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MASTER

HEAVY WATER MODERATED POWER REACTORS

PROGRESS REPORT
NOVEMBER-DECEMBER 1963

Technical Division
Wilmington, Delaware

REG. U. S. PAT. OFF.

ISSUED BY

Savannah River Laboratory

Aiken, South Carolina

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HEAVY WATER MODERATED POWER REACTORS
PROGRESS REPORT
NOVEMBER-DECEMBER 1963

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Wilmington, Delaware

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ABSTRACT

The HWCTR was shut down during early November for cleanup of the liquid D_2O loop after a fuel failure occurred during an irradiation test. During the second shutdown that began later in the month, all of the driver assemblies were replaced, new control rods were charged, and miscellaneous repairs were effected.

Further postirradiation examinations of Zircaloy-clad UO_2 tubes confirmed earlier indications that columnar grain growth began at a thermal rating ($fkd\theta$) of 25 to 35 watts/cm.

As the first step in developing a tubular fuel element of thorium that would be suitable for use in a D_2O -thorium breeder reactor, an HWCTR irradiation test of two thorium metal tubes has been designed.

Tentative design data were formulated for use in a design study of a D_2O -cooled-and-moderated prototype reactor that is capable of operation on either the U^{238} -plutonium cycle or the thorium- U^{233} cycle.

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HEAVY WATER MODERATED POWER REACTORS
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INTRODUCTION

This report reviews the progress of the Du Pont development program on heavy-water-moderated power reactors. The over-all goal of the program is to advance the technology of these reactors so that they could be used in large power stations to generate electricity at fully competitive costs. Program emphasis is being placed on reactors that are cooled by liquid D_2O . The principal phases of the program are: (1) the irradiation of candidate fuels and other reactor components in the Heavy Water Components Test Reactor (HWCTR), (2) the development of low-cost fuel tubes for use in large water-cooled reactors, and (3) the technical and economic evaluation of various reactor design concepts.

SUMMARY

The HWCTR was shut down during early November for removal of radioactivity that was released to the liquid D_2O loop when an assembly of uranium oxide tubes failed during an irradiation test. The cleanup operations were successful in reducing the general radiation level in the vicinity of the loop piping to less than 200 mr/hr. The reactor was operated at full power the latter half of the month. A shutdown was forced on November 29 by failure of a well pump. During the shutdown, all of the driver assemblies were replaced, new control rods were charged, and miscellaneous repairs were effected. Operation of the reactor was resumed on December 30. The failure in August of a Zircaloy bayonet in the HWCTR was traced to vibration of the bayonet and its internal components.

Further postirradiation examinations of Zircaloy-clad UO_2 tubes confirmed earlier indications that columnar grain growth began at a thermal rating ($\int kd\theta$) of 25 to 35 watts/cm. It was reported in DP-875 that a sharp increase in fission gas release also was observed at these ratings. Grain growth extended to about 50% of the core cross section at 35 watts/cm and to 85% of the cross section at 45 watts/cm. The Zircaloy sheaths of these tubes were free of highly localized concentrations of zirconium hydride.

As the first step in developing a tubular fuel element of thorium that would be suitable for use in a D₂O-thorium breeder reactor, an HWCTR irradiation test of two thorium metal tubes has been designed, and preparations have been made for fabrication of the fuel tubes. The tubes will be about 10 feet long and will be clad with Zircaloy by a coextrusion process. Uranium²³⁵ will be used to simulate the U²³³ that would be present in the freshly charged thorium tubes of a breeder reactor.

Tentative design data were formulated for use in a design study by the Du Pont Engineering Department of a D₂O-cooled-and-moderated prototype reactor that is capable of operation on either the U²³⁸-plutonium cycle or the U²³³-thorium cycle. These data include the size of the core, the power rating (~300 MWe), the average k_{eff} (29 watts/cm for UO₂ tubes), and the control requirements.

DISCUSSION

I. THE HEAVY WATER COMPONENTS TEST REACTOR (HWCTR)

The HWCTR is a D₂O-cooled-and-moderated test reactor in which candidate fuel assemblies and other reactor components are being evaluated under conditions that are representative of large D₂O-moderated power reactors.⁽¹⁾ Currently, fuel assemblies of uranium metal (coextruded with Zircaloy cladding) and assemblies of uranium oxide (mechanically compacted in Zircaloy sheaths) are being irradiated in this reactor.

