coolant in time to close the isolation valves and prevent fission products from being circulated throughout the coolant loops. The reactor would be scrammed and the decay heat removal loop, which is normally kept circulating, would remove the shutdown heat load.

In addition to the three primary coolant heat transfer loops, the main coolant system includes means for pressurizing the system, an independent loop for removing decay heat from the core, protection against possible fires in the event of a coolant leak, and provisions for venting and draining the system.

2. Coolant Process System

During reactor operation, the organic coolant experiences composition 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 required composition for heat transfer, low damage rate, anti-fouling characteristics and safety, three process systems are provided: degasification, adsorption, and coolant recovery.

The degasification system removes decomposition gases from the coolant by spraying a sidestream of coolant into a tank operating at atmospheric pressure and conveying the released gases to a waste gas system. Water which may leak into the coolant via small leaks in the steam generator is removed as vapor in the same manner. The degasification system also includes a filter for the removal of particulate material from the coolant.

The adsorption system removes impurities from the organic coolant so that film deposits on heat transfer surfaces are minimized. These impurities are selectively deposited on an activated clay adsorbent. The system employs three adsorption columns; normally, two columns are on-line in series flow operation on a coolant sidestream and the third is off-line for regeneration.

In the coolant recovery system, the high boilers which are formed in the coolant are removed by distillation, and are converted to usable coolant by catalytic hydrocracking. Distillation takes place in a flash distillation column. The flashed portion is condensed and returned to the coolant system, and the unflashed liquid containing the high boilers is fed to the hydrocracker.

D. CONTROLS AND INSTRUMENTATION

The control systems for the plant are designed primarily for base-loaded operation. The principal design requirements are:

- 1) Manual operation from 0 to 100% of rated power.
- 2) Automatic operation from 20 to 100% of rated power at constant load levels, with capability for matching minor demand fluctuations in the range of 60 to 100% of rated power.

The nuclear instrumentation system consists of sixteen channels of instrumentation covering the source, intermediate, and power ranges. The system is designed to perform the following functions:

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

Included in the reactor protective system are the interlocks and scram, setback, and loop shutdown circuits for protecting the reactor plant components from damage as a result of all credible occurrences. It monitors pertinent plant parameters and, when these parameters exceed pre-set limits, automatically initiates alarm, setback, or scram action, depending on the severity of the condition.

E. TURBINE AND STEAM EQUIPMENT

The plant utilizes a single steam turbine which is a tandem compound, six-flow, 1800-rpm, four-casing unit provided with 52-in. last-stage blades and internal moisture removal. Steam from the superheaters enters the double-flow high-pressure casing of the turbine at 900 psig and 725°F. Steam leaving this casing flows through the reheaters and is returned to the three double-flow low-pressure casings where it expands to the condenser pressure of 1.5 in. Hg abs. Extraction steam from the turbine and moderator heat are used for feed-water heating.

The drives for the main coolant pumps and feedwater pumps are dual-inlet condensing steam turbines. Normally, a portion of the reheated steam is diverted to these turbines. However, at low plant loads, they receive steam directly from the main steam header.

F. CONDENSER AND FEEDWATER SYSTEM

Three main-exhaust steam condensers are provided, one for each of the turbine low-pressure sections. These are of single-pass design, with divided water box construction. The three hot-wells are cross connected to equalize their levels.

Three auxiliary condensers receive exhaust steam from the pump drive turbines. Condensate from these auxiliary condensers is pumped to the main condensers.

Condensate water-level control is maintained by level controllers mounted on the hot wells. Air removal is accomplished by the use of steam-jet air ejectors.

Turbine extraction steam and moderator heat are used for condensate and feedwater heating. Extraction steam is taken from the main turbine high-pressure casing for the final feedwater heater, and from the crossover pipes for the fourth heater. Extraction steam from the low pressure casings is utilized in the second and third feedwater heaters. The initial condensate heater uses the heat generated in the heavy-water moderator of the reactor.

G. ELECTRICAL SYSTEMS

The plant electrical systems include:

- 1) Station Generator and Transformer - The station generator is a single, hydrogen conductor-cooled unit rated at: 24 kv, 1280 MVA, 1088 Mw, 3 phase, 60 cycles, 1800 rpm, 0.58 SCR at 60 psig hydrogen. The generator exciter is a 6000 kw motor-driven D-C generator. Two main transformers

are each rated at: 24-161 kv, 600 MVA, 3 phase, 60 cycles, delta-wye.

2) Plant Service - Normal power is provided by a 24-4.16 kv, 20 MVA transformer connected directly to the station generator. Startup and backup power is provided by a 161-4.16 kv, 20 MVA transformer connected to the 161 kv main bus.

Emergency electric power is provided by an automatic-starting diesel-powered 480-volt A-C generator and by a 250-volt battery. Equipment items which require continuous power are connected to a 250-volt D-C bus which is normally energized through rectifiers with the emergency battery floating on the line at all times.

