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**HEAVY WATER MODERATED REACTOR
DESIGN STUDIES
STATE-OF-THE-ART SURVEY**

OCTOBER 1968

**AEC RESEARCH &
DEVELOPMENT REPORT**

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HEAVY WATER MODERATED REACTOR
DESIGN STUDIES
STATE-OF-THE-ART SURVEY

By

K. R. Wise and W. W. Waddel

Systems Engineering Department
Physics and Engineering Division

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K. R. Wise and W. W. Wadde1

PREFACE

This report was prepared for the U.S. Heavy Water Reactor Base Program. Its purpose is to review the status of technology in the subject area, and to identify required research and development for heavy water reactors and related systems.

HEAVY WATER MODERATED REACTOR
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ABSTRACT

As part of the Heavy Water Reactor Program Office effort to define the "state-of-the-art" in heavy water moderated reactors a survey of reactor designs and design studies was undertaken. This survey includes:

1. A list and description of the heavy water moderated power reactors either operating or under construction
2. A list and description of the more recent design studies done on heavy water moderated reactors, with the exception of reactors using organic coolant
3. A discussion of the various reactor types, as determined by type of coolant, indicating development trends
4. A discussion of various design features or characteristics that many heavy water reactors have in common, such as pressure tubes, on-line refueling, and D_2O loss rates.

TABLE OF CONTENTS

PREFACE	iii
ABSTRACT	v
INTRODUCTION	1
Major Reactors Types	4
PRESSURIZED HEAVY WATER REACTORS	4
PHWR Experience at Agesta	6
PHWR Experience at NPD-2	7
The Pickering Nuclear Generating Station	8
Canadian General Electric - Heavy Water Reactor	9
Advanced Converter Evaluation	10
BOILING LIGHT WATER COOLED REACTORS	11
CANDU-BLW-250	13
SGHWR	14
Dual Purpose	14
Advanced Converter Task Force 1000 MW _e Design Study	15
OTHER COOLANTS	17
Boiling Heavy Water Cooled Reactors	17
Fog Cooled Reactors	18
Liquid Light Water Cooled Reactors	18
Gas Cooled Reactors	19
ASSOCIATED CONCEPTS AND TECHNOLOGY	20
Pressure Containment	20
Heavy Water Management	22
Fuel and Fuel Management	23
Thorium Fuel Cycles	26
Dual Purpose Applications	26
Spectral Shift	27
CONCLUSIONS	28
REFERENCES	29
APPENDIX A - REACTORS	A-1
APPENDIX B - DESIGN STUDIES	B-1
DISTRIBUTION	Distr-1

HEAVY WATER MODERATED REACTOR
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INTRODUCTION

This state-of-the-art report on heavy water moderated reactor design is a survey of the major features of existing reactors. The reactors included in the report are listed in Table I. Design studies, possibly better indicators of present day or near future technology, have also been surveyed. The design studies examined are listed in Table II. Most of the design studies are of U.S. or Canadian origin; European design studies were not readily available. The design studies included were selected as the more recent efforts. When one design study appeared to take the place of a previous one, the older one was left out unless it included considerations not surveyed in the more recent study. More detailed data on the characteristics of each particular reactor and an outline of each design study can be found in the Appendices.

The purpose of this survey is to provide the reader with a general background of heavy water moderated reactors and the associated technology.⁽¹⁾ This report is organized in such a way that the major reactor types, as determined by coolant, are examined individually. The discussions attempt to point out the present status and development trends for the reactor type.

A few reactors are discussed to some length when the discussion points out trends resulting from operating experience. These discussions also reflect the present day development level from which design studies to indicate future potential are extrapolated. Design features such as pressure

TABLE I. *Reactors Examined^(a)*

Agesta	Kanupp
AKB	Lucens
CANDU-BLW	Marviken
Cirene	MZFR
CVTR	NPD-2
Czech	Pickering
Douglas Point	PRTR
EL-4	Rapp
Essor	SGHWR
Halden	Sulzer
HWCTR	Vulcain
Kalpakkem	Yugozlav

(a) See Appendix A for details of each reactor

TABLE II. *Design Studies Examined^(a)*

	<u>Document No.</u>
An ORNL Evaluation of an AECL Proposed 1000 MW _e HWBLW	(draft)
A Comparative Evaluation of Advanced Converters	ORNL-3636
Heavy Water Moderated Power Reactors Cooled by Liquid D ₂ O or H ₂ O	DPW-64-135
An Evaluation of Heavy Water Moderated Power Reactors	DP-830
Heavy Water Moderated Power Reactors Engineering and Economic Evaluations	
Volume I Summary	DP-510
Volume II Engineering Studies and Technical Data	DP-520
Conceptual Design of 500 MW _e Natural Uranium Boiling Light Water Reactor	APPE-26
Power Reactor Development Evaluation	AECL-1730
Thorium-Fueled D ₂ O Moderated Power Reactors	DP-864

TABLE II. (contd)

	<u>Document No.</u>
Carolinas Virginia Tube Reactor Large Plant Study	CVNA-184
Saline Water Conversion Power Reactor Plants	SL-1998
Heavy Water Reactors for Sea Water Distillation Plants	DP-866
Canadian General Electric Design Simplifications in the HWR	
Prospective D ₂ O Moderated Power Reactors	A/Conf. 28/P/10
A Large Swedish Nuclear Power Station	A/Conf. 28/P/605

(a) See Appendix B for an outline of each design study

tubes that are common among a number of the reactors are discussed in the section on Associated Concepts and Technology. Concepts such as thorium fuel cycles and dual purpose applications are also included in that section.

The most important characteristic of a HWR that makes it a candidate for power production is its high neutron economy. Since relatively few neutrons are captured by the moderator, efficient use is made of the fuel. One consequence of this efficiency is that a HWR plant can produce more power per ton of uranium mined than can the present light water reactor stations. Hence, the total power cost for a HWR is less dependent on the price of U₃O₈ than is the light water reactor power cost. Another consequence of the high neutron economy is that natural uranium may be used as fuel.

One of the disadvantages of the HWR's is the high capital investment required. Where interest rates are lower, the HWR is more competitive with light water reactors. Because of the widely varying economic conditions and industrial capabilities in the various countries examining heavy water reactors, and

the many different economic ground rules used in the design studies, direct comparison of capital cost or unit energy cost is difficult. Hence, in this report no attempt has been made to compare actual investment or unit energy costs among the various reactors or design studies.

MAJOR REACTOR TYPES

The type of coolant used in the reactor is a characteristic which can be used effectively to divide the heavy water moderated reactors for discussion. As well as the two major categories receiving the most attention presently, i.e., pressurized heavy water cooled and boiling light water cooled reactors, there are a number of other types that have been built or considered. Studies or designs using boiling heavy water, fog cooling liquid H_2O , and gas cooling were also examined in this survey.

The major U.S. effort in the immediate past was directed at heavy water moderated reactors using organic coolants. Heavy water moderated reactors utilizing coolants other than organic have received virtually no attention during the past five years. Organic coolants were excluded from this survey due to the required coolant technology development.

PRESSURIZED HEAVY WATER REACTORS

Over half of the heavy water moderated reactors in operation or under construction today are cooled by pressurized D_2O . Considerably more operating experience has been logged with PHWR's than with any other type of D_2O moderated reactor. Experience with PHWR's prototypical of large power plants began in the late 1950's. Five power prototypes were commissioned by 1963. Seven full scale power PHWR's are now under construction.

Power Prototypes

	<u>Date Critical</u>	<u>Power Level</u>
PRTR	1960	70 MW _t
NPD-2	1962	20 MW _e
HWCTR	1962	60 MW _t
CVTR	1963	17 MW _e
Agesta	1963	65 MW _t

Power Pressurized Heavy Water Cooled
and Moderated Reactors

	<u>Scheduled Date Critical</u>	<u>Power Level</u>
Douglas Point	1967	200 MW _e
Kanupp	1968	125 MW _e
Rapp	1969	200 MW _e
Kalpakkem	1971	200 MW _e
Pickering		
No. 1	1970	505 MW _e
No. 2	1971	505 MW _e
No. 3	1972	505 MW _e

The early heavy water moderated reactors utilized pressurized D₂O as a coolant because economical power costs with a minimum of development were forecast. Design studies have been conducted^(2,3,4) comparing various reactor designs and coolants in terms of unit energy cost and the research and development required to put the reactor on-line. A direct comparison of these studies is difficult because of the different economic ground rules and technical assumptions made. However, in most of the studies liquid D₂O coolant showed power costs comparable with other coolants, and considerably less development was necessary to put the reactor on-line. In one study by du Pont⁽¹⁾ the power costs for the various coolants were:

<u>Coolant</u>	<u>Total Energy Cost Mills/kW-hr</u>
liquid D ₂ O	5.79
boiling D ₂ O	5.85
organic	5.02
H ₂ O fog	5.65

In the recommendations made to the USAEC in this report (1963) it was stated that both liquid D₂O and organic coolants should be considered for further development but that the liquid D₂O design was "... the only coolant concept on which a firm design start could be made...."

Two major designs of PHWR's have been developed, the pressure vessel and the pressure tube types. Two pressure vessel PHWR's have been constructed. The Agesta reactor in Sweden, designed for power production and district heating, went critical in 1963 and has since demonstrated the technical feasibility of this type of plant. The other pressure vessel reactor, MZFR, in Germany is both a power prototype and research reactor. The pressure tube concept for PHWR's has been developed in the United States with the CVTR and PRTR and in Canada with the CANDU (Canadian-Duterium-Uranium) since 1962. Four large power CANDU reactors are presently under construction at Pickering and three others are being built for foreign customers. The Canadian General Electric Company has just proposed a number of design simplifications for the CANDU to reduce capital investment and improve their competitive position in the world reactor market.

PHWR EXPERIENCE AT AGESTA

There are numerous different coolant path choices available to the designer of a pressure vessel reactor. The primary flow path in the Agesta reactor is upward through the fuel channels and then down through the moderator space. It was realized at

the time of the design that other coolant paths would require less D_2O because of cooler moderator. However, this design was chosen because of its simplicity, good self-regulating properties, and a minimum number of development problems.⁽⁵⁾

The reactor station was basically designed as a prototype for power production and district heating, but it has been used for testing of experimental fuel elements and development of core physics analysis schemes. The reactor is scheduled to operate only nine months each year, from September to June. During the summer months when the district heating requirements are low the reactor is shut down for refueling, maintenance, and critical experiments. Because of this three month downtime each year the plant availability factors have only a limited application to a large plant which could not afford to have up to three months available for maintenance. However, if one does not include the summer shutdown or the downtime for experiments during the year, the availability for the 1965/66 season was 92% and for the 1966/67 season was 97.5%.⁽⁶⁾

The Agesta reactor has claimed low D_2O losses.⁽⁶⁾ During the four years of operation only 620 kg of D_2O have been lost. Of this figure, 320 kg were lost in a short period of time as a result of leakage in the inspection pipes which penetrate the vessel head. It is estimated that the normal leakage rate for D_2O while the reactor is operating at power is about 3 to 5 g/hr (0.04%/yr).