A. REACTOR OPERATION

The HWCTR was shut down during the first half of November for removal of radioactivity that was released to the liquid D₂O loop when an assembly of uranium oxide tubes failed (see DP-875). Activity levels were reduced sufficiently by purging loop blanket gas and by recirculating loop D₂O through filters and deionizers to allow an uneventful discharge of the failed assembly five days after the reactor was shut down. After twenty days of cleanup operations, the general radiation level in the vicinity of the loop piping was less than 200 mr/hr, although radiation intensities as high as 300 R/hr at contact persisted at several locations that could not be flushed thoroughly.

The reactor was operated at full power during most of the last half of November. On November 29, the reactor was scrammed following a failure of a pump in one of the two wells that supply cooling water to the area. The pump was damaged beyond repair, and it was necessary to procure a replacement. In view of an estimate that two weeks of reactor downtime would be required to effect pump replacement, it was decided to replace the 24 driver assemblies during the shutdown. The burnup of the old drivers had reached the point that they were incapable of providing enough reactivity to operate the reactor at full power for more than a few additional days. Other major items completed during the reactor outage are listed below. The reactor was returned to operation on December 30.

1. Conducted low-power physics tests for measurement of neutron flux distribution in depleted driver fuel and control rods.
2. Charged new control rods.

3. Repaired D_2O leaks in one of the steam generators.
4. Discharged three irradiated test fuel assemblies.
5. Charged three new test assemblies.
6. Installed permanent continuous temperature monitors for effluent coolant from individual fuel assemblies.

Operating data for the HWCTR during this report period are summarized in Tables I and II and in Figures 1 and 2. Irradiation tests currently in progress are summarized in Table III.

B. BAYONET FAILURE

Detailed examination of the Boiling Loop bayonet that failed in the HWCTR in August (see DP-865) revealed that the failure was caused by severe vibration of the bayonet and its internal component, an empty fuel element housing tube. Both the bayonet and the housing tube displayed several areas of extensive vibration damage. The failure was found to be a hole through the bottom of the bayonet. The bayonet had never been operated with a fuel element.

Indications of vibration were first detected in July 1962, when clicking noises were heard in a reactor nozzle directly below the bayonet. To aid in investigating the noise, and the possibility of bayonet vibration, an empty fuel element housing tube was charged to the bayonet in September 1962. As nuclear operation for the bayonet was not scheduled until September 1963, it was planned to leave the housing in the bayonet for several months, and then discharge it to look for signs of wear or damage. The housing was a four-ribbed Zircaloy tube with a flare at each end to which stainless steel fittings were attached. The fitting at the lower end was a stainless steel cross, which supported the housing on the bottom of the bayonet. The components of this fitting are shown in Figure 3.

The bayonet failure apparently developed as follows: The eccentric end bushing, which was pinned to the bottom of the bayonet and positioned it horizontally in the reactor, separated from the bayonet soon after its installation. When the bayonet was discharged in August, the bushing was found in the bottom of the reactor. It was recovered and found to be

severely worn, as was the end of the bayonet. Because of the vibration of the unrestrained bayonet, the flare at the bottom of the Zircaloy housing tube sheared off. The housing tube then moved downward until it contacted the upper end of the support cross. Since the diameter of the housing was larger than that of a cylindrical sleeve at the upper end of the cross, the housing must have deformed before it made contact with the cross. Vibration caused the four legs of the cross to cut slots through the wall of the housing, allowing the housing to continue its downward movement as four separate pieces. These pieces finally contacted the bottom of the bayonet. As pieces of the housing subsequently broke off, the housing continued to move downward. Concurrently with the above events, the bottom fitting cross was also wearing a mating groove in the bottom of the bayonet. The hole in the bayonet was caused by a housing tube rib that projected below the bottom of the cross and acted as a cutting tool. Presumably, the rib was energized by the vibration and was forced downward by the weight of the housing. Figure 4 is a photograph of the inside surface of the bayonet bottom end. Visible in this figure are a cross-shaped groove, which was estimated to be $5/8$ inch deep, and a hole extending through the remaining $5/16$ -inch thickness of the bayonet. The lower end of the stainless steel cross and the projecting housing rib which produced the hole are shown in Figure 5. Although the cross was severely worn, its length decreased by only $1/8$ inch. However, the Zircaloy housing tube was 20 inches shorter than when originally charged into the bayonet. Wear damage was also observed on the outer surface of the Zircaloy section of the bayonet where it passed through the HWCTR top shield. This damage is additional evidence that the bayonet itself was in motion.