H. SERVICE SYSTEMS

The principal plant service systems are:

- 1) Reactor and Turbine Plant Cooling Water Systems
- 2) Component Cooling Systems
- 3) Domestic Water and Feedwater Makeup Systems
- 4) Spent-Fuel Pool Cooling and Purification System
- 5) New-Coolant Handling System
- 6) Gas Service Systems
- 7) Fire Protection System.

I. RADIOACTIVE WASTE SYSTEMS

Systems are provided for the processing and disposal of radioactive gaseous and liquid wastes. The waste gases are treated by adsorption, storage (for radioactive decay), and dilution prior to controlled discharge to the atmosphere through the plant stack. Flue gases from the coolant adsorbent and hydrocracker catalytic regeneration processes are cooled and filtered. Aqueous wastes from areas which could be contaminated, e.g. process area floor drains and wash rooms, are collected in a sump and processed by settling and decanting, filtration, and dilution before discharge to the river. Solid wastes are

packaged and shipped for burial.

J. PLANT ARRANGEMENT AND STRUCTURES

The reactor and moderator systems and the on-power refueling machine* are housed in a leak-tight carbon steel and concrete cylindrical building which is 140 ft dia x 187 ft high above grade and has a hemispherical head and concave base. Personnel and equipment access airlocks are provided. Piping between the reactor and externally located portion of the primary coolant loops is equipped with double valves.

The remaining plant buildings are grouped around the reactor building. These buildings, and the principal systems or components they house, are listed below:

- 1) Steam Generator and Pump Building-Main organic coolant loops, including steam generator units and pumps, and the feedwater pumps
- 2) Reactor Auxiliary Building-Organic purification systems, radioactive waste systems, heating and ventilating units, and reactor plant maintenance shop
- 3) Fuel Handling Building-Spent-fuel storage pool, and new and spent fuel handling facilities
- 4) Heavy-Water Service Building-Heavy-water moderator purification and recovery systems
- 5) Turbine Building-Turbine-generator, main condensers, feedwater heaters, and related auxiliary equipment
- 6) Service Building-Shipping, receiving, and storage space and facilities
- 7) Administration Building-General offices, control room, laboratory, and change areas.

The steam generator and pump, reactor auxiliary, fuel handling, and heavy water service buildings are of tilt-up reinforced concrete panel construction, and have atmospheres controlled at slightly negative pressure. The turbine

*A description of the on-power refueling machine is given in Section II. E. 2 of Volume II.

building has a structural steel frame and aluminum wall panels.

Shielding of activity-containing reactor plant components, where required, is primarily in the form of reinforced concrete. Aside from the reactor, shielding requirements arise principally from activity induced in the heavy water and, to a much lesser degree, in the organic coolant.

III ECONOMIC ANALYSIS

The economic bases and procedures used for establishing the capital cost estimate and the components of the energy generation cost estimates are in accordance with those proposed by the AEC and ORNL's Reactor Division. The analyses presented are based on two representative types of utility financing; i. e., investor-owned and publicly-owned plants. The principal economic factors for these two types of financing are shown in Table III-1.

TABLE III-1
REFERENCE ECONOMIC BASES

	Investor- Owned	Publicly- Owned
Fixed charges on plant capital (%/yr)	12	7
Fixed charges on non-depreciated assets - includes D ₂ O and fuel investment (%/yr)	10	5
Present worth discount rate (%/yr)	6	4
Annual plant factor	0.8	0.8

Other economic bases are included in the detailed discussions of the components of the unit energy cost. In some areas, the factors are varied from the reference values to show their effect on power generation costs.

The economics presented in this section reflect technology which would be available and demonstrated through the construction and operation of a 300-500 Mwe prototype plant by the early 1970's. Economic parameters are representative of one of several 1000 Mwe units, committed for on-line service in the 1970's, which are forerunners of a growing HWO CR economy. Accordingly, economic parameters related to fuel cycle costs are based on large scale processing geared to service an expanding HWO CR economy.

For the purposes of this analysis, the energy generation cost for the HWO CR is divided into the following components:

a. Fixed Charges On Invested Capital

1. Plant Capital
2. Moderator and Coolant Investment
3. Fuel Investment

b. Operating Costs

1. Fuel Cycle
2. Operation and Maintenance (including fluid make-up)
3. Nuclear Liability Insurance

These components are discussed in detail in the following sections.

A. FIXED CHARGES ON INVESTED CAPITAL

The fixed charges include carrying charges on the invested capital to cover return on investment, taxes, insurance, etc., as well as charges to provide for the recovery of capital invested in depreciable items when applicable.

1. Plant Capital

The plant is assumed to be the first unit constructed on an undeveloped hypothetical site in New England, as described in TID 7025, "Guide to Nuclear Power Cost Evaluation". A summary of the plant capital costs is given in Table III-2. The total depreciable-capital cost for the reference plant is \$120,505,700 as an investor-owned plant, and \$116,590,400 as a publicly-owned plant. Based on the rated net generating capacity of 1076 Mwe, the unit costs are \$112/kwe and \$108/kwe as an investor-owned plant and publicly-owned plant, respectively.

Direct construction costs are compiled according to the AEC preferred system of accounts given in the "Guide to Nuclear Power Cost Evaluations", TID 7025. These costs are given in Table III-3. Direct construction cost estimates are based on detailed take-off and vendor estimates for major equipment items according to the descriptions contained in Volume II of this report.