Burnups in the Agesta core have been calculated continuously with three computer codes, REBUS, HETERO, and BURN-UP-5. These codes have been continuously revised as new experimental data become available. At the present time the codes can predict burnup within 2 to 3%.

PHWR EXPERIENCE AT NPD-2

Two different types of runs have been conducted at NPD-2, demonstration runs and improvement/test runs. The prime

objective during a demonstration run is to operate with a high capacity factor. During these runs the plant is shut down only for necessary maintenance. The average net capacity factor for these demonstration runs is about 84%; and during two recent runs, of three months duration each, net capacity factors of 97% and 98% were obtained.⁽⁷⁾ These high capacity factors have only limited application to power reactors because of the short duration of the demonstration runs.

In the last two years the NPD containment system was converted to a "dry room" system (see Heavy Water Management Section). The recovery efficiency for D_2O was improved from 67.8% in 1963 to 89.8% in 1966 by the use of this method. With this high recovery efficiency, D_2O loss rates of 210 g/hr (2%/yr) are claimed.⁽⁷⁾

Other concepts have been tested in the NPD reactor. Experiments on the use of zirconium alloys for pressure tubes and for cladding material has demonstrated the ability of these materials to withstand the pressure, temperature, and radiation in the reactor. Early problems with on-line refueling were overcome and over 1000 fuel bundles have now been replaced with the reactor at full power.

Many of the characteristics of NPD-2 can be seen in the recent Canadian designs. The Canadians use these design features not necessarily because they are inherently the best but because they have had experience with them.

THE PICKERING NUCLEAR GENERATING STATION

A design study of large CANDU type reactors was made in 1963.⁽⁴⁾ The design was updated in 1964,⁽⁸⁾ and the Pickering reactors are virtually unchanged from this later design. The reactor, except for the 500 MW_e power rating, is very similar to both NPD and Douglas Point, a horizontal pressure tube reactor with bi-directional on-line refueling.

A 500 MW_e unit was chosen for the Pickering Station because this was the largest unit the power utility could accept in 1970. Three more identical units are to go on-line each succeeding year and provision has been made to add four additional units at a later date. Use of this multiunit station concept is expected to effect a considerable reduction in cost since many construction, maintenance, and operating functions can be combined.

One of the major factors in reducing the cost per reactor in this multiunit station is the use of a common containment envelope. Four of the units are connected together and a negative pressure is maintained in the whole system. If a major accident in one reactor should render the containment system incapable of containing another accident, the remaining reactors would be shut down. However, it is believed that the probability of a major accident occurring is small enough that the economic risk involved is acceptable.⁽⁹⁾

CANADIAN GENERAL ELECTRIC - HEAVY WATER REACTOR

Although not presented in a design study as such, several design simplifications have been proposed by CGE^(10,11,12) to reduce the capital investment in a HWR without sacrificing reliability or spending considerable development time and money.

Two major changes proposed are to use a vertical core and to load fuel on-line with one simplified refueling machine at the bottom of the reactor. These changes cause the pressure tubes to need a closure at one end only, with a resulting savings, and it also becomes possible to assemble the tubes at the factory, eliminating expensive on-site assembly. Provisions are also made to remove the refueling machine from the reactor vault for on-power maintenance. To save space, the moderator dump tank is made integral with the calandria. It has been

found that the reactor can be scrammed by dumping only half of the moderator; hence the dump tank has been made smaller. Also the thermal shields are simplified by using light water radially around the core and alternating layers of steel and light water on the ends. This entire shield utilizes the same coolant circuit.

Another change is to use a small number of large vertical steam generators with integral steam drums. All equipment which does not have to be in the containment building is moved out. These changes, along with the elimination of the sweep volume of a second refueling machine, lead to a 50% reduction in the volume of the containment building. The reactor building layout is planned to minimize the shielding requirements by grouping all accessible areas together and all inaccessible areas together.

ADVANCED CONVERTER EVALUATION

A 1965 evaluation of advanced converter reactors⁽¹³⁾ included two pressurized heavy water reactors (1000 MW_e). This evaluation is the most recent examination of a pressurized HWR available. The designs are basically those developed by du Pont,⁽¹⁴⁾ one using enriched uranium oxide fuel and the other using thorium-uranium oxide fuel. The designs both use a three concentric ring fuel element. The feasibility of this fuel element is the major technical extrapolation involved in the designs. An important difference between the du Pont design and the ORNL design is the throttle steam conditions and the resulting thermal efficiency. The du Pont design with 507 °F, 650 psi steam had a net efficiency of 28.9% while in the ORNL evaluation the steam generator design was changed, with resulting steam conditions of 466 °F, 480 psi, and an efficiency of 26.8%. In the ORNL evaluation all of the reactors evaluated were designed for a common 42 °F pinch point steam generator

temperature difference. The PWR design, since it uses steam reheat, still had a 31.1% efficiency with this pinch point temperature difference, but the HWR seems to have been penalized in comparison. The Canadian GE design discussed above has a net efficiency of 28.8% with 434 psi saturated steam, and a pinch point temperature difference of about 9 °F is suggested as an optimum.⁽¹⁵⁾

The ORNL evaluation had some cost information of interest:

- Fuel cycle costs in the range of 1.0 to 1.2 mills/kW-hr for the UO₂ design
- Fuel cycle costs of 1.2 to 1.4 mills/kW-hr for the ThO₂-UO₂ design
- Adjusted capital costs (millions of dollars)

PWR	133.0
HWR - Th	135.4
HWR - U	124.7
HTGR	117.9

The du Pont design had total capital costs of 151.1 and 162.1 (millions of dollars) for the uranium and thorium designs respectively.

BOILING LIGHT WATER COOLED REACTORS

Boiling light water cooled heavy water moderated reactors have some inherent advantages.

- Reduced heavy water losses should be possible since heavy water is not circulated as the coolant.
- Direct cycle operation is possible.
- Heavy water inventory requirements are reduced.

The U.S. studies of boiling light water cooled heavy water moderated reactors have been made through participation in joint AECL-U.S. programs.

Since 1962 the Canadians have been evaluating various alternatives for development based on their CANDU type reactors.

One area considered has involved changing the coolant conditions or the coolant. Evaluations were made of liquid D_2O , boiling D_2O , boiling H_2O , and organic coolants in 1964.⁽³⁾ The ground rules for this economic evaluation varied from the ORNL ground rules because of the different economic environment in Canada. The reactor designs considered were for 450 MW_e reactors. Boiling light water cooled designs appeared economically attractive in this Canadian study and in studies conducted in the U.S. A du Pont study of H_2O fog-cooled reactors indicated slight power cost advantages when compared to D_2O cooled systems.⁽²⁾

A Canadian conceptual design of a 500 MW_e natural uranium boiling light water reactor was completed in 1964.⁽¹⁶⁾ The design study included the evaluation of both tube-in-shell and fuel pin geometries. The tube-in-shell geometry is of interest for this coolant choice because of the high fuel-to-coolant ratio within the pressure tube.

This design study included an extensive sensitivity analysis. As well as considering the different fuel geometries, figures indicating the effect of a number of variables on power cost were included. Even though the economic ground rules used varied from the present ORNL ground rules, the way costs are affected by the various parameters is of interest. The variables and their effect on power costs follow.

Tube and shell thicknesses for the tube-in-shell design. An increase in shell thickness from 40 to 60 mills raises the power cost 0.015 mills/kW-hr.

Pressure tube design stress. Increasing the pressure tube design stress from 22,000 to 30,000 psi yields a cost savings of nearly 0.03 mills/kW-hr.

Maximum channel rating. Power cost can be reduced by 0.03 mills/kW-hr if the maximum channel rating can be raised from 12 to 14 kW/cm.

Lattice pitch. Decreasing the 10.75 in. lattice pitch to 10 in. raises the power cost 0.025 mills/kW-hr. Increasing the lattice pitch to 11.5 in. raises the power cost 0.01 mills/kW-hr.

Pressure tube diameter. Decreasing the pressure tube diameter from 4.09 in. to 3.75 in. raises the power cost nearly 0.03 mills/kW-hr. Increasing the pressure tube diameter to 4.5 in. also raises the power cost about 0.03 mills/kW-hr.

Outlet quality. A decrease in outlet quality from 60 to 45% raises the power cost by 0.03 mills/kW-hr. An increase in outlet quality to 75% decreases the power cost 0.02 mills/kW-hr.

Plant size. An increase in plant size from 500 to 750 MW_e decreases the power cost from 3.35 to 2.85 mills/kW-hr. The shape of the curve indicates that a further increase in size would not decrease the power cost as significantly as did this increment.

A reference outlet quality of 60% was used for this design study. Outlet qualities as high as 90% were suggested as being possible with heat transfer fluid flow development work.

CANDU-BLW-250

The AECL has started construction of a prototype 250 MW_e plant, the CANDU-BLW-250.⁽¹⁷⁾ This plant will operate with a direct cycle, using one of the potential advantages of a boiling light water system. The present reference design specifies an outlet steam quality of 16.5%. The reactor is oriented vertically to permit developing the design to high outlet steam qualities. The fuel geometry to be used, based on previous experience, will be rod bundles.

On-power refueling is to be done from the lower end of the reactor by a single refueling machine. The lower end was chosen

because single phase flow exists at the inlet (lower end) and because the large refueling fittings are less constraining at the single-phase-flow end of the reactor. The fuel is to be changed a complete channel at a time.

SGHWR

The 100 MW_e SGHWR (Steam Generating Heavy Water Reactor) has recently gone on line in England. Many of the uncertainties in the design of heavy water moderated boiling light water reactors will be defined by the operation of this prototype reactor. Outlet steam quality for this pressure tube reactor is 11.2%. This reactor design is different from most heavy water designs in that the fuel is slightly (1.8 to 2.2%) enriched uranium.^(18,19) The resulting burnup is 18,000 MWd/ton.

SGHWR fuel channel length was selected to permit scale-up to larger plants with little uncertainty. The reactor includes fuel channels with separate cooling circuits to permit fuel testing. A superheat region is included to learn more of the potential in that direction. The SGHWR is unique in that the moderator to fuel ratio has been made variable by locating tubes within the lattice in which the amount of D₂O moderator in the core can be varied. This feature should provide information for future BLW cooled heavy water reactors.

DUAL PURPOSE

Another design study, included here since boiling light water is used as a coolant, involved a dual purpose application (power and desalination).⁽²⁰⁾ The design study was for a three reactor 25,000 MW_t station and a 3500 MW_t prototype station. Pertinent features in this 1963 design study were:

- Outlet quality 12.5%
- Natural uranium fuel
- Vertical pressure tubes
- On-line refueling.

Note that the system was again limited to the natural uranium on-line refueling approach, rather than enrichment and shutdown fuel moving and replacing.

ADVANCED CONVERTER TASK FORCE 1000 MW_e DESIGN STUDY

The most current boiling light water design is the 1000 MW_e design study done for the advanced converter task force.⁽²¹⁾ This study eliminates many of the uncertainties that would be encountered in examining the other studies.