II. REACTOR FUELS

A. GENERAL

Two types of Zircaloy-clad fuel elements are currently under development in the Du Pont program on D_2O power reactors: mechanically compacted tubes of uranium oxide and coextruded tubes of uranium metal. In the development of these two alternative fuels, primary attention is being given to fuel element designs and fabrication methods that offer promise of low fabrication costs when the elements are produced in the volume required for several full-scale reactors. At present, the uranium oxide tubes are receiving program emphasis pending the outcome of current irradiations of both types of fuel in the HWCTR.

In addition to the program on uranium fuels, a modest irradiation program has been initiated on thorium fuels. The ultimate objective of this program is to develop fuel elements that would be suitable for use in D₂O-thorium breeder reactors.

B. FABRICATION OF UO₂ TUBES FOR IRRADIATION TESTS

The over-all Du Pont program for development of a low-cost tubular UO₂ fuel element for D₂O power reactors consists of three phases, as outlined below.

Phase I

1. Develop basic techniques for fabricating tubular elements with powdered UO₂ cores and Zircaloy sheaths, including methods for obtaining dense UO₂ particles of acceptable size and quality.
2. Establish operating limits for reference fuel elements containing slightly enriched uranium oxide.

Phase II

1. Extrapolate techniques developed in the first phase to larger elements with approximate dimensions predicted for D₂O-cooled-and-moderated power reactors.
2. Continue tests of most promising UO₂ treatments and fabrication techniques to extend operating limits of reference elements.

Phase III

1. Develop tube spacing methods and proof test assemblies containing concentric tubes with dimensions and operating conditions that approximate those predicted for a power reactor.

Fabrication of test elements for the first phase has been completed, and irradiation tests are in progress. Elements in this phase included those in the SOT-1, SOT-2, SOT-5, and SOT-7 tests (see Table III of this and previous progress reports). Results of these tests have been reviewed

in previous reports; results of current irradiation tests will be reported as they become available.

Fabrication of elements for the second phase of irradiation tests is underway; the first assembly is scheduled to begin irradiation in January 1964. The tubular elements for these tests were designed to mock up the two largest tubes in a fuel assembly containing three concentric fuel tubes as described in DP-830.⁽²⁾ Enrichment of the test elements was selected to provide peak operating conditions in the HWCTR that are representative of operating conditions expected in a power reactor. Because the coolant pressure drop available for test assemblies in the HWCTR is less than that required for the three-tube design of interest, these tubes must be irradiated individually rather than as nested assemblies. Test assemblies will contain columns of short tubes (~1 ft long) rather than the long tubes contemplated for power reactors; the short tubes provide more flexibility in the test assemblies and represent more severe tests than long tubes. Dimensions of the test elements are shown in the following table:

Dimensions of UO₂ Tubes for HWCTR Irradiation Tests

(SOT-6, SOT-8, and SOT-9 tests;
dimensions are in inches)

	<u>Intermediate Tube</u>	<u>Outer Tube</u>
OD	2.544	3.664
ID	1.832	2.984
Core thickness	0.316	0.280
Clad thickness	0.020	0.030
Test designation	SOT-6 and SOT-9	SOT-8
Maximum thermal rating, watts/cm	30 for SOT-6 40 for SOT-9	30

Fuel elements of natural UO₂ for two SOT-6 assemblies have been fabricated; the first assembly is scheduled for irradiation beginning in January 1964. Fuel tubes containing UO₂ enriched to 1.2% U²³⁵ have been fabricated for the SOT-9 test and are also scheduled to begin irradiation in January 1964. Fabrication of the large oxide tubes (SOT-8 test) is scheduled to begin in January 1964.

C. POSTIRRADIATION EXAMINATION OF UO₂ TUBES

Postirradiation examinations were continued on two assemblies of Zircaloy-clad tubes of compacted uranium oxide that failed during irradiation tests in the HWCTR (see DP-865, DP-875). Macroexamination of mounted and ground transverse sections of the tubes confirmed earlier indications that columnar grain growth began at a thermal rating of 25 to 35 watts/cm. Long columnar grains formed in all instances in which the thermal rating was greater than 35 watts/cm. Grain growth extended over about 50% of the core cross section at 35 watts/cm and over 85% of the core at 45 watts/cm. The original shapes and sizes of the UO₂ particles were easily detectable in sections that operated at 10 watts/cm, but were largely obliterated at the higher thermal ratings mentioned above.

Preliminary examinations of polished and etched sections of the Zircaloy sheaths revealed no regions of highly localized zirconium hydride such as were encountered previously in tubes that displayed severe sheