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CIVILIAN POWER REACTOR PROGRAM

Part II

Economic Potential and Development Program
Heavy Water-Moderated Power Reactors

Compiled by:

J.H. Hutton
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Reviewed by SROO

August 19, 1960

Work Performed for the
Savannah River Operations Office of the USAEC
under Contract AT(30-1)-2303(XIV)

NDA -

NUCLEAR DEVELOPMENT CORPORATION OF AMERICA

WHITE PLAINS, NEW YORK

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H. POTENTIAL AND PROGRAM FOR D₂O-MODERATED, NATURAL URANIUM-FUELED REACTORS

This document is an updated version of Section H of TID-8517, Part II which was issued in 1959. The reactor presented in 1959 was a pressure-vessel type. In the past year sufficient progress has been made to change the reference design to a pressure-tube type, primarily on the basis of current construction and design projects such as the Plutonium Recycle Test Reactor (PRTR), Carolinas-Virginia Tube Reactor (CVTR), Nuclear Power Demonstration Reactor (NPD-2), and Canadian Deuterium Uranium Reactor (CANDU).

1. SUMMARY

The reactor design which forms the base for the current economic status of D₂O-moderated reactors has been estimated from developments in several reactor programs. However, since a heavy water-moderated reactor has not been operated on natural uranium fuel at power reactor conditions, considerable improvement from this current status can be foreseen. The summary of improvements is presented in two parts: (1) improvements in the concept which would result solely from operation of succeeding generation plants without a parallel development program, and (2) improvements which would result from the successful completion of the development program presented in Section 3.

One plant size was used in the evaluation of plant potential, with a 300 MW_e nominal rating. Table 1 summarizes the two steps in reducing power cost for the 300 MW_e plant. The boiling D₂O-cooled, pressure tube direct cycle plant was used.

The current development program is shown in Fig. 1. This work includes several items leading to the long-range development of the concept. By the end of FY 1961, sufficient data should be available for proceeding with the design of a prototype plant.

Table 1 — Cost Reduction Potential — 300 MW_e Plant

Cost Item	Current Technology, mills/kwh	Successive Plant Improvements, mills/kwh	Plant Potential, mills/kwh
Capital investment	4.70	4.11	3.94
D ₂ O inventory	1.28	1.10	0.64
Fuel cycle	1.51 (1.75)*	1.03	0.90
D ₂ O makeup	0.21	0.18	0.11
Operation and maintenance	0.58	0.58	0.58
Working capital	0.20	0.13	0.07
Insurance	0.13	0.13	0.13
Total	8.6 (8.8)*		

* 7500 MW-d/metric ton U average burnup.

2. EVALUATION STUDIES

Both the prototype and full scale plants include an evaluation phase prior to conducting Title II design. These studies will evaluate the status of the various development programs, incorporate the applicable portions into the preliminary plant design, and estimate the technical and economic improvements which would result from their use. In this way, up to date information will be available on which to make selection of the reactor parameters. Items that might be considered in these studies are:

1. Sintered Uranium Product (SUP). A metallic fuel with higher temperature and irradiation stability than normal uranium metal.
2. Plutonium Recycle. Slight enrichment performance with natural uranium feed.
3. Th-U²³³ Cycle. Slight enrichment with normal fuel feed.
4. Improved Steam Separation. Lower capital investment and D₂O inventory.
5. Insulated Pressure Tube vs Calandria Comparison.
6. Boiling D₂O plus Nuclear Superheat.
7. H₂O Fog Cooling. Elimination of D₂O inventory and make-up in primary system.
8. H₂O Fog plus Nuclear Superheat. Decreased D₂O inventory and improved cycle efficiency.
9. Steam Cooling.
10. Gas Cooling.
11. Organic Cooling.
12. Direct vs Indirect Cycle. Review when more firm D₂O loss data is available.
13. On-Power vs Off-Power Refueling.
14. In-Pile Instrumentation. A method of improving plant performance by closer control of in-pile conditions.
15. Updating Plant Design and Economics.