- This study is for a 1000 MW_e plant, therefore not requiring an extrapolation to this reference size.
- The study is quite recent, reflecting the up-to-date thinking of the designing organization.
- The study was evaluated using ORNL economic ground rules rather than Canadian ground rules.

The capital cost presented for this design was 142 \$/kW_e. Total power costs and the various components are summarized below:

Fuel cycle	0.682
D ₂ O inventory	0.288
Operating	0.336
Capital	<u>2.430</u>

Total 3.74 mills/kW-hr

This 1000 MW_e study does reflect some degree of extrapolation, particularly in the heat transfer-fluid flow portion of the design. The areas where work is needed are discussed in the study and the problem generally is that available test facilities are too small to simulate the full size fuel channel. The effects of length, mixing devices, and high flow rate-high quality combinations are uncertain. Some of these uncertainties will be answered by CANDU-BLW-250 but some, such as fuel element length and high flow rate-high quality steam conditions, will require additional development efforts.

Outlet steam quality is a variable that through development will permit improved reactor performance. Although the 1000 MW_e conceptual design specifies a 30% steam quality, the CANDU-BLW-250 value of 16.5% reflects the present day quality to which one is limited to insure against dryout.

Other areas requiring research and development efforts are:

1. Core neutronics
2. Reactor safety
3. Fuel element and pressure tube integrity
4. Reactor stability and control.

The questions in the areas of neutronics, safety, and stability, and control will be answered in part through the operation of the SGHWR and the CANDU-BLW-250. Reactivity coefficient uncertainties need data from these reactors. Size effects will require additional experimental work.

In the 1000 MW_e design, fretting corrosion caused by vibration, creep, and irradiation appears to be another area of concern. The long fuel channels make the problem more severe and also more difficult to study.

The core is separated into two circuits to lessen the effect of a loss of coolant accident. Control of this 1000 MW_e design is to be done with rods, rather than by the use of moderator dump as in the CANDU-BLW-250, to reduce heavy water inventory. Soluble poison would be used to supplement and back up the control rods.

This Canadian 1000 MW_e BLW design study is confined to natural uranium fuel and on-line refueling. The task force evaluation stated that fuel enrichment raised fuel cycle cost, but a complete optimization of the system design for enriched fuel was not performed.

U.S. safety requirements could require slightly tighter lattices than those used in Canadian designs to make the coolant void coefficient negative. The Canadian 500 MW_e design study⁽¹⁶⁾ indicates the cost penalty, due to reduced burnup for the natural uranium system, to be on the order of 0.02 mills/kW-hr. The large dual purpose plant design study⁽²⁰⁾ done by ORNL in 1963 indicates a similarly small effect on fuel burnup in changing the lattice pitch to obtain a negative coolant coefficient. The requirements associated with voiding coefficients seem to have a relatively small economic penalty for the boiling water cooled systems. The sensitivity of power cost to lattice spacing may also be changed slightly for an enriched uranium reactor.

OTHER COOLANTS

Several other options for cooling heavy water moderated reactors have been examined in various design studies, and reactors have been built using coolants other than liquid D₂O or boiling H₂O.

BOILING HEAVY WATER COOLED REACTORS

One boiling heavy water cooled reactor, Halden, has been operating since 1959. A second, Marviken, is scheduled for completion in the spring of 1969. Two U.S. design studies have been made which consider boiling heavy water cooling.

The advantages of boiling heavy water cooling are neutron economy as found with the pressurized heavy water, plus a simplified system using direct cycle operation. Disadvantages come from potential heavy water losses, particularly if direct cycle operation is used. Heavy water losses are discussed in more detail in the section on Associated Concepts and Technology.

In a design study done by du Pont in 1960, boiling D₂O and liquid D₂O cooling for 100 to 400 MW_e plants was considered

and lower power costs for the boiling system were found.⁽²²⁾ The second study, also done by du Pont, was completed in 1963⁽²⁾ and updated the first study. The 1963 study for 500 MW_e plants included both organic coolant and fog light water coolant, both of which had lower power costs than did the boiling heavy water cooled reactor. In this study slightly lower power costs were also found for the liquid D₂O cooled reactor than for the boiling D₂O cooled reactor, due primarily to increased D₂O inventory. The D₂O loss rate was assumed to be 2% in this study so the increased inventory of the boiling D₂O system increased loss costs.

The Halden reactor, a boiling heavy water cooled reactor, has operated since 1959. It delivers steam at 356 °F psi to an adjacent pulp mill. Its operation has been fairly successful with programs to study fuel, heavy water handling, control, and water chemistry.⁽²³⁾ During the entire operation of the second core, 2400 kg of D₂O were lost in a total of about 570 days, about half of this time was at power, for a loss rate of about 4 kg/day overall (9%/yr).

FOG COOLED REACTORS

One portion of a 1963 design study done by du Pont concerned fog cooling with light water.⁽²⁾ This concept is actually an advanced boiling light water system in which the light water inventory in the core is reduced by using low quality steam as the inlet coolant. The lower light water inventory in the core of the fog cooled system would improve the neutron economy over the boiling light water cooled reactor. In this study a 6.49 versus 6.82 mill/kW-hr cost advantage was found for the 500 MW_e H₂O fog cooled system when compared to the pressurized HWR.

LIQUID LIGHT WATER COOLED REACTORS

Two du Pont studies, 1963 and 1964,^(2,14) included reactor designs cooled with pressurized light water. The designs are

based on the D_2O cooled designs, but the volume fraction of fuel in the pressure tube is increased to remove light water from the core. The first of the design studies suggested a slight cost penalty when compared to the D_2O cooled system. The second study pointed out that the costs are nearly the same for the D_2O cooled and H_2O cooled systems if the D_2O losses are held to 2 to 3%. If the D_2O losses should exceed this level the H_2O cooled reactor would exhibit an advantage.

Although these studies did not include a boiling light water cooled reactor the first did include the fog cooled reactor discussed above. The fog cooled system was reported to have a lower power cost than both the D_2O and H_2O cooled systems.

GAS COOLED REACTORS

There is European interest in gas cooled heavy water moderated reactors. Four gas cooled heavy water moderated reactors are in operation or being constructed. The four reactors are listed below:

<u>Reactor</u>	<u>Country</u>	<u>On Power Date</u>	<u>Power MW_e</u>
EL-4	France	1967	73
Lucens	Switzerland	1967	7
Bohunice	Czechoslovakia	1968	110
KKN	Germany	1971	100

One U.S. design study⁽²²⁾ in which a gas coolant was considered was completed in 1960 and the costs were found to be comparable with D_2O cooling at the 100 MW_e size. There was no examination of the gas cooled case for larger size since the D_2O cooled reactor has decreasing cost as plant size increases, while the gas cooled reactor was felt to scale up with more difficulty and not to benefit as much by the size increases.

ASSOCIATED CONCEPTS AND TECHNOLOGY

There are features common to the various heavy water moderated reactors that can be discussed best in separate sections. Such features included here are:

- Pressure containment
- Heavy water management
- Fuel and fuel management
- Thorium fuel cycle
- Dual purpose application
- Spectral shift.

PRESSURE CONTAINMENT

For a number of reasons pressure tube HWR's have received more attention than those using a pressure vessel. During the initial development of HWR's it was recognized that coolants other than D_2O might be desirable and that large reactors would be needed to compete with fossil-fired plants. Since the tube design is adaptable to coolants different from the moderator and since very large pressure vessels are difficult and expensive to construct, most research and development has been directed toward the use of pressure tube HWR's.

The earliest pressure tube reactors utilized an aluminum calandria (e.g., NPD-2 and PRTR). Since these reactors were constructed, a great deal of progress has been made in working with zirconium alloys, and various methods of joining zirconium and stainless steel have been developed. The calandria under construction at the present time (e.g., Pickering) consists of a stainless steel shell with zirconium alloy (Zircaloy-2) tubes.

Pressure tubes have been made of Zircaloy-2 for a number of years. However, a Zr-2.5 wt% Nb alloy is now being tested and may replace Zircaloy-2 for this application because of its substantially higher yield and ultimate tensile strength.

One of the disadvantages of the pressure tube design is that the relatively thick pressure carrying walls are positioned directly between the fuel and moderator. Because of the presence of this parasitic neutron absorber, the minimum critical size of the core is increased, resulting in a larger D_2O and fuel inventory. Another disadvantage of the pressure tube design is the heavy water losses which have been experienced when compared to pressure vessel HWR's. This point is discussed further under the subject of Heavy Water Management. To date, the largest calandria which has been designed and contracted for is the 25.4 ft diam calandria for Pickering. A design study⁽²¹⁾ has indicated that a calandria on the order of 30 ft diam would be necessary for large (1000 MW_e) plants.

Sweden, Germany, and Norway have all built pressure vessel HWR's. As mentioned earlier, there are a number of different ways of cooling a pressure vessel type reactor. The Agesta reactor utilizes a coolant flow path that keeps the moderator "hot" at the outlet temperature of the coolant (430 °F). The German MZFR has the coolant and moderator separated by shroud tubes insulated with stagnant water. The moderator temperature can be varied from 250 to 430 °F by using heat exchangers coupled with the coolant flow, thus providing a reactivity shim control.

One of the problems associated with pressure vessel HWR's is the size of the vessel required for a large power reactor. The design studies examined do not consider pressure vessel containment for reactors approaching the 1000 MW_e reference size. Due to the high moderator-to-fuel ratio required in heavy water moderated reactors, the pressure vessel for such a 1000 MW_e plant would be quite large. The Marviken reactor, capable of producing a net 193 MW_e with the use of integral nuclear superheat, has a reactor vessel of about 17 ft diam.

A Swedish design study⁽²⁴⁾ indicates that a pressure vessel of about 17 ft diam could contain a core capable of producing a net power of 350 MW_e with 1.5% enriched fuel. This size of vessel is comparable to those being built for light water reactors in the U.S. today.

Czechoslovakia is building a D₂O moderated, CO₂ cooled pressure vessel reactor for operation in 1968. It has a gross power output of 150 MW_e and is contained in a 15.8 ft diam vessel.

HEAVY WATER MANAGEMENT

One of the important problems that must be considered in the design and operation of a HWR is loss and degradation of the heavy water. Heavy water accounts for up to 20% of the total capital investment of the entire plant. Also, D₂O must be controlled, especially in a reactor that has been on-line for any length of time, because of the buildup of radioactive tritium.

Since there are no existing large power HWR's with considerable operating experience, it is difficult to establish a realistic loss rate. It has been estimated for D₂O cooled pressure tube HWR's that losses of about 1 to 2%/yr of the total inventory could be expected for 500 MW_e plants.⁽²⁾

Experience in operating NPD and PRTR^(7, 25) has shown that the major source of D₂O loss is from the primary heat transport system. This is not surprising since this system, with numerous valves, pumps and fittings, operates at a relatively high temperature and pressure compared to the moderator system.