TABLE III-2
1000 Mwe HWO CR PLANT
ESTIMATED TOTAL CAPITAL COST

<u>Account Number</u>	<u>Description</u>	<u>Cost</u>	
21	Structures and Improvements	\$ 11,926,000	
22	Reactor Plant Equipment	38,719,900	
23	Turbine-Generator Units	30,925,600	
24	Accessory Electric Equipment	3,345,300	
25	Miscellaneous Power Plant Equip.	<u>785,400</u>	
	Total Direct Construction Cost	\$ 85,702,200	
	<u>Indirect Construction Cost</u>		
	General and administrative	6%	5,142,100
	Sub-total		<u>\$ 90,844,300</u>
	Miscellaneous construction	1%	908,400
	Sub-total		<u>\$ 91,752,700</u>
	Engineering design and Inspection		
	Architectural and engineering services	5%	4,587,600
	Sub-total		<u>\$ 96,340,300</u>
	Nuclear engineering	2%	1,926,800
	Sub-total		<u>\$ 98,267,100</u>
	Start-up costs 35% of O&M/yr		605,400
	Sub-total		<u>\$ 98,872,500</u>
	Contingency	10%	<u>9,887,200</u>
	TOTAL CONSTRUCTION COST	\$108,759,700	\$108,759,700
	<u>Customer Cost</u>		
	Interest during construction	*10.8% & †7.2%	* 11,746,000 † 7,830,700
	TOTAL DEPRECIABLE CAPITAL COST	120,505,700	116,590,400
20	Land and Land Rights	<u>360,000</u>	<u>360,000</u>
	TOTAL CAPITAL COST	\$120,865,700	\$116,950,400

*Investor-owned

†Publicly-owned

TABLE III-3
1000 Mwe HWO CR PLANT
ESTIMATE OF DIRECT CONSTRUCTION COST

Account Number	Description	Total
20	LAND AND LAND RIGHTS	\$ 360,000
21	STRUCTURES AND IMPROVEMENTS	
211	Ground Improvements	735,000
212	Buildings	
	A-212 Steam Generator Building	612,400
	B-212 Turbine Generator Building	2,218,000
	C-212 Auxiliary Building	516,000
	D-212 Administration Building	220,000
	E-212 Fuel Handling Building	531,000
	F-212 Service Building	127,000
	G-212 Screen Well	551,000
	H-212 D ₂ O Service Building	315,000
	I-212 Pump Building	603,000
	J-212 Gate House	10,000
	K-212 Well Pump House	2,600
	Total Cost, Item 212	\$ 5,706,000
218	Stacks (in C-212)	
219	Reactor Containment Structure	\$ 5,485,000
	Total Cost, Account No. 21	\$11,926,000
22	REACTOR PLANT EQUIPMENT	
221	Reactor Equipment	
	.1 Reactor vessel	\$ 6,283,800
	.2 Reactor controls	474,900
	.3 Reactor shielding	1,460,200
	.4 Reactor auxiliary cooling and heating systems	837,900
	.5 Reactor plant containers (in 219)	
	.6 Moderator and reflector (listed elsewhere)	
	.7 Reactor plant cranes and hoists	160,500
	Total Cost, Item 221	\$ 9,217,300

(TABLE III-3 - ESTIMATE OF DIRECT CONSTRUCTION COST, continued)

Account Number	Description	Total
22	222 Heat Transfer Systems	
	.1 Reactor coolant system	\$ 4,799,000
	.3 a) Steam generators	2,838,000
	b) Superheaters	1,443,500
	c) Reheaters	881,500
	.4 Reactor coolant receiving, supply and treatment	1,286,800
	.5 Reactor moderator auxiliary systems	1,232,200
	.6 Operating fluids	10,000
	Total Cost, Item 222	\$12,491,000
	223 Nuclear Fuel Handling and Storage Equipment	\$ 3,182,100
	225 Radioactive Waste Treatment and Disposal	\$ 137,500
	226 Instrumentation and Control	\$ 7,461,800
	227 Feed-water Supply and Treatment	\$ 2,899,300
	228 Steam, Condensate and Feed- water Piping	\$ 3,195,900
	229 Other Reactor Plant Equipment	\$ 135,000
	Total Cost, Account No. 22	\$38,719,900
23	TURBINE-GENERATOR UNITS	
	231 Turbine-Generators	\$26,291,100
	232 Circulating Water Systems	\$ 1,580,500
	233 Condensers	\$ 2,677,100
	235 Turbine Plant Boards, Instruments and Controls	\$ 326,900
	236 Turbine Plant Piping (in 228)	
	237 Auxiliary Equipment for Generators	\$ 50,000
	238 Other Turbine Plant Equipment (in 232)	
	Total Cost, Account No. 23	\$30,925,600
24	ACCESSORY ELECTRIC EQUIPMENT	\$ 3,345,300
25	MISCELLANEOUS POWER PLANT EQUIPMENT	\$ 785,400

Indirect construction costs have been estimated in accordance with the guidelines established in ORNL 3686, p. 88. Based on these guidelines, General-and-Administrative, Miscellaneous-Construction, Engineering, Start-up, Contingency, and Interest-During-Construction costs are fixed percentages applied to the direct construction costs in an accumulative manner. Start-up charges are estimated at 35% of the annual operating and maintenance costs, including supplies but excluding fuel. The Interest-During-Construction costs depend on the type of utility ownership. The annual interest rates applicable to investor-owned and publicly-owned utilities are assumed to be 6 and 4 percent, respectively, in keeping with the reference bases given in Table III-1. It should be noted that these estimates are based on October, 1965 dollars with no allowance for escalation. For the purposes of the estimate, the plant terminates at the low voltage side of the main transformer.