3. RESEARCH AND DEVELOPMENT

The heavy water-moderated reactor program has two objectives. The more immediate objective is the production of electrical power using natural uranium fuel. The second objective is the production of competitive electrical power. The first objective can be met by the construction of a prototype reactor using the results of the current development program. Fig. 1 summarizes both the current construction programs and the general research and development programs, exclusive of those being carried out as part of the constructions projects. Each of the subjects of development are discussed in the Part III report of the ten-year program.

The attainment of the second objective, competitive electrical power, can be met by the successful completion of a long-range program. The CANDU reactor and a full scale U. S. station will contribute substantially to the attainment of the "intermediate improvements" discussed in Section 6. Substantial improvements can be made in succeeding generation plants after a prototype and full scale plant are in operation.

Large reductions in power cost can be obtained by concentrating a development program on (1) increasing plant efficiency, (2) decreasing capital investment, (3) decreasing fuel cycle costs, and (4) decreasing D₂O inventory and make-up. The long-range development program will extend the technology substantially in ten years. These improvements, most of which are discussed in Section 5, are not necessarily part of the heavy water reactor program. For example, both the boiling and pressurized reactor programs are developing high burnup, low cost fuel elements. Natural uranium reactors with maximum burnup capability and minimum fuel fabrication costs should give the natural uranium-fueled reactor concept the lowest possible fuel cycle cost. The plutonium recycle and thorium-U²³³ concepts are being investigated and both may produce substantial power cost savings when adapted to the heavy water reactor. These programs should be followed and supplemented whenever it appears desirable to do so.

† Schedules are shown to the nearest quarter

‡ Prototype decision not dependent on these programs.

§ If swaged tubes cannot be developed in time for HWCTR startup, rod bundles (swaged rods or sintered pellets) will be substituted.

Fig. 1 — Schedule of planned program for D₂O moderated power reactors

(Schedule development work in other D₂O reactor programs has not been included; only the schedule for operating data from these reactors is shown.)

4. PLANT CONSTRUCTION

The HWCTR, CVTR, and, if authorized, the Boiling D₂O Prototype and Full Scale Demonstration Reactor will be the main projects in the D₂O-moderated reactor program. The Florida West Coast Nuclear Group gas-cooled reactor is summarized in two programs: the heavy water and gas-cooled reactor programs. The PRTR is part of the Plutonium Recycle Program but the choice of heavy water moderation has resulted in major contributions to heavy water technology. The Canadian Reactors, NPD-2 and CANDU, are the only natural uranium reactors now scheduled for construction. The Canadian reactors are contributing major improvements to the technology but studies in the U.S. have continued to recommend a concept different from that arrived at in Canada. This results in the necessity for R&D along somewhat different lines in these two countries and in the need for different prototypes.

The status of the prototype and demonstration reactor is presented below. A brief description and status of HWCTR, PRTR, CVTR, FWCNG, NPD-2, and CANDU can be found in Part I of this report. A more detailed description of these reactors can be found in Part III of this report.

Boiling D₂O-Cooled, Heavy Water-Moderated Prototype Reactor. A natural uranium-fueled prototype plant should be constructed to provide operating experience with this type of reactor prior to constructing a full scale plant. The physics program being conducted at the present time will provide accurate data from which to predict the initial reactivity of the reactor. Should this indicate good long-term performance of the full scale reactor, design and construction should proceed. The plant size would probably be in the 70 MW_e range.

A Title I design study of a prototype plant was conducted by NDA and S&L in 1959. Modification of this design would be required in light of current development work. If authorization to construct is given by mid-1961, the reactor could be put into operation by January, 1965.

300 MW_e Demonstration Plant. A full scale U.S. station should be programmed for construction after the prototype reactor has been in operation. Design could start in 1967 with construction completed in 1970. For planning purposes, the full scale plant is presently assumed to be a 300 MW_e boiling D₂O-cooled, natural uranium-fueled, direct cycle pressure tube reactor plant.