An improvement in the recovery system at NPD was made in early 1964. The boiler room was converted to a "dry room" where a dew point of -10 °C is maintained. The reactor vault was converted to a dry room in early 1966. The dry room principle has helped to reduce D₂O losses at NPD to 2 to 3%/yr (4 to 6 kg/day) during trouble free operation.^(7, 26)

As mentioned earlier, the pressure vessel Agesta reactor in Sweden has experienced average D_2O losses of about 70 to 120 g/day or 0.04%/yr.⁽⁶⁾ This figure is about a factor of 50 smaller than the comparable figures at NPD. The MZFR reactor is "guaranteed" to have a D_2O loss rate of less than 2.5 kg/day. Although no figures are available, the designers feel the actual leak rate will be well below the guaranteed value.⁽²⁷⁾ The Halden reactor in Norway, similar to Agesta and MZFR in that all these are pressure vessel type HWR's, reports D_2O losses of about 4 kg/day⁽²³⁾ which is 9%/yr for this reactor. One of the reasons for this loss rate at Halden is that a large number of flanges and seals are not seal welded or equipped with a leakage collection system.

The leakage figures above are taken from prototype reactors which normally operate with a lower net capacity factor than would be economically feasible for a large power station. For example, the Agesta reactor is "down" for three months each year. During this time a significant number of repairs and checks can be made to the system which would be difficult to perform on a large power reactor.

FUEL AND FUEL MANAGEMENT

An attractive feature of HWR's is their efficient use of nuclear fuels. Also, because of the low neutron absorption of D_2O , natural uranium can be used to fuel a HWR. One of the disadvantages of using natural uranium for a power reactor is that the reactor must be refueled about every six months to maintain reactivity. The alternative to a shutdown twice a year is to refuel the reactor on-line.

Studies conducted by the Canadians⁽²⁸⁾ for natural uranium fueled reactors indicate that off-power refueling twice a year increases the power cost for a natural uranium fueled reactor almost 1.5 times that for one with on-line refueling.

Shutdown refueling three or four times a year yields power costs 1.25 times those of on-power refueling. This cost differential is attributable to the very low burnup that is possible and the high fuel costs with shutdown refueling resulting from reactivity limitations. Although the natural uranium fuel cycle is attractive in many countries that are without enrichment facilities, the use of enriched fuels has a number of advantages in this country. The advantage in using enriched fuels over that of natural uranium is that longer burnups are possible without on-line refueling or shutdown refueling more often than once a year. The Marviken Reactor, using 1.35% enrichment, is expected to achieve about 13,000 MWd/ton. This compares with the Douglas Point Reactor, with natural uranium fuel and on-line refueling, where burnups of the order of 8,500 MWd/ton are expected.

In a du Pont design study⁽²⁾ the optimum (for the economic ground rules used) fuel enrichment for a 300 MW_e plant was found to be 1.2%. It was stated in this report that the contribution to the total power cost is not very sensitive to the burnup achieved since lower enrichment costs compensate for reductions in burnup. However, by using the enriched fuel, shutdown refueling was possible.

The costs of using natural and enriched fuels for two different types of fuel bundles are compared in the CVNA-Large Plant Study.⁽²⁹⁾ In each case, the total unit energy costs are reduced by over 15% with enriched fuel. This reduction is attributed to the more compact core arrangement, fewer pressure tubes and smaller D₂O inventory made possible with the enriched fuel.

The incapability* of the NPD reactor due to problems with the refueling machines averaged over 4% for the three years 1964 through 1966.⁽⁷⁾ However, the incapability caused by fueling problems in 1966 was just slightly greater than 1%. The Canadians hope to reduce this factor to less than 1% with the installation of a more reliable fueling system in 1968.

As mentioned earlier, CGE has proposed a new fueling scheme for the CANDU reactors with refueling from a single face of the reactor.^(10,11,12) A number of important changes in the design were made to reduce the number of operations the machine must perform while loading fuel into a channel. The pressure tube end fittings presently used on the CANDU reactors have to be removed by the refueling machine and stored out of the way while the fuel is changed. In the new design a ball valve is used to gain access to the fuel elements. Another simplification proposed is to have the machine remove the entire fuel string from the pressure tube and insert another fuel string. The exposed fuel is then discharged into a storage tank where reshuffling of the fuel bundles is accomplished. This minimizes the number of fuel storage magazines required in the refueling machine. This method of refueling a full channel at a time is not expected to significantly alter the fuel shuffling program used with the bi-directional refueling scheme since the replacement of partially exposed bundles can still be accomplished. Since the number of operations required of the refueling machine has been reduced, it is possible to operate the machine manually by means of a closed circuit TV. This eliminates the need for expensive computer control of the refueling process.

* *Capability* = (net energy unit capable of producing x 100) /
(net energy with perfect continuous operation
at full production)

Incapability = 100 - *capability*

With the present fuel reshuffling program, the average burnup for the NPD core is about 3,200 MWd/ton, but burnups as high as 10,000 MWd/ton have been achieved on some experimental fuel bundles. It is predicted that Douglas Point and the Pickering Station will achieve fuel burnups of about 8,500 MWd/ton, and the successful operation of the experimental bundles in NPD indicate that such a burnup is feasible.

THORIUM FUEL CYCLES

Du Pont has done the most previous work on the Th-²³³U fueled heavy water reactor.^(14,30) The most recent comparison of a reactor using this fuel cycle with other reactors was the ORNL evaluation of advanced converters.⁽¹³⁾ For this evaluation one of the du Pont designs was used as a starting point and was changed somewhat to fit the ground rules of the evaluation. All of these designs used coaxial ring fuel geometry, the major technology extrapolation. In the evaluation by ORNL (1965) slightly higher power and capital costs were found for the thorium fueled system than for the enriched uranium fueled reactor (1.4 to 1.2 mills/kW-hr versus 1.2 to 1.0 mills/kW-hr and \$135.4 x 10⁶ versus \$124.7 x 10⁶). Ground rules used in this evaluation to obtain these costs were:

1. U₃O₈ \$8.00/lb
2. ThO₂ \$5.00/lb
3. D₂O \$20.00/lb

A reactor using thorium fuel, although more expensive with present costs, utilizes a fuel not used presently. With higher uranium costs the fuel cycle costs for this system would be more competitive.

DUAL PURPOSE APPLICATIONS

Capital cost per unit of output for heavy water reactors decreases at a higher rate as plant size is increased than it does for light water reactors. The HWR is, therefore, more

competitive as size increases. The pressure tube HWR's also can be fairly readily increased in size due to the somewhat modular characteristic of pressure tubes. These two features make heavy water moderated reactors attractive for large size dual purpose (power and water desalination) application.

Two studies were completed in 1963. One design study uses pressurized heavy water coolant;⁽³¹⁾ the other uses boiling light water coolant.⁽²⁰⁾

These studies are primarily economic evaluations using heavy water moderated reactors in dual purpose applications. The economic ground rules used are not consistent with present ORNL economic ground rules. The studies use concentric tube fuel elements with natural UO_2 . Both studies include a 3500 MW_t prototype using 1963 technology. The D_2O cooled 3500 MW_t design uses slightly enriched fuel, and the boiling light water design uses natural uranium fuel. On-line refueling is used in the natural uranium fueled design.

Dual purpose applications for nuclear plants can be expected to increase as the demand for water rises. Public financing of such plants will tend to make systems having high capital, low operating costs appear more attractive than these plants would appear with private financing for power applications.

SPECTRAL SHIFT

One European reactor, BR-3, has a prototype spectral shift controlled core, Vulcain, in operation. A U.S. design study has also been done for this concept.⁽³²⁾ The approach, to dilute the D_2O with H_2O as a function of core lifetime, appears to be an extremely costly control system. The cores must have close lattice spacing and, on the average, are undermoderated. In reality, the cores look more like light water systems and lack the neutron economy usually associated with heavy water systems.

CONCLUSIONS

The U.S. design studies were done nearly five years ago. Studies using up-to-date economic ground rules and technology are needed if valid comparisons are to be made of the various heavy water moderated reactor types with each other and with other reactor types. The studies should include consideration and optimization of plant design as well as core design. This procedure is especially important for this reactor type due to the heavy water inventory costs and the large contribution of capital costs to the total power costs. The study should, at a minimum, include pressurized heavy water cooled and boiling light water cooled pressure tube reactors. Expansion of the study might include liquid light water cooling for the pressure tube reactor and pressure vessel containment for the D₂O cooled system. To suggest the potential of each design, enrichment and plant design should be optimized for each reactor type. The sensitivity of costs to changes in the design and in the ground rules should be included in the study for future reference purposes.

REFERENCES

1. H. Harty. Heavy Water Reactor Program Plan, BNWL-656. Pacific Northwest Laboratory, Richland, Washington, March 1968.
2. D. F. Babcock, R. R. Hood, L. Isakoff, J. C. Jensen, D. S. St. John, and J. W. Wade. An Evaluation of Heavy Water Moderated Power Reactors, DP-830. E. I. du Pont de Nemours & Company, Atomic Energy Division, Aiken, South Carolina, June 1963.
3. G. A. Pon, W. B. Lewis, L. R. Haywood, D. B. Primeau, G. J. Phillips, and E. E. Merlo. "Prospective D₂O Moderated Power Reactors," paper no. 10, Third International Conference on the Peaceful Uses of Atomic Energy, Geneva, August 31 - September 9, 1964.
4. Power Reactor Development Evaluation, AECL-1730. Atomic Energy of Canada Limited, Chalk River, Ontario, May 1, 1963.
5. P. H. Margen, H. Canuthes, B. Hargo, G. Lindberg, and B. Pershagen. "R-3-A Natural Uranium Heavy Water Reactor for Combined Electricity Production and District Heating," paper no. 135, Second International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958.
6. E. Eriesson and W. Hasling. "The Agesta Reactor Plant, Operational Experience 1963-1967," paper no. 42, IAEA Symposium on Heavy Water Power Reactors, Vienna, September 11-15, 1967.
7. E. P. Horton. "NPD Operating Experience," paper no. Sm 99/27, Symposium on Heavy Water Power Reactors, Vienna, September 11-15, 1967.
8. I. L. Wilson, C. E. Beynon, W. G. Morison, and N. L. Williams. "Studies of the CANDU-Type Reactors in the 500 MWe Range," paper no. 6, Third International Conference on the Peaceful Uses of Atomic Energy, Geneva, August 31-September 9, 1964.
9. W. G. Morison. "Multi-Unit Aspects of the Pickering Generating Station," paper no. 29, IAEA Symposium on Heavy Water Power Reactors, Vienna, September 11-15, 1967.
10. I. N. Mackay. "Design Simplifications in the HWR," Canadian Nuclear Technology, pp. 25-27. March-April, 1967.