Based on a Plant Factor of 0.8, 7.55×10^9 net kilowatt-hours are generated per year. The contribution of the plant capital investment to the energy generation cost is 1.92 and 1.09 mills per net kilowatt-hour for the investor-owned and publicly-owned cases, respectively.

2. Moderator and Coolant Investment

The plant requires a total initial D₂O charge of 654,000 pounds plus 2,300,000 pounds of the organic coolant. At a D₂O price of \$20/lb and organic price of 12¢/lb in large quantities, this represents an initial non-depreciated investment of \$13,080,000 plus \$276,000 or \$13,356,000. Depreciation is not

charged here since these materials are continuously purified and make-up is supplied during operation. The annual fixed charges and the resulting contribution to the energy generation cost depend on the utility ownership. These costs are summarized in Table III-4.

TABLE III-4
FIXED CHARGES
ON MODERATOR AND COOLANT INVESTMENT

	<u>Investor- Owned</u>	<u>Publicly- Owned</u>
Annual fixed charge rate (%)	10	5
Annual cost (10^3 \$)	1, 336	668
Energy cost contribution (mills/kwh)	0.18	0.09

3. Fuel Investment

The initial fuel loading in the reactor represents an expense which is quite similar to the capital initially invested in the plant. The return on this investment and its amortization are treated in a similar fashion to the plant capital costs with two exceptions. First, interim replacements of fuel are not included in this item since they represent a large expense. These are part of operating costs designated Fuel Cycle Cost. Secondly, the final loading of fuel remaining in the reactor at the end of the assumed plant life of 30 years has a scrap value which cannot be ignored. In some cases, this scrap value could be negative if the cost of reprocessing the final loading exceeds its market value.

These costs are covered by a carrying charge on the fuel investment plus a factor to cover depreciation, i.e., the change in value from initial to final core. The depreciation factor is the cost of a 30-year sinking fund to recover the working capital invested in the initial fuel after allowing for the value of the final core. Therefore, the annual fixed charge rate, C , on the initial fuel investment is:

$$C = 10\% + 1.26 \left(1 - \frac{V_s}{V_o}\right) \% \text{ for investor-owned plants,}$$

and,

$$C = 5\% + 1.78 \left(1 - \frac{V_s}{V_o}\right) \% \text{ for publicly-owned plants.}$$

The values of 10% and 5% are the non-depreciated carrying charges from Table III-1, and the values 1.26% and 1.78% are the sinking fund deposits required to recover the investment in 30 years for 6% and 4% sinking funds, respectively. The V_o term is the total cost of providing the initial core loading and a 30-day spare fuel supply. It includes the fabrication and shipping cost, uranium cost, and carrying charges on the costs incurred prior to plant operation. The V_s term is the net scrap value of the final fuel loading which is assumed to be fully discharged from the reactor at the end of 30 years plant life. This net scrap value is obtained by computing all of the recovery costs; i.e., shipping, reprocessing, etc., for the discharged loading and subtracting the value of the plutonium and useful uranium recovered. Credit for the spare fuel supply is also applied here. If the net scrap value were zero, then the depreciation term would merely provide for the amortization of all costs of the initial loading. The annual carrying charges on fuel are computed by multiplying V_o by C . These are given in Table III-5. The details of the initial core cost and final core value are given in the following section with the fuel cycle costs.

TABLE III-5
FIXED CHARGES ON FUEL INVESTMENT

	Investor- Owned	Publicly- Owned
Initial Fuel Investment, V_o (10^3 \$)	9,692	9,476
Final Core, Net Value, V_s (10^3 \$)	2,508	2,508
Fixed Charge Rate, C (%/yr)	10.9	6.3
Fixed Charges (mills/kwh) at 0.8 Plant Factor	0.14	0.08

B. OPERATING COSTS

The operating costs include the fuel cycle cost, operation and maintenance cost including make-up of D_2O and organic coolant, and the cost of nuclear liability insurance.

1. Fuel Cycle

In addition to recovering the initial capital investment in fuel, V_0 , the cost of the fuel which is periodically charged into the reactor must also be recovered. During the first few years of plant operation, the fuel cycle costs vary somewhat. The reference design for the HWOCR is based on starting the core in approximately equilibrium condition to minimize the initial investment in uranium needed to start the plant. Essentially, no excess reactivity for burnup is held down in poisons or control rods and the on-power fuel management program is initiated at the time the plant begins operating. For the purposes of evaluating the costs conservatively, it is assumed that the fuel feed rate into the core is constant and equal to the equilibrium rate. The fuel discharged from the channels reaches the equilibrium condition after about two years.