5. INTERMEDIATE PLANT IMPROVEMENTS

An estimate was made of those improvements in successive generation plants which would result from normal improvements in technology applied to the "current status" reactor type. The most likely items are summarized in Table 2 for the 300 MW_e plant. The capital and operating costs resulting from the summation of these items is shown in Table 3. The boiling D₂O-cooled, direct cycle reactor plant was used for the basis of cost estimates. The reactor design is described in Section 7.1 of Part III of this ten-year program report (NDA 2153-3).

Table 2 — Potential Power Cost Reductions for Succeeding Generation 300 MWe Boiling-D₂O, Pressure Tube, Cold Moderator, Natural UO₂-Fueled Reactors

			Power Cost Reductions, mills/kwh							
Technical Improvement		Effects	Capital Investment	D ₂ O Investment	Fuel Costs	D ₂ O Makeup	Operation and Maintenance	Working Capital	Insurance	Total
1	Improved plant design (based on but not including cost reduction of vapor suppression concept)	a Consolidated equipment arrangement for better utilization of space	0 231	0 064	—	0 01	—	—	—	0 305
		b Saving in equipment cost and D ₂ O inventory								
		c Improved fabrication techniques for core and D ₂ O headering								
		d Estimated cost reduction of 5% in capital and D ₂ O investment								
2	Improved fuel scheduling by on-power refueling	a Fuel burnup increased from 8500 to 10,000 MW-d/metric ton U	(+0 029)	—	0 261	—	—	0 001	—	0 233
		b Number of control rods reduced by 50%								
		c Cost of refueling machine increases								
		d Design in accordance with NDA 2109-4 concept discussed in Reference Section 3 2 2								
3	Zircaloy pressure tube fabrication cost reduced	a Reduction in cost of Zircaloy tubing from \$30 to \$15 per lb as a result of fabricating experience and quantity procurement	0 192	—	—	—	—	—	—	0 192
4	Decreased cost of fuel fabrication	a Reduction in cost of fuel fabrication from \$64 to \$48 80 per kg U as a result of fabricating experience and quantity procurement	0 003	—	0 233			0 045		0 281
5	Vapor suppression in place of containment	a Small steel housing around reactor complex in lieu of containment building as described in Reference S&L-1815	0 096	—	—	—	—	—	—	0 096
6	Increased fuel specific power (cost reductions based on and additive to lower values resulting from above improvements)	a Fuel element centerline temperature limit increased from 4000 to 4500°F	0 083	0 116	(+0 015)	0 019	—	0 013	—	0 216
		b Based on the assumption that fuel burnup, reactivity, and steam conditions remain unchanged, fuel element specific power increases and number of elements decrease								
Total power cost reduction			0 576	0 180	0 479	0 029	—	0 059	—	1 323

Table 3 -- Comparative Summary of 1960 and 1970 Capital and Operating Costs for 300 MWe, Boiling D₂O-Cooled, Pressure Tube, Natural UO₂-Fueled, Power Reactors

	1970			1960		
	2235 × 10 ⁶ kwh/yr at 0.8 Operating Factor			2235 × 10 ⁶ kwh/yr at 0.8 Operating Factor		
	Investment \$10 ⁶	Annual Cost \$10 ⁶ /yr	Power Cost mills/kwh	Investment \$10 ⁶	Annual Cost \$10 ⁶ /yr	Power Cost mills/kwh
Investment						
Plant investment	65.771	9.208	4.12	74.970	10.496	4.696
D ₂ O investment	<u>19.616</u>	<u>2.452</u>	<u>1.097</u>	<u>22.839</u>	<u>2.855</u>	<u>1.277</u>
Total investment	85.387	11.660	5.217	97.809	13.351	5.973
Operation and Maintenance						
Fuel costs		2.302	1.030		3.372	1.509
D ₂ O makeup		0.402	0.180		0.468	0.209
Operating and maintenance payroll		0.751	0.336		0.751	0.336
Operating supplies and maintenance materials		0.546	0.244		0.546	0.244
Insurance		0.293	0.131		0.293	0.131
Working capital		<u>0.324</u>	<u>0.145</u>		<u>0.456</u>	<u>0.204</u>
Total operating costs		<u>4.618</u>	<u>2.066</u>		<u>5.886</u>	<u>2.633</u>
Total capital and operating costs		<u>16.278</u>	<u>7.283</u>		<u>19.237</u>	<u>8.606</u>