11. J. L. Irvine, J. D. Pritchard. "Design Simplifications in the HWR: Part II," Canadian Nuclear Technology, pp. 42-43. May-June, 1967.
12. A. C. Hoyle, "Design Simplifications in the HWR: Part III," Canadian Nuclear Technology, pp. 25-26. July-August 1967.
13. R. E. Adams, M. W. Rosentha, L. L. Bennett, W. L. Carter, D. A. Douglas, R. E. Hoskins, C. G. Lawson, A. L. Lotts, R. C. Olson, A. M. Perry, J. T. Roberts, R. Salmon, and D. R. Vondy. Evaluation of Advanced Converters, ORNL-3686. Oak Ridge National Laboratory, Oak Ridge, Tennessee, January 1965.
14. J. M. Boswell, W. G. Holmes, R. R. Hood, C. P. Ross, D. S. St. John, and J. W. Wade. Heavy Water Moderated Power Reactors Cooled by Liquid D₂O or H₂O, DPW-64-135. E. I. du Pont de Nemours and Co., Atomic Energy Division, Wilmington, Delaware, March 1964.
15. R. C. Johnston and R. L. Beck. "Design Features of Current Canadian Natural Uranium Reactor Power Plants," International Nuclear Industries Fair, Basle, Switzerland, September 1966.
16. Conceptual Design of 500 MW_e Natural Uranium Boiling Light Water Reactor, APPE-26. Atomic Energy of Canada Limited, Chalk River Ontario, December 1964.
17. G. A. Pon. "CANDU-BLW-250," paper no. SM 99/32, Symposium on Heavy Water Power Reactors Vienna, September 11-15, 1967.
18. "SGHWR Advanced Economic and Simple," Nucl. Eng. vol. 11, pp. 468-470. June 1966.
19. S. Fawcett and J. E. Holmes. "General Design of the Steam Generating Heavy Water Reactor," paper no. 29, Third International Conference on the Peaceful Uses of Atomic Energy, Geneva, August 31-September 9, 1964.
20. I. Spiewak. "A Large Desalinization Reactor Based on Current Technology," Nucleonics, vol. 21, no. 7, pp. 64-68. July 1963.
21. An ORNL Evaluation of an AECL Proposed 1000 MW_e HWBLW (draft). Oak Ridge National Laboratory, Oak Ridge, Tennessee, June 1967.

22. Heavy Water Moderated Power Reactors Engineering and Economic Evaluations, vol. I - Summary Report, DP-510.
E. I. du Pont de Nemours & Company, Atomic Energy Division, Wilmington, Delaware, June 1960.
23. E. Jamne, J. A. Firing, M. Ovreeide, and T. Wullum. "Operational Experience on the Second Charge for the Halden Boiling Heavy Water Reactor," paper no. 594, Third International Conference on the Peaceful Uses of Atomic Energy, Geneva, August 31-September 9, 1964.
24. A. Johnson and B. McHugh. "A Swedish Large Nuclear Power Station with a Pressurized Heavy Water Reactor with an Open Lattice Core," paper no. 605, Third International Conference on the Peaceful Uses of Atomic Energy, Geneva, August 31-September 9, 1964.
25. H. Harty. Plutonium Recycle Test Reactor (PRTR) Operating Experience and Supporting R&D--Its Applications to Heavy Water Power Reactor Design and Operation, BNWL-SA-1269.
Pacific Northwest Laboratory, Richland, Washington, September 1967.
26. L. W. Woodhead and W. M. Brown. "Performance and Problems of NPD," paper no. 8, Third International Conference on Peaceful Uses of Atomic Energy, Geneva, August 31-September 9, 1964.
27. H. J. Krans. "Experience with the MZFR Nuclear Power Station," paper no. 25, IAEA Symposium on Heavy Water Reactors, Vienna, September 11-15, 1967.
28. K. K. Brown. "NBD Performance Indicates Merit of On-Power Refueling," Power Reactor Technology, vol. 9, no. 4, pp. 180-186. Fall 1966.
29. R. G. McGrath. Carolinas Virginia Tube Reactor Large Plant Study, CVNA-184. Westinghouse Electric Corporation, Pittsburgh, Pennsylvania, June 1963.
30. D. F. Babcock, R. R. Hood, and D. S. St. John. Thorium-Fueled D₂O Moderated Power Reactors, DP-864. E. I. du Pont de Nemours and Company, Savannah River Laboratory, Aiken, South Carolina, December 1963.

31. D. S. St. John, C. P. Ross, and J. W. Wade. Heavy Water Reactors for Sea Water Distillation Plants. OP-866. E. I. du Pont de Nemours and Company, Savannah River Laboratory, Aiken, South Carolina, January 1964.
32. T. C. Engelder, R. H. Clark, M. N. Baldwin, E. J. DeRoche, G. T. Fairburn, J. W. Hallam, D. H. Roy, N. Vutz, and T. M. Schuler. Spectral Shift Control Reactor Basic Physics Program, BAW-1273. The Babcock and Wilcox Company, Lynchburg, Virginia, November 1963.

APPENDIX A

REACTORS

APPENDIX A

REACTORSAGESTA (R/3 - ADAM)

Location	Agesta, Sweden
Date Critical	July 1963
Type	Pressure Vessel
Coolant	Liquid (D ₂ O)
Fuel	Natural UO ₂ pellets
Thermal Power	65 MW
Net Output	10 MW _e 55 MW steam generating for district heating
Maximum Heat Flux	104,000 Btu/(hr)(ft ²)
Average Burnup	5000 MWd/ton
D ₂ O Inventory	154,500 lb
Coolant Inlet Temperature	204.4 °C (400 °F)
Coolant Outlet Temperature	221.1 °C (430 °F)
Coolant Pressure	510 psia
Fuel Cladding	Zircaloy-2
Fuel Assembly	19 rods/bundle, 4 bundles/ element, 140 elements/core
Reactor Vessel	Steel vessel, inner stainless steel cladding, 4.5 m diam x 6 m high 2.75 in. wall thickness

REFERENCES

1. P. H. Margen, et.al. R3 "A Natural Uranium, Heavy Water Reactor for Combined Electricity Production and District Heating." Second U.N. International Conference on Peaceful Uses of Atomic Energy, P/135, Geneva, 1958.
2. B. McHugh. "The Agesta Reactor," Nuclear Energy, pp. 252-261. September 1964.
3. "R/3 - Adam. Combined Heating and Power Project," Nucl. Eng. vol. 5, pp. 202-5, May 1960.

BR3/VULCAIN

Location	Mol, Belgium
Date Critical	1966
Type	Pressure Vessel
Coolant	Variable mixture of liquid H_2O and D_2O
Fuel	7% enriched UO_2
Thermal Power	41 MW
Net Output	11 MW
Average Burnup	25,000 MWd/ton (anticipated)
Number of Coolant Channels	18 assemblies
Core Geometry	Regular hexagonal lattice
Fuel Cladding	Stainless steel (20 mils thick and 15 mils to be tested)
Fuel Assembly	37 fuel rods/channel
Reactor Vessel	Stainless steel Vessel

REFERENCES

1. "Vulcain: A Practical Proposition," Nucl. Eng. pp. 293-297, April 1967.
2. "The Vulcain Reactor," *Power Reactor Experiments*, vol 2, pp. 253-273. 1962.

CANDU-BLW-250

Location	Gentilly, Quebec, Canada
Date Critical	1971
Type	Vertical pressure tube
Coolant	Boiling light water
Fuel	Natural UO_2
Thermal Power	800 MW
Net Output	250 MW
Net Efficiency	31.3%
Maximum Heat Flux	99.1W/cm ²
Average Burnup	7000 MWd/ton
D ₂ O Inventory	212 tons
Coolant Inlet Temperature	267 °C
Coolant Outlet Quality	16.5%
Coolant Pressure	950 psia
Number of Coolant Channels	308
Core Geometry	Square pitch of pressure tubes
Fuel Cladding	Zircaloy-4
Fuel Assembly	50cm bundles, 18 rods/bundle
Reactor Vessel	Zr-Nb pressure tubes within gas gap insulated calandria tubes (Zircaloy-2), 3 zone calandria; core, reflector, dump annulus

REFERENCE

1. G. A. Pon. "CANDU-BLW-250," IAEA Symposium on Heavy Water Power Reactors, SM 99/32, Vienna, September 1967.

CIRENE (CISE REATTONE NEBBIA)

Location	Milan, Italy
Date Critical	(Design only, at present)
Type	Heavy water moderated, fog cooled with H ₂ O
Fuel	Natural uranium metal tubes, internally cooled, or uranium oxide rods
Average Burnup	10,000 MWd/ton
Coolant Outlet Temperature	285 °C
Coolant Pressure	220 psia
Core Geometry	Core length 3.5 m (11 ft, 8 in.)
Fuel Cladding	Zircaloy-2

REFERENCES

1. F. Accinni, et al. "The Physics of a Steam-Water Mixture Cooled Heavy Water Power Reactor," Third U.N. Conference on Peaceful Uses of Atomic Energy P/625, Geneva, 1964.
2. S. Bertoletti, et al. "Heat Transfer Crisis with Steam-Water Mixtures," Energia Nucleare, vol. 12, p. 121. March 1965.

CVTR*

Location	Parr Shoals, South Carolina
Date Critical	March 1963
Type	Pressure tube (U-tube)
Coolant	Liquid D ₂ O
Fuel	UO ₂ pellets, enriched 2% ²³⁵ U outer zone, 1.5% ²³⁵ U inner zone
Thermal Power	56 MW
Net Output	17 MW
Net Efficiency	30.3%
Maximum Heat Flux	374,000 Btu/(hr)(ft ²)
Average Burnup	8404 MWd/ton
Coolant Inlet Temperature	263 °C
Coolant Outlet Temperature	283 °C
Coolant Pressure	1500 psia
Number of Coolant Channels	36 (U-tube, 72 fuel assemblies)
Core Geometry	Square
Fuel Cladding	Zircaloy-4 0.0215 in. thick
Fuel Assembly	19-rod bundle (hex-coolant-flow baffle around bundle)
Reactor Vessel	Stainless steel moderator tank

* *This reactor has been shutdown*

REFERENCE

"Design Practice. The Carolinas Virginia Tube Reactor." Power Reactor Technology, pp. 63-81. Fall 1963.

CZECHOSLOVAKIA NUCLEAR POWER STATION

Location	Czechoslovakia
Date Critical	1968
Type	Pressure Vessel
Coolant	CO ₂
Fuel	Natural uranium metal
Net Output MW	Gross output 150 MW _e
Coolant Inlet Temperature	97 °C
Coolant Pressure	794 psia

REFERENCE

J. Hulovec. "Problems of Development and Construction of the First Czechoslovak Nuclear Power Station," Third U.N. International Conference on Peaceful Uses of Atomic Energy, P/532. Geneva, 1964.

DOUGLAS POINT

Location	Ontario, Canada
Date Critical	Late 1967
Type	Horizontal Pressure tube (CANDU)
Coolant	Liquid D ₂ O
Fuel	Natural UO ₂
Thermal Power	655 MW
Net Output	203 MW
Net Efficiency	29.1%
Maximum Heat Flux	333,000 Btu/(hr)(ft ²)
Specific Power	4.85 kW/kg
Average Burnup	8,400 MWd/ton
D ₂ O Inventory	155 tons moderator, 43.5 tons coolant, 198.5 total
Coolant Inlet Temperature	249 °C
Coolant Outlet Temperature	293 °C
Coolant Pressure	1480 psia inlet, 1310 psia outlet
Number of Coolant Channels	306
Core Geometry	Octagonal lattice
Fuel Cladding	Zircaloy-2, 16 mils thick
Fuel Assembly	19-rods bundles, 12 bundles/channel end to end
Reactor Vessel	Calandria: stainless steel shell, 19 ft 8 in. ID, 16 ft 5 in. length Zircaloy-2 tubes 49 mils thick Pressure tube: Zircaloy-2 155 mils thick, 3.25 in. ID

REFERENCE

"The World's Reactors, No. 37, CANDU (Douglas Point)"
Nucl. Eng., pp. 289-294. August 1964.