Since the plutonium content in the fuel discharged during the first year does not economically justify recovery, this fuel is held in storage until such time as recovery may be warranted. Plutonium returned for credit after the cooling and reprocessing steps reaches an equilibrium level after about three years. The fuel cycle cost is constant after this initial period.

The effects of these few years of variable fuel cycle costs are factored into the total energy cost by use of a concept termed the Levelized Annual Fuel Cost (LAFC). The LAFC is determined using a standard technique of computing the present value of all future costs for fuel over the life of the plant. The LAFC is the fixed yearly payment (or annuity) which is required to provide for all of these future fuel cycle cost payments at the time they fall due. The interest rates used for these calculations, from Table III-1, are four percent per year

for publicly-owned, and six percent for investor-owned, plants. In this way, variations in the fuel cycle costs from year to year are properly accounted for, including the cost of money.

In accordance with the guidelines for this analysis, the calculations assume that all payments and revenue collections are made at six-month intervals. Therefore, the 30-year plant life is divided into 60 accounting periods using interest rates of two and three percent per period for the two cases. A final period, the 61st, covers the last plutonium credit from fuel remaining in the reprocessing cycle at the end of the 30-year plant life.

The formula for computing the LAFC is:

$$LAFC = A \cdot \sum_{i=1}^{61} (PV)_i C_i$$

where:

$(PV)_i$ is the fractional present value of a payment in accounting period i at the compound interest rate being used.

C_i is the fuel cycle cost in accounting period i .

A is the fractional 60-period annuity whose present value is one.

$A = 0.02877$ at 2% interest

$A = 0.03613$ at 3% interest

The present value factors are listed in Table III-6.

TABLE III-6
PRESENT VALUE FACTORS

Accounting Period		(PV) _i	
<u>i</u>	(Rate)	<u>2%</u>	<u>3%</u>
1		0.9804	0.9709
2		0.9612	0.9426
3		0.9423	0.9151
4		0.9238	0.8885
5		0.9057	0.8626
6		0.8880	0.8375
7		0.8706	0.8131
$i = 60$			
$\sum_{i=8} (PV)_i =$		28.289	21.445
61		0.2988	0.1648

For each accounting period, the fuel cycle cost, C_i , includes the cost of the uranium purchased and charged to the reactor, the cost of fabrication and shipping of this material, and the recovery costs of fuel discharged and reprocessed minus the plutonium credit. The highly depleted uranium is left in the form of nitrates for the purposes of these calculations. The only uranium credit is for fuel from the final core with a value large enough to justify the cost of conversion to UF_6 .

The data for, and results of, the fuel cost calculations are given in Tables III-7 through III-12. Further details concerning the core will be found in Volume II of this report.

TABLE III-7
REFERENCE FUEL COST BASES

	<u>Initial Fuel</u>	<u>Replacement Fuel</u>
Uranium Price		
U ₃ O ₈ (\$/lb)	8.0	8.0
Separative Work (\$/kg)	30.0	30.0
U ₃ O ₈ to UF ₆ Conversion (\$/kgU)	2.7	2.7
Fabrication and Shipping Cost (\$/kgU)	40	36
Pre-irradiation Time (years)	~ 0.5 (avg)	~0.2
Chemical Recovery Cost		
Spent Fuel Shipping (\$/kgU)	2.0	2.0
Separations (\$/kgU)	18.0	18.0
Conversion of UNH to UF ₆ (\$/kgU)	3.0	3.0
Uranium and Pu Losses (%)	1.0	1.0
Post-irradiation Time (years)	0.67	0.67
Plutonium Credit (\$/fissile gram)	10.0	10.0
Fuel Storage in Lieu of Recovery (\$/kgU)	3	-
Equilibrium Fuel Cycle Data at 0.8 Plant Factor		
Feed Enrichment (wt. % U-235)		1.16
Discharge Enrichment (wt. % U-235)		0.21
Fissile Pu Discharge (g/initial kgU)		3.16
Core Loading (metric tons of U)		123
Specific Power (kw/kgU)		24.8
Average Burnup (Mwd/metric ton of U)		15,000
Average Residence Time (years)		2.05
Time to Reach Equilibrium (years)		2 (approx)
Net Energy Generation at 0.8 Plant Factor		
Electrical Power Output (megawatts)		1076
Annual Energy Output (kwh/yr)		7.55 x 10 ⁹

TABLE III-8

INITIAL FUEL INVESTMENT

			\$, in thousands
Fabrication and Shipping Cost (including 30-day spare fuel supply)			5,100
Uranium Cost			
Initial Core Enrichment (wt. % U-235)			
	<u>Axial Zone</u>	<u>Radial Zone</u>	
		<u>Inner</u>	<u>Outer</u>
1		1.06	1.06
2		.90	.95
3		.73	.79
4		.62	.69
5		.57	.63
Spare Fuel (at feed enrichment of 1.16 wt. %)			<u>313</u>
Sub-Total, Uranium Cost			<u>4,160</u>
Total, Initial Fuel Cost			<u>9,260</u>
		Investor- <u>Owned</u>	Publicly- <u>Owned</u>
Carrying Charges During Fabrication*		<u>432</u>	<u>216</u>
TOTAL, INITIAL FUEL INVESTMENT = $V_o (10^3 \$)$		9,692	9,476

* Includes fuel-in-process to supply feed fuel to the core at the start of operation.