6. POTENTIAL OF D₂O-MODERATED, NATURAL URANIUM-FUELED PLANTS

The heavy water-moderated, natural uranium-fueled reactor plant for which the "current status" cost estimates are presented is based on design criteria which have been demonstrated in other reactors, or are sufficiently conservative to entail no undue risk. This "current status" reactor could be designed and built starting July 1, 1960. The power generation costs for this reactor type are tabulated in the Summary of this report.

The improvements which will normally be derived from operation of succeeding generation plants of the same type are discussed in Section 5. The improvements which are the aim of the development program are presented here, and it has been assumed that those discussed in Section 5 have been applied. That is, the improvements made possible by prototyping the reactor have been achieved prior to applying the future potential factors. The two steps in the development program are additive. The main items in the future potential development program are summarized in Table 4 for the 300 MW_e plant. It is not known whether all of these improvements could be attained by 1970 but the most probable ones are fog cooling, metallurgically-bonded pressure tube joints and reduced fuel fabrication costs. These three items will reduce the power cost to 6.4 mills/kwh for the 300 MW_e plant.

The other items shown on Table 4, namely, nuclear superheat and improved fuel cladding and structural materials, would result in substantial power cost reductions but may not be realized in the prescribed ten year period. No credit has been taken for these latter items in the future potential economic estimates.

Other improvements which may have major effects on power cost, but for which data are not now available, are plutonium recycle and Th-U²³³ fuel cycle.

The items in Table 4 are discussed below:

H₂O "Fog" Coolant

It would be very desirable to eliminate the use of D₂O in the cooling circuit of this type of reactor. This would markedly reduce the D₂O inventory charges, eliminate the largest possibility of D₂O leakage and accidental loss, and eliminate any need for specially designed turbine and condensor equipment. An excellent coolant for this application appears to be H₂O "fog" consisting of fine water droplets dispersed in steam. This coolant has been shown by CISE (Centro Informazioni Studi Esperienze) to have very high heat removal capabilities and has a low enough density so that neutron absorption by the light water is reasonable even in a natural uranium reactor.

NDA and CISE and Ansaldo of Italy are currently conducting a research and development program, including heat transfer and fluid flow experiments, on this concept under joint AEC-Euratom sponsorship. The Canadians have currently initiated a study of fog cooling.

The power cost reductions obtained with fog cooling arise, primarily, from the following effects:

1. Reduced D₂O inventory.
2. Reduced turbine plant capital investment by use of conventional steam plant equipment without special D₂O seals. This may represent a saving of \$2 to $\$3 \times 10^5$ per turbine.

Nuclear Superheat

Conventional power generating equipment which is used in fossil-fueled power plants may be supplied with superheated steam. Nuclear power plants are attempting to gain the high plant efficiency possible with superheat but have been deterred from doing so by the lack of suitable high temperature fuel materials. In the natural uranium-fueled reactors, the problem is compounded by the necessity of a low neutron cross section, high temperature material. This being the case, it cannot be assumed that nuclear superheat will result from the heavy water reactor ten-year program. However, to illustrate the incentive for proceeding with the development of superheat, turbine throttle conditions of 1000 psia and 950°F, made possible by beryllium structural materials and cladding, would reduce power cost by 1.7 mills/kwh in the 300 MW_e plant size.

Improved Reactor Materials

Low cross section, good high temperature mechanical properties, and water corrosion resistance are a few of the properties sought in improved clad and structural materials. For example, if improvements can be made in zirconium alloys such that the amount of structural and cladding material in the reactor is cut in half, the fuel burnup could be increased by 25% and power cost would be reduced by 0.32 mill/kwh in the 300 MW_e plant size.