EL-4

Location	Brennilis, Brittany
Date Critical	1967
Type	Horizontal pressure tube
Coolant	CO ₂
Fuel	UO ₂ pellets, 1.4% enriched
Thermal Power	250 MW
Net Output	70 MW
Net Efficiency	28%
Average Burnup	10,000 MWd/ton
D ₂ O Inventory	110 tons
Coolant Inlet Temperature	260 °C
Coolant Outlet Temperature	485 °C
Coolant Pressure	870 psia
Fuel Cladding	Stainless steel
Reactor Vessel	Zircaloy pressure tubes

REFERENCE

"Progress Report - EL-4" Nucl. Eng., vol. 11, p. 473. June 1966.

ESSOR*

Location	Ispra Center, Italy
Date Critical	1967
Type	Experimental vertical pressure tube
Coolant	Liquid (D ₂ O)
Fuel	Natural uranium-aluminum alloy
Thermal Power	38 MW
Net Output	0 MW
Specific Power	5.7 kW/kg
Average Burnup	5000 MWd/ton
Coolant Inlet Temperature	47 °C
Coolant Outlet Temperature	98 °C
Coolant Pressure	3 atmospheres absolute
Number of Coolant Channels	28
Core Geometry	12 experimental channels surrounded by 16 feed channels
Fuel Cladding	Aluminum
Fuel Assembly	Full length tubular
Reactor Vessel	Calandria tube of aluminum or zirconium Pressure tube of sintered aluminum

* *Experimental reactor for testing of ORGEL components.*

REFERENCE

J. C. Leny, et.al. "Essor - - Specific Test Reactor for Heavy Water Reactor Concepts Developed by Euratom," Third U.N. Conference on Peaceful Uses of Atomic Energy, P/78. Geneva, 1964.

HALDEN*

Location	Halden, Norway
Date Critical	1959
Type	Pressure vessel
Coolant	Boiling D ₂ O
Fuel	1st core: Natural uranium; 2nd core: 1.5% enriched UO ₂
Thermal Power, MW	1st core: 5 MW, 2nd core: 10 MW, later 20 MW
Net Output	0 MW
D ₂ O Inventory	16 tons
Coolant Inlet Temperature	204 °C
Coolant Outlet Temperature	230 °C
Coolant Pressure	400 psia
Core Geometry	Hexagonal, 316 pins
Fuel Cladding	Finned Aluminum, 0.08 in. thick
Reactor Vessel	Stainless steel clad wall 2.4 in. thick

* *Uses natural circulation*

REFERENCES

"Halden BHWR," Nucl. Eng., vol. 4, pp. 106-113. March 1959.
"Halden Boiling Heavy Water Reactor," Nucl. Eng., p. 467.
June 1966.

HWCTR (HEAVY WATER COMPONENTS TEST REACTOR)*

Location	Savannah River, Georgia
Date Critical	March 1962
Type	Pressure vessel
Coolant	Liquid D ₂ O
Fuel	Driver tubes of zirconium alloy, enriched 93% ²³⁵ U
Thermal Power	60 MW
Net Output	0 MW
Maximum Heat Flux	420,000 Btu/(hr)(ft ²)
Average Burnup	Operating life 33 months
Coolant Inlet Temperature	214 °C
Coolant Outlet Temperature	239 °C
Coolant Pressure	1015 psia
Core Geometry	24 driver elements on outside of core, 36 positions for test elements in center of core.
Fuel Cladding	Zircaloy-2, 0.015 in. thick
Reactor Vessel	Carbon steel, stainless steel lined

* This reactor has been shut down.

REFERENCE

L. M. Arrett, et.al. Final Hazards Evaluation of the Heavy Water Components Test Reactor (HWCTR), DP-600. December 1962.

KALPAKKAM*

Location	India
Date Critical	1971
Type	CANDU
Coolant	Liquid D ₂ O
Fuel	Natural UO ₂
Thermal Power	694 MW
Net Output	200 MW
Net Efficiency	29%

** Very similar to Douglas Point Plant*

KANUPP (KARACHI NUCLEAR POWER PROJECT)

Location	Karachi, Pakistan (Paradise Point)
Date Critical	1968 Target
Type	Horizontal pressure tube
Coolant	Liquid D ₂ O
Fuel	UO ₂ pellets
Thermal Power	431 MW
Net Output	125 MW
Net Efficiency	29%
Number of Coolant Channels	208
Core Geometry	Calandria tubes 4 in. ID with inner 3 1/4 in. ID coolant tubes 9 1/4 in. pitch for tubes
Fuel Cladding	Zirconium alloy
Fuel Assembly	19-rod bundles, 11 bundles/fuel channel, 208 fuel channels in core
Reactor Vessel	Horizontal pressure tube of zirconium alloy; simplified CANDU design; integrated calandria, dump tank, and light water thermal shield; on-load refueling; withdrawal of refueling machines to shielded area for maintenance while reactor is at full power

REFERENCE

"Pakistan Turnkey Nuclear Contract for CGE." Canadian Nuclear
Tech. vol. 4, pp. 23-24. Summer 1965.

LUCENS

Location	Lucens, Switzerland
Date Critical	1966
Type	Pressure tubes
Coolant	CO ₂
Fuel	Uranium - chromium alloy, rod 17 mm diam x 650 mm long, 4 segments, 0.96% ²³⁵ U enrichment
Thermal Power	30 MW
Net Output	6.5 MW
Net Efficiency	22%
Specific Power	12 kW/kg
Average Burnup	3000 MWd/ton
D ₂ O Inventory	20.7 M ³
Maximum Heat Flux	82.5 W/cm ²
Coolant Inlet Temperature	221 °C
Coolant Outlet Temperature	386 °C
Coolant Pressure	882 psia
Core Geometry	Square lattice with reduced pitch in the center, pitch 240 mm to 290 mm, 10 control rods
Fuel Cladding	Magnesium-zirconium alloy, finned, 1.75 mm thick
Fuel Assembly	7-rod element (graphite support in the pressure tube, into which rods are inserted) core is cylindrical with 2 concentric zones, 73 elements.
Reactor Vessel	Aluminum calandria with zircaloy pressure tubes

REFERENCES

1. P. Krafft. "The Lucens Experimental Nuclear Power Station," Third U.N. Conference on Peaceful Uses of Atomic Energy, P/692, Geneva, 1964.
2. P. Verstraete. "The Nuclear Experimental Station at Lucens," Industries Atomiques, 3/4. pp. 55-67. 1964.

MARVIKEN

Location	Marviken, Sweden
Date Critical	December 1968
Type	Pressure vessel
Coolant	Boiling heavy water
Fuel	UO ₂ pellets, 1.35% enriched
Thermal Power	463 MW
Net Output, MW	132 MW _e
Net Efficiency	28.6%
Maximum Heat Flux	405,000 Btu/(hr)(ft ²)
Specific Power	18 kW/kg
Power Density	57 kW/liter
Average Burnup	13,000 MWd/ton
D ₂ O Inventory	180 tons
Coolant Inlet Temperature	120 °C
Coolant Outlet Temperature	260 °C
Coolant Pressure	695 psia
Number of Coolant Channels	147 boiling channels, 32 superheat channels
Core Geometry	Vertical, 14.5 ft high x 14.1 ft diam
Fuel Cladding	0.0236 in. thick Zircaloy-2
Fuel Assembly	0.49 in. diam rods, 36 rods/bundle
Reactor Vessel	Steel vessel 3 in. thick, 0.197 in. stainless steel clad 24 safety rods, 16 control rods, silver-cadmium clad in stainless steel, control rods driven on hydraulic impulse principle. Superheat section has 32 chan- nels, when operating yield 593 MW _t , 193 MW _e

REFERENCE

R. Nilsen. "Heavy Water Steam in Direct Cycle - Marviken,"
Nucl. Eng., vol. 11, pp. 456-60. June 1966.

MZFR (MEHR ZWECK FORSCHUNGS REAKTOR)

Location	Karlsruhe, West Germany
Date Critical	February 1966
Type	Pressure tube-pressure vessel combination
Coolant	D ₂ O
Fuel	UO ₂ pellets, 10.5 mm diam, rods 1.86 m active length
Thermal Power	200 MW
Net Output, MW	55 MW _e
Net Efficiency	27.5%
Average Burnup	4000 MWd/ton
Coolant Inlet Temperature	252 °C
Coolant Outlet Temperature	280 °C
Coolant Pressure	1330 psia
Number of Coolant Channels	121
Core Geometry	Vertical Hexagonal
Fuel Cladding	Zircaloy-2, 0.6 mm tube thickness
Fuel Assembly	37-rod bundle, 2 elements stacked in fuel channel, 242 elements/core
Reactor Vessel	Cylinder 13.45 ft ID, containing a second suspended vessel (12.5 ft ID) holding the moderator; vessel perforated by shroud tubes insulated by layers of stagnant water; shroud tubes are Zircaloy-2 inside the core and stainless steel outside the core.

REFERENCE

A. Zeigler. "The Siemens Multipurpose Reactor Design," Nuclear Power 6, pp. 72-4. March 1961.

NIEDERAICHBACH NUCLEAR POWER STATION (KKN, AKB)

Location	Niederaichbach, Germany
Date Critical	1969
Type	Vertical pressure tube
Coolant	CO ₂
Fuel	Natural UO ₂
Thermal Power	316 MW
Net Output	100 MW
Net Efficiency	31.6%
Coolant Inlet Temperature	253 °C
Coolant Outlet Temperature	550 °C
Coolant Pressure	882 psia
Number of Coolant Channels	351
Core Geometry	Square grid
Fuel Cladding	Beryllium
Fuel Assembly	19 rods/bundle, 4 fuel elements/ pressure tube

REFERENCES

1. "Niederaichbach Nuclear Power Station," Euratom, June 1965.
2. Wolfgang Keller. "Potentialities of Heavy Water Moderated Gas Cooled Pressure Tube Reactors," Third U.N. Conference on Peaceful Uses of Atomic Energy, P/778, Geneva, 1964.