TABLE III-9
FINAL CORE DISPOSAL

Recovery Costs and (Credits)	<u>\$, in thousands</u>
Ship Spent Core	244
Fission Product Removal	2,190
Conversion to UF ₆ *	217
Ship UF ₆ *	72
Uranium (Credit) *	(2,060) †
Pu (Credit)	(2,750) †
Spare Fuel (Credit)	<u>(421)</u>
NET FUEL SCRAP VALUE (CREDIT) = V _s	(2,508)

* Only the uranium from the first three (newest fuel) axial zones is converted to UF₆ for credit.

† Net after losses.

TABLE III-10
APPROACH TO EQUILIBRIUM FUEL CYCLE COST
Plant Factor = 0.8

\$ per Accounting Period, in thousands							
Accounting Period, i	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>
Fabrication and Shipping	1,083	1,083	1,083	1,083	1,083	1,083	1,083
Uranium Purchase	1,878	1,878	1,878	1,878	1,878	1,878	1,878
Chemical Recovery							
Shipping			59	59	59	59	59
Separation			0	529	529	529	529
Pu (Credit)			0	(698)	(821)	(906)	(936)
Net Recovery Cost or (Credit)	90*	90*	59	(110)	(233)	(318)	(348)
FUEL CYCLE COST = C_i	3,051	3,051	3,020	2,851	2,728	2,643	2,613

* Storage at \$3/kg

TABLE III-11
EQUILIBRIUM FUEL CYCLE COST

	<u>\$/Kg U</u>	<u>10³ \$ per Accounting Period (Plant Factor = 0.8)</u>
Fabrication and Shipping	36.00	1,083
Uranium Purchase (Burnup)	62.38	1,878
Chemical Recovery		
Shipping	2.00	59
Separation	18.00	529
Pu (Credit), Net After Losses	(31.30)	(942)
	<u> </u>	<u> </u>
Net Recovery Cost or (Credit)	(11.30)	(354)
	<u> </u>	<u> </u>
EQUILIBRIUM FUEL CYCLE COST = C _i (For Accounting Periods 8 through 60)	87.08	2,607

TABLE III-12
LEVELIZED ANNUAL FUEL COST
Plant Factor = 0.8

<u>Accounting Period, i</u>	<u>\$, in thousands</u>	
	<u>Investor-Owned</u>	<u>Publicly-Owned</u>
1	2,960	2,990
2	2,880	2,930
3	2,760	2,860
4	2,540	2,630
5	2,360	2,470
6	2,210	2,350
7	2,120	2,270
Σ for i = 8 to 60	56,100	73,800
61 (Credit)	(68)	(124)
TOTAL	73,862	92,176
LAFC (10^3 \$ per Accounting Period)	2,669	2,652
LAFC (mills/kwh)	0.707	0.703

2. Operation and Maintenance

The operation and maintenance cost estimates, including make-up of heavy water and organic coolant, are shown in Table III-13.

TABLE III-13
OPERATION AND MAINTENANCE
SUMMARY COST ESTIMATE

	<u>Annual Cost \$, in thousands</u>
Direct Payroll	469
Payroll Adders and G & A	211
Materials, Supplies and Contract Services	1,050
Organic Coolant Make-up	126
Heavy Water Make-up	74
	<hr/>
TOTAL	1,930
Operation and Maintenance (mills/kwh)	0.255

The annual cost of plant operating and maintenance personnel is estimated at \$469,000. The permanent staff is estimated to be 70 persons. An allowance of 25% is added for payroll fringe benefits and 20% for general and administrative expense. The cost of operating materials and supplies including contract services are estimated at 0.05 mills per thermal megawatt hour which is consistent with current practices and experience in the electric utility industry.

Organic makeup costs are predicated on the use of a coolant recovery unit as described in Volume II, Section III. C. 3. Briefly, this unit employs a

catalytic hydrocracking process which converts the high-molecular compounds in the organic coolant back to useful coolant. The high-molecular compounds or "high boiler" stream is introduced into the hydrocracking unit where it reacts with hydrogen in the presence of a catalyst. This reaction takes place at a temperature of about 900°F and a pressure of 1000 psia. The hydrogen is produced on-site by electrolysis of water. Laboratory work performed by Phillips Petroleum Company has demonstrated the feasibility of the process. Work is currently in progress for the installation and testing of such a unit at Piqua. The yield, or product recovery, for this process is defined as the ratio of the useful coolant recovered to the high boiler converted. The estimated organic makeup cost is based on a product recovery of 90% and a cost for new coolant of 12 cents per pound, * delivered to the site. For the methods and specific decomposition rate data used in calculating the organic coolant makeup, refer to Volume II, Section III. A. 4. The net decomposition rate estimated in Table III-13 is 150 pounds per hour at full power using the hydrocracker.