Improved Zircaloy-to-Stainless Steel Joint

The current development program includes a metallurgically-bonded pressure tube joint which is showing promise of success. With this type of joint, it will be possible to place the joints at the edges of the reactor core, thus shortening the Zircaloy section by about one half. This results in a capital cost reduction, for the 300 MW_e plant, of \$1,700,000 or 0.11 mill/kwh.

Fuel Fabrication Cost Reduction

Each reactor project includes a fuel element development program and the AEC is sponsoring other research projects on fuels. In addition, fuel element manufacturers are constantly improving production techniques. This work will undoubtedly result in substantial fabrication cost reductions. It has been assumed that the UO₂ fabrication cost is cut from \$48.30 kg-U to \$40 kg-U with a subsequent reduction in power cost of 0.15 mill/kwh for the 300 MW_e plant.

Table 4 — Potential Power Cost Reductions for 300 MW_e Reactors as a Result of the 10-Year D₂O-Moderated Reactor Development Program
(Cost Reductions Refer to Succeeding Generation Reactor Concept, Table 3)

				Power Cost Reductions, mills/kwh							Total	Revised Power Cost
Technical Improvements	Advantages	Disadvantages and Uncertainties	Basis of Estimate	Capital Investment	D ₂ O Investment	Fuel Costs	D ₂ O Makeup	Operation and Maintenance	Working Capital	Insurance		
1. H ₂ O fog-cooled concept (dispersion of liquid drops in steam)	a. Low density of coolant permits substitution of H ₂ O for D ₂ O coolant to obtain the following: 1. Reduction in turbine plant capital investment. 2. Reduction in D ₂ O in- ventory investment and D ₂ O makeup.	a. Large steam pumping equipment and special spray equipment required. b. Power coefficient of reactivity may be unfavorable.	a. Lattice spacing increased from 11.1 to 12.8 in. to hold burnup at 10,000 MW-d/metric ton U. b. Steam conditions remain the same as current boiling D ₂ O reactor. c. 20% inlet quality, 50% exit quality. d. Cost of steam pumping equip- ment assumed to offset savings in steam drums and recircu- lating piping.	0.061	0.457	0.003	0.073	—	—	—	0.594	6.689
2. Improved Zircaloy-to- steel joints	a. Metallurgically-bonded instead of mechanically- bonded joints permit shorter Zircaloy pressure tube sections from 48 to 21 ft.		a. Cost of Zircaloy assumed to be \$15/lb.	0.108	—	—	—	—	—	—	0.108	7.175
3. Decreased cost of fuel fabrications as result of fuel fabrication development program	a. Lower fuel and working capital costs. b. Fuel costs reduced from \$48.80 to \$40/kg U including shipping of nonirradiated fuel and losses during fabrication.			—	—	0.129	—	—	0.022	—	0.151	7.132
4. Superheat concept	a. All advantages of fog-cooled concept above. b. Higher cycle efficiency from 28.6 to 34.5% with reheat turbine.	a. Requires beryllium alloy or beryllium alloy insulated pressure tubes. b. Requires beryllium alloy fuel element cladding. c. Burnout and heat transfer data must be developed in order to design the core. d. Control may be more difficult.	a. Single region core-steam enters saturated and leaves at 1500 psi, 950°F. b. Beryllium alloy pressure tubes. c. Beryllium alloy clad fuel elements. d. Burnup assumed to be 15,000 MW-d/metric ton U. e. Beryllium cost estimated at \$150/lb or 2.7 times more costly than Zr.	0.461	0.565	0.491	0.091	0.099	(0.021)	0.022	1.750	5.533
5. Improved reactor materials	a. Lower neutron capture cross section loading to increased reactivity and increased burnup to 12,500.	a. Increased fabrication cost.	a. Steam conditions assumed to be the same as reference design. b. All savings assumed to be increased burnup. c. New material assumed to have 1/2 the poisoning effect of reference design Zr-2 pressure tube.	—	—	0.324	—	—	—	—	0.324	6.959