NPD-2, NUCLEAR POWER DEMONSTRATION-2

Location	Das Joachims, Ontario, Canada
Date Critical	April 1962
Type	Horizontal pressure tube
Coolant	Liquid D ₂ O
Fuel	Sintered natural UO ₂ pellets
Thermal Power	83 MW
Net Output	20 MW
Net Efficiency	24%
Specific Power	5.55 kW/kg
Average Burnup	3200 MWd/ton
Coolant Inlet Temperature	485 °F
Coolant Outlet Temperature	530 °F
Coolant Pressure	1030 psia
Number of Coolant Channels	132
Core Geometry	10 1/2 in. pitch, square lattice, 12 ft 7 in. long, 14 ft 8 in. diam @ center 12 ft diam @ ends
Fuel Cladding	Zircaloy-2 25 mils thick
Fuel Assembly	1 in. OD rod, 7 elements/slug, 9 slugs/channel
Reactor Vessel	Zircaloy pressure tubes; aluminum calandria tubes; control-moderator level, moderator temperature, booster rod - enriched uranium for poison override; air flow between calandria and pressure tubes for insulation

REFERENCE

I. N. MacKay. "The Canadian NPD-2 Nuclear Power Station,"
Second U.N. Conference on Peaceful Uses of Atomic Energy, P/209,
Geneva, 1958.

PICKERING

Location	Fairport, Ontario, Canada
Date Critical	#1 1970, #2 1971, #3 1972, #4 1973
Type	Horizontal pressure tube (CANDU)
Coolant	Liquid D ₂ O
Fuel	Natural UO ₂
Thermal Power	1700 MW
Net Output	505 MW (each)
Net Efficiency	29.7%
Maximum Heat Flux	355,000 Btu/(hr)(ft ²)
Specific Power	18.8 kW/kg
Average Burnup	8000 MWd/ton
D ₂ O Inventory	341 tons moderator, 111 tons coolant, 452 tons total
Coolant Inlet Temperature	249 °C
Coolant Outlet Temperature	293 °C
Coolant Pressure	1285 psia
Number of Coolant Channels	390
Core Geometry	Octagonal
Fuel Cladding	Zircaloy-2, 16 mils thick
Fuel Assembly	29-rod bundle, 12 bundles/channel
Reactor Vessel	Calandria: stainless steel shell 27.7 ft ID, 23.4 ft long Zircaloy-2 tubes Pressure tubes: Zircaloy-2, 19.3 mils thick

REFERENCE

*I. L. Wilson, C. E. Beynon, W. G. Morison, N. L. Williams.
"Studies of CANDU-Type Reactors in the 500 MW_e Range," Third
U.N. Conference on Peaceful Uses of Atomic Energy, P/6,
Geneva, 1964.*

PRTR (PLUTONIUM RECYCLE TEST REACTOR)

Location	Hanford, Richland, Washington
Date Critical	December 1960
Type	Vertical pressure tube
Coolant	Liquid D ₂ O
Fuel	Plutonium/UO ₂ rods
Thermal Power	70 MW
Maximum Heat Flux	400,000 Btu/(hr)(ft ²)
Specific Power	15 kW/kg
Average Burnup	5000 to 8000 MWd/ton for UO ₂ , Plutonium-Aluminum 50%
D ₂ O Inventory	8210 gal
Coolant Inlet Temperature	248 °C
Coolant Outlet Temperature	277 °C
Coolant Pressure	1065 psia
Number of Coolant Channels	85
Core Geometry	Traingular lattice
Fuel Cladding	Zircaloy-2, 0.030 in. thick
Fuel Assembly	19-rod assemblies
Reactor Vessel	Aluminum calandria tank, fuel channels and process tubes mounted vertically; process tubes are Zircaloy-2 with gas gap thermal insulations

REFERENCE

"The Plutonium Recycle Test Reactor," Power Reactor Technology 3,
pp. 53-57. June 1960.

RAPP/RAJASTHAN ATOMIC POWER PROJECT

Location	Rana Pratap Sagar, Rajasthan State, India
Date Critical	Construction target 1969
Type	Pressure tube
Coolant	Heavy water
Fuel	UO ₂
Thermal Power	694 MW
Net Output	200 MW
Net Efficiency	31%
Average Burnup	9000 MWd/ton

Note: Similar to Douglas Point

SGHWR (STEAM GENERATING HWR)

Location	Winfrith Heath, Dorset, England
Date Critical	1967
Type	Vertical pressure tube
Coolant	Boiling H ₂ O
Fuel	UO ₂ pellets, 1.8 to 2.2% enriched
Thermal Power	294 MW
Net Output, MW	93 MW _e
Net Efficiency	31.7%
Maximum Heat Flux	328,000 Btu/(hr)(ft ²)
Average Burnup	18,000 MWd/ton
Coolant Inlet Temperature	280 °C
Coolant Outlet Temperature	283 °C (504, superheat)
Outlet Quality	11%
Coolant Pressure	1005 psia (935, superheat)
Number of Coolant Channels	112
Core Geometry	Core 123 in. high x 144 in. long, lattice pitch is 10.25 in. sq.
Fuel Cladding	0.026 in. Zircaloy-2 in boiling region, 0.011 in. stainless steel in superheat region
Fuel Assembly	Boiling region, 36-rod cluster, 104 channels; superheat region, 23-rod cluster (peripheral), 8 channels
Reactor Vessel	Aluminum-magnesium alloy moderator tank mounted inside water filled shield tanks; Aluminum-magnesium calandria tubes, Zircaloy in-core pressure tubes.

REFERENCE

H. Cartwright. "SGHWR, A Dark Horse Competitor," Nucleonics 24, pp. 60-63. September 1966.

SULZER

Location	Zurich, Switzerland
Date Critical	Under construction
Type	Heavy water moderated and cooled, pressure tube
Coolant	Liquid D ₂ O
Fuel	1% enriched uranium metal
Thermal Power	30 MW
Net Output	0 MW
D ₂ O Inventory	18 tons
Coolant Inlet Temperature	190 °C
Coolant Outlet Temperature	220 °C
Coolant Pressure	882 psia
Core Geometry	88 elements/core
Fuel Cladding	Zircaloy
Fuel Assembly	Tube in shell, 8 tubes/rod
Reactor Vessel	Thin-walled aluminum moderator tank

REFERENCE

P. de Haller and A. F. Fritzsche. "Sulzer Project for a Prototype Heavy Water Power Reactor for Location in an Underground Cavern," Second U.N. Conference on Peaceful Uses of Atomic Energy, P/246, Geneva, 1958.

YUGOSLAV REACTOR

Location	Yugoslavia
Date Critical	Target 1971-72
Type	Heavy water moderated and cooled BWR
Coolant	D ₂ O
Thermal Power	200-400 MW

REFERENCE

Business Atomics Report, March 16, 1966, p. 4, News Release

APPENDIX B

DESIGN STUDIES

APPENDIX B

DESIGN STUDIESAN EVALUATION OF HEAVY WATER MODERATED POWER REACTORS

I. Introduction

A. Purpose

The intent of this study is the comprehensive evaluation of the economic and technical status of heavy water moderated power reactors as of March 1963.

B. Scope

1. Two sizes of reactors are used as reference designs, 300 MW_e and 500 MW_e.
2. Six coolants are analyzed: liquid D₂O, boiling D₂O, organic, liquid H₂O, H₂O fog, and gas.

II. Description of Reference Design

- A. The reactor sizes are 300 MW_e (1060 MW_t) and 500 MW_e (1750 MW_t).
- B. Vertical pressure tubes (Zircaloy) are used.
- C. Fueling consists of 1.2% enriched UO₂ clad in Zircaloy, three concentric rings of fuel/channel and full length of channel.
- D. Shut down refueling was assumed.
- E. The basic reference design was used for all coolants. However, some dimensions and conditions were changed.
- F. It is stated in the paper that the reference designs may not be the best concept, because they were formulated primarily for economic evaluation purposes.

III. Optimization Studies

- A. A computer program DP-707 was used to optimize the core design for each coolant to give the minimum power generation costs.

- B. For the liquid D₂O cooled design 200 core designs were investigated. Varied parameters were:
- Lattice pitch
 - Linear fuel mass
 - Coolant inlet and outlet temperature
 - Power flattening
 - ²³⁵U enrichment
 - Linear fuel rating
 - Reflector thickness.
- C. "The cost equations in the optimization code were developed especially for 300 MW_e plants. In lieu of detailed design studies for 500 MW_e plants, the equations for the 300 MW_e stations were reviewed to ensure their applicability to the larger capacity."

IV. Economics

A. Ground Rules

1. Estimates are based on accounting procedures and ground rules recommended in the AEC Cost Evaluation Handbook (1961).
2. Costs, in general, are based on present day (1963) technology, or that which can be expected by 1970.

- B. Results: As an example of the results presented in the study the following are listed for liquid D₂O coolant and a 500 MW_e plant:

Private financing: 5.79 mills/kW hr
Federal financing: 3.23 mills/kW hr
Capital Cost: 101.2 million dollars.

V. R&D Problems

- A. Few problems arise with the liquid D₂O coolant because of testing and experience in Canada, Europe, and the United States.
- B. Development of stable organic coolant and fabrication process for SAP cladding would be required.

A COMPARATIVE EVALUATION OF ADVANCED CONVERTERS, ORNL 3686

I. Introduction

A. Purpose

The reactor types which could be classified as advanced converters were compared on a common basis.

B. Scope

Six reactor types, basically as designed by sponsoring organizations, were evaluated.

II. Description of Heavy Water Moderated Designs

A. The reactor size is 1000 MW_e.

B. Vertical Zr-2.5 wt% Nb pressure tubes are used.

C. Fueling consists of the following:

1. Enriched UO₂ clad in Zircaloy; three concentric ring geometry.
2. ThO₂-UO₂ clad in Zircaloy; three concentric ring geometry.

III. Economics

A. Ground rules

1. Capital costs were arranged as suggested in the AEC Cost Evaluation Handbook.
2. Material Values assumed were:
 - a. U₃O₈: \$8/lb
 - b. ThO₂: \$5/lb
 - c. Pu: \$7/g as nitrate
 - d. D₂O: \$20/lb
3. 2% D₂O loss rate.

B. Results

Power costs, mills/kW-hr, were figured.

PWR	SSCR	HWR-U	HWR-Th	HTGR	SGR
4.3-4.4	4.1-4.4	3.9-4.1	4.4-4.6	3.6-3.7	3.9-4.0

V. R&D Problems

Development work on fuel element is the main technological extrapolation.

HEAVY WATER MODERATED POWER REACTORS COOLED
BY LIQUID D₂O OR H₂O, DPW-64-135

I. Introduction

A pressurized heavy water cooled enriched uranium reactor design is presented.

II. Description

- A. The reactor size is 1000 MW_e (3500 MW_t).
- B. 516 vertical Zr-2.5 wt% Nb pressure tubes are used.
- C. Fueling consists of 1.2% enriched uranium fuel in a 3 concentric ring fuel geometry.
- D. 300 MW_e prototype and 2400 MW_e scale-up designs are also presented.
- E. H₂O use as a coolant is discussed.

III. Optimization Studies

A computer code was used to optimize design based on present day (1964) construction costs and uranium prices.

IV. Economics

Ground rules are not clearly specified.

V. R&D Problems

- A. Pressure tube joint development is needed.
- B. Fueling machine development will be required.
- C. Fuel geometry is the greatest technology extrapolation.

PROSPECTIVE D₂O MODERATED POWER REACTORS A/CONF. 28/p/10

I. Introduction

A. Purpose

The effects of using various coolants, fuel enrichments, and fuel composition on unit energy costs in large CANDU-type reactors are evaluated.