The heavy water net loss is estimated to be 10 pounds per day as discussed in Volume II, Section IV. A. 3.

3. Nuclear Liability Insurance

Nuclear insurance is based on \$60,000,000 per year and federal indemnity at \$30 per thermal megawatt per year up to a total coverage of \$500,000,000. The total estimated annual premium and fee for financial protection, therefore, is \$353,000 or 0.047 mills/kwh.

* Letter of August 13, 1965; Monsanto Co. to Atomics International; Estimate of Santowax OM prices in large quantity.

C. ENERGY GENERATION COST

The energy generation costs are summarized in Table I-1. These costs are based on an 80% annual plant factor and a net electrical generating capacity of 1076 Mwe. The bases for the various cost components are discussed in the preceding sections with the exception of the cost for "Other Working Capital." The latter include the working capital requirements for operating the plant outside of those related to reactor fuel. These other working capital requirements are estimated at 3% of the annual operating and maintenance expense excluding fuel, plus 25% of the annual cost of maintenance and materials supplies. This cost, viz., \$287,000 of working capital, is absorbed in the totals shown in Table I-1. The cost of Land and Land Rights is an arbitrary allowance in accordance with costing ground rules suggested by the AEC in TID-7025.

The effect of variations in the plant factor on the energy generation cost is shown graphically in Figure III-1. The reduction in cost of energy with increased plant factor is of special significance to the HWOCR. With on-power refueling capability and low incremental operating costs, as compared to alternate energy sources except for hydroelectric plants, it would compete successfully for the load and tend to operate at a higher plant factor than most units.

The importance of on-line refueling is borne out by the detailed study performed in the U. K. in comparing the AGR with the BWR. The British concluded that the BWR, primarily because it has to be shut down for refueling, will be available about 20 days less per year than the AGR with on-line refueling.

Even though a power plant features high availability, it may still have a low plant factor if its incremental power generation cost is high relative to other units on a grid. Since the HWOCR offers unusually low fuel cycle costs, its incremental generation costs are quite low as can be seen in Table I-1. Hence, it is plausible to expect that the HWOCR will, in fact, enjoy a higher plant factor, limited only by its availability. An increase from 80% to 90%, which should be attainable by the HWOCR would reduce the total energy generation cost seven to eight percent.

FIG III-1. Energy Generation Cost vs Plant Factor

IV. FUEL UTILIZATION

The general term, fuel utilization, is applied to nuclear reactors or nuclear power plants to designate their effectiveness in minimizing the drain on the natural resource of fissile isotope while supplying some specified demand for nuclear energy. The Heavy Water Organic Cooled Reactor Project has been initiated, with one of its principal objectives being the improvement of fuel utilization over that afforded by current types of conventional reactors. A quantitative method of specifying fuel utilization is needed not only to measure the progress made toward a given objective, but also to serve as a means of evaluating the alternative reactor concepts being developed under the National Civilian Reactor Program. The purpose of this section is to define such a method, and to reduce it to a figure of merit which can be applied to different reactor designs without ambiguity. The HWOCR design described in this report is compared here with a reference LWR, using this new figure of merit for fuel utilization.

Because of the critical mass requirement, typical power reactors contain, at all times, an inventory of fissile isotope which is several times greater than the amount of fissile isotope actually destroyed by the reactor in a year of power operation. If the demand for nuclear reactors is increasing with time, the fissile isotope required for inventory in the additional reactors built must be supplied from the natural resource, just as surely as must the net fissile isotope consumed in nuclear reaction. To characterize the fuel utilization of a particular reactor faithfully, one must take into account not only the fissile isotope destroyed by nuclear reaction, generally referred to as burnup but that tied up in inventory as well. This presents a problem, for the ratio of the inventory requirement to the burnup depends upon the rate of growth of the installed nuclear capacity--that is, upon the rate of growth of the nuclear power industry.

The difficulty is to arrive at a scheme for weighting the two types of fuel requirements--burnup and inventory--in an equitable manner. This is a most important consideration, since past deficiencies in characterizing fuel utilization have resulted from failure to recognize the importance of the inventory requirement.

It is well known that, for many years past, the exponential has been the simplest mathematical function by which the growth of the electric utility industry can be described. It is true that the doubling time has not remained precisely constant, and it is also true that ridiculous conclusions can be reached by the thoughtless extrapolation of an exponential; but it seems entirely legitimate to utilize the simplifying properties of the exponential in order to arrive at a figure of merit for fuel utilization in a rapidly expanding nuclear power industry. This is the course proposed here. It is important to recognize that the intent is only to generate a figure of merit in terms of the exponential function, and that this is not equivalent to predicting that the growth of the industry will in fact proceed along an exponential with a constant doubling time.