B. Scope

1. The four coolants considered are liquid D₂O, boiling D₂O, boiling H₂O, and organic.
2. Both natural and 1.42% enriched fuels are considered.
3. UO₂, uranium alloy, and UC fuels are considered.
4. Thorium ²³³U fuel cycle is included.

II. Reference Design

- A. All reactors produce a net 457 MW_e power.
- B. The reactor with organic cooling is vertical and all others are horizontal pressure tube.
- C. Reactors are typical CANDU-type.

III. Optimization Studies

Mass flow velocity and outlet steam quality are varied to obtain lowest unit power cost for boiling H₂O case.

IV. Economics

- A. All costs are given in 1964 Canadian dollars. The ground rules are based on Canadian economic conditions.
- B. Less than 0.5 mills/kW-hr difference are indicated for all cases considered. Power costs are in the range of 3.4 to 3.9 mills/kW-hr.

V. Research and Development

- A. Development is needed to assure burnup presented for the various fuel types.
- B. Development of organic coolant would be necessary.
- C. Study of Th-²³³U fuel cycle is required.
- D. Need for development of tube-in-shell fuel elements is indicated.

CONCEPTUAL DESIGN OF 500 MW_e NATURAL URANIUM BOILING
LIGHT WATER REACTOR APPE-26

I. Introduction

A. Purpose

Conceptual design of a natural uranium boiling light water cooled reactor was the object of this study.

B. Scope

1. Reactor output was set at 500 MW_e and the reactor was to be on power by 1975.
2. Two fuel geometries, tube-in-shell and rod bundles, were considered.

II. Description of Reference Design

- A. Reactor output is 500 MW_e (1505 MW_t)
- B. Vertical pressure tubes are used.
- C. Natural Uranium, zircaloy cladding, and both tube-in-shell and rod bundles were examined.
- D. Fuel is loaded on-line from below with a single refueling machine. The steam produced has direct cycle utilization.

III. Optimization Studies

- A. Quite complete tradeoff studies were made to show sensitivity to various parameters as well as to choose values for the reference design.
- B. Fuel cycle cost as a measure of reactor performance was presented as a function of a number of geometry variables, as well as outlet quality, fuel linear heat rating, core outlet pressure, fuel density, etc.
- C. Conclusions are shown in a number of figures presenting the sensitivity analysis results.

IV. Economics

Costs were based on 1964 technology. Canadian economic basis makes the absolute value of cost figures in error for U.S. application.

V. R&D Problems

- A. A positive coolant void coefficient is the area requiring the most attention if the reactor were to be built as designed.
- B. Heat transfer limits were extrapolated to a reasonably optimistic level.

HEAVY WATER MODERATED POWER REACTORS ENGINEERING
AND ECONOMIC EVALUATIONS DP-510, DP-520

I. Introduction

A. Purpose

Design and cost analysis of numerous types of HWR's is considered in this study.

B. Scope

Twenty-nine individual reactors were studied and a cost analysis was performed on 17 of these reactors.

II. Reference Designs

A. Four different nominal sizes are considered, 100, 200, 300, 400 MW_e.

B. Types considered were:

1. Vertical pressure tubes - liquid and boiling D₂O
2. Pressure vessel - both hot and cold moderator with liquid and boiling D₂O and D₂O steam
3. Natural uranium metal fuel clad in Zircaloy-2.

III. Economics

A. Cost estimates were based on private financing and projected 1962 costs.

B. Unit energy costs varied from 9.4 mills/kW-hr for a 430 MW_e pressure tube reactor with boiling D₂O coolant to 20.4 mills/kW-hr for a 100 MW_e pressure vessel reactor cooled by D₂O steam.

IV. Research and Development

Irradiation tests are necessary to increase burnup from 4000 to 8000 MWd/ton.

HEAVY WATER REACTORS FOR SEA WATER DISTILLATION PLANTS DP-866

I. Introduction

A. Purpose

Preliminary design and cost estimates of reactor plants for dual purpose use were made in this study.

B. Scope

Design and cost estimates were made for two different plants:

1. 3500 MW_t liquid D₂O cooled and moderated
2. 8300 MW_t, D₂O moderated, organic cooled.

II. Reference Design

- A. The reactor size is 3500 MW_t.
- B. Vertical pressure tube of zirconium alloy is used.
- C. Fueling consists of 1.2% enriched UO₂ clad in Zircaloy, three concentric fuel rings.

III. Optimization Studies

Because of the short time available to complete the study, very little optimization was done. However, the computer code described in DP-707 was used to design the plant.

IV. Economics

Ground rules for a public owned utility are based on 1963 dollars.

V. Research and Development

- A. No research and development would be needed to build the 3500 MW_t prototype reactor.
- B. Specifications for the reactors were obtained from DP-830 with the help of the computer code described in DP-707.

- C. The preliminary designs were sent to Sargent and Lundy for refinement and cost analysis and then transmitted to the Bechtel Corp. The fuel design was sent to ORNL for evaluation and estimate of fuel cycle costs.

SALINE WATER CONVERSION POWER REACTOR PLANTS SL-1998

I. Introduction

A. Purpose

This study was conducted to provide construction cost estimates for 2 ORNL dual purpose designs.

B. Scope

Two plants, a 25,000 MW_t full size and a 3500 MW_t prototype, were studied.

II. Description of Reference Design

A. The 25,000 MW_t plant has 3-8333 MW_t reactors; about 4000 MW_e is produced.

B. Vertical pressure tube (Zircaloy-2) was used.

C. Natural uranium clad in Zircaloy-2 was the fuel.

D. Refueling on-line is done.

III. Optimization

No studies were done.

IV. Economics

The study was to find construction costs only for the 25,000 MW_t plant and the 3500 MW_t prototype:

A. 25,000 MW_t total cost \$607,787,000

B. 3500 MW_t total cost \$126,095,000.

CAROLINAS VIRGINIA TUBE REACTOR LARGE PLANT STUDY CVNA-184

I. Introduction

A. Purpose

This study was made to find out how well CVTR has "prototyped" a large plant and to indicate the area where CVTR research should be directed.

B. Scope

1. This study was limited to reactors similar to CVTR.

2. Four cases were studied:

Case Number	I	II	III	IV
Rods/cluster	19	19	37	37
Fuel enrichment	Natural	1.5%	Natural	1.5%

II. Reference Design

A. Plant size was 300 MW_e.

B. U-tube pressure tubes were used.

C. Reactor was liquid D₂O cooled.

III. Economics

A cost analysis is made to compare the four cases mentioned above. No optimization was performed.

IV. Research and Development

A. Methods of reducing D₂O inventory need investigation.

B. A need for better fuel cycling was found.

C. Improvements in fabrication of U-tubes need to be developed.

POWER REACTOR DEVELOPMENT EVALUATION, AECL-1730

I. Introduction

A. Purpose

Economic evaluation of various coolants in a large CANDU-type reactor was the object of this study.

B. Scope

1. Four coolants are considered: liquid D_2O , H_2O fog, boiling H_2O , and organic.
2. A reference design is presented.
3. Capital and unit energy costs are included.
4. Effects of multi-unit siting are discussed.

II. Reference Design

- A. Each reactor produces 457 MW_e and is a scale-up of the CANDU-type.
- B. Horizontal pressure tubes are used for the liquid D_2O and boiling H_2O while the other coolants utilize a vertically oriented core.
- C. Natural UO_2 is used as fuel except for natural UC fuel in the organic reactor.

III. Economics

- A. All costs are given in 1963 Canadian dollars without escalation. Ground rules are based on Canadian economic conditions.
- B. Power costs of from 3.89 to 3.45 mills/kW-hr are obtained with the H_2O fog coolant having the highest and organic coolant having the lowest cost.

IV. Research and Development

1. In all of the reactors studied, Zr-2 1/2 wt% Nb is used in the pressure tubes. Development work is indicated in this area.
2. Design and development work is required for the vertical core orientation.
3. Development of organic coolant is necessary.

AN ORNL EVALUATION OF AN AECL PROPOSED 1000 MW_e HWBLW (DRAFT)

I. Introduction

A. Purpose

The objective was to provide an advanced converter task force with a natural uranium, heavy water moderated, boiling light water cooled reactor design.

B. Scope

Design study and economic evaluation of a 1000 MW_e reactor design was included.

II. Description of Reference Design

A. The reactor size is 1000 MW_e (3242 MW_t).

B. Vertical pressure tube is used with Zr-2 1/2 wt% Nb.

C. Fueling consists of natural uranium clad in Zircaloy-4.

D. Refueling is done on-line.

III. Optimization Studies

No tradeoff studies were included. Basically this was a scale-up of CANDU-BLW-250.

IV. Economics

The evaluation uses ORNL ground rules. Final power cost of 3.74 mills/kW-hr was found.

V. R&D Problems

Comprehensive listing of problem areas is included; areas of greatest importance:

1. Boiling heat transfer limits
2. Stability and control.

THORIUM-FUELED D₂O MODERATED POWER REACTORS, DP-864

I. Introduction

A. Purpose

The technical status of using a Thorium-²³³U fuel cycle in a heavy water moderated reactor is appraised.

B. Scope

1. A summary was made of the aspects of the thorium breeding cycle.
2. Use of D₂O for neutron economy and fuel utilization was investigated.
3. Description of a reference design is included.
4. Needed development work and a program to carry out that development has been outlined.

II. Reference Design

A. The reactor size is 1000 MW_e, very similar to the smaller reactors described in DP-830.

B. Changes include:

1. 1.5% ²³³U instead of 1.2% ²³⁵U
2. More fuel positions
3. "Breeding" channels of pure thorium in reflector
4. Extra control rods made of thorium.

III. Economics

A. Ground rules are similar to DP-830 study.

B. Power cost of 5.2 mills/kW-hr with the thorium fuel cycle is predicted.

IV. Research and Development

A. A complete research and development program leading to construction of a prototype reactor is outlined.

B. Cost and time scheduled for a research and development program are included. About \$136 million over 6 yr would be required for a research and development program, including construction of a prototype reactor.

A LARGE SWEDISH NUCLEAR POWER STATION WITH A PRESSURIZED
HEAVY WATER REACTOR WITH AN OPEN LATTICE CORE, A/CONF-28/P/605

I. Introduction

A. Purpose

The object of this study was to develop a design consistent with Swedish industrial capabilities.

B. Scope

A single reactor design of 1200 MW_t is discussed.

II. Description of Reference Design

A. 1200 MW_t was used since pressure vessels larger than for this size were beyond industrial capabilities.

B. Pressure vessel containment permits using an open lattice where bouyant forces in the coolant tend to distribute more flow to the hotter core regions.

C. 1.5% enriched UO₂ with a throw-away fuel cycle is considered.

D. Shutdown refueling is to be used with a coolant change from heavy to light water for refueling. The open lattice is less sensitive to heavy water degradation than are clustered lattices.

III. Optimization Studies

The plant was optimized for the throw-away fuel cycle but the optimization studies were not discussed.

IV. Economics

A 1964 capital cost of \$240/kW, including site and D₂O, is presented.

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