Two terms must first be defined. Assuming the nuclear power industry is growing at an exponential rate characterized by a doubling time, T_d , the defined quantities are:

- 1) The Exponential Investment (E.I.) of natural uranium is the ratio of the number of tons of natural uranium as U_3O_8 which have been fed into the industry up to any time, t , for both burnup and inventory, to the number of megawatt years of electric energy produced up to the time, t . Obviously, the value of the E.I. will depend upon the doubling time, and it will be necessary to select an appropriate doubling time in order to arrive at a value of the E.I. which has a meaningful relationship to the fuel supply problem.

2) The Dynamic Utilization (D. U.) of natural uranium is the reciprocal of the E. I. It is the D. U. which is proposed as the figure of merit, evaluated for a suitably selected doubling time.

The remainder of this discussion will develop the two quantities defined above in terms of more familiar numbers, and will relate them to some other quantities of importance.

Let:

$C = C_0 e^{0.693 t/T_d}$ = Installed capacity at time t , in electric megawatts.

S = Specific inventory including ex-core requirements = tons of U_3O_8 required to provide the U-235 for 1 Mwe of installed reactor capacity.

F = Plant factor.

B = Specific make-up for burnup, in equivalent tons of U_3O_8 per megawatt-year of electrical energy produced.

W = Total electric energy produced from $t = 0$ to $t = T$.

N = Total natural uranium, as tons of U_3O_8 , put into the system for burn-up plus inventory, from $t = 0$ to $t = T$.

Then:

$$W = \int_0^T F C_0 e^{0.693 t/T_d} dt = \frac{F C_0 T_d}{0.693} (e^{0.693 T/T_d} - 1) \quad (1)$$

$$N = BW + SC = \frac{B F C_0 T_d}{0.693} (e^{0.693 T/T_d} - 1) + S C_0 e^{0.693 T/T_d} \quad (2)$$

Assume $e^{0.693 t/T_d} \gg 1$, so

$$E. I. = \frac{N}{W} = \frac{\left[\frac{B F C_0 T_d}{0.693} + S C_0 \right] e^{0.693 T/T_d}}{\frac{F C_0 T_d}{0.693} e^{0.693 t/T_d}} = B + \frac{0.693 S}{F T_d} \quad (3)$$

The applications of the E.I. and D.U. are shown in Table IV-1 for the HWOOCR compared with the reference light water reactor system from ORNL-3686. The value of T_d used for this evaluation is 7 years. This value is selected as being appropriate based on AEC projections of the nuclear power industry for the next several decades as shown in Figure IV-1. Most projections fall within a T_d range of 5 to 10 years before the year 2000.

It is evident from Table IV-1 that, in terms of the dynamic utilization, the HWOOCR is much more effective in utilizing nuclear resources than the light water reactor. This advantage for the HWOOCR stems partly from the lower make-up requirement and, more importantly, from the very low fissile fuel inventory requirement. Consequently, a growing nuclear power economy based primarily upon HWOOCR advanced-converters would substantially increase the energy obtainable from available uranium ore reserves. Furthermore, any increase in the price of uranium has less influence on the energy generation cost of the HWOOCR since its higher fuel utilization makes the fuel costs a smaller fraction of the total.

TABLE IV-1
COMPARISON OF DYNAMIC FUEL UTILIZATION

	<u>LWR</u>	<u>HWO CR</u>
<u>Basic Data</u>		
Thermal Efficiency (%)	31.1	34.8
Average Specific Power (kw/kgU)	31.2	25
Discharge Burnup (Mwd/kgU)	21	15
Feed Enrichment (wt. % U-235)	2.20	1.16
Discharge Enrichment (wt. % U-235)	0.63	0.21
Discharge Fissile Pu (gms/initial kgU)	3.8	3.2
<u>Utilization Factors</u>		
*Specific Inventory (tons U ₃ O ₈ /Mwe)	0.57	0.24
Specific Burnup (tons U ₃ O ₈ /Mwe-yr)	0.19	0.12
**Exponential Investment (tons U ₃ O ₈ /Mwe-yr)	0.261	0.156
**Dynamic Fuel Utilization (Mwe-yr/ton U ₃ O ₈)	3.8	6.5

* Based on average fissile enrichment and a 1 year ex-core residence time.

** Assumes the nuclear economy doubles in 7 years and Plant Factor = 0.8.

FIG IV-1. Forecast of Nuclear Capacity Growth in the U.S.A.

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

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

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>Hot</u>	<u>Cold</u>
a.	D ₂ O/UC (volume ratio) [†]	15.2
b.	Organic/UC (volume ratio) [†]	1.11
c.	D/U*, New Fuel (atom ratio)	30.3
d.	Organic Volume Fraction	0.446
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.

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.

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 Rage	
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

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

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.	<u>Evaporator</u>	
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

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

i.	Organic Flow (lb/hr)	10.3×10^6
j.	Organic Pressure Drop (psi)	18
k.	Organic Inlet Temperature ($^{\circ}\text{F}$)	750
l.	Organic Outlet Temperature ($^{\circ}\text{F}$)	672.5
m.	Steam Side Design Conditions (psig/ $^{\circ}\text{F}$)	300/750
n.	Organic Side Design Conditions (psig/ $^{\circ}\text{F}$)	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 ($^{\circ}\text{F}$)	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/ $^{\circ}\text{F}$)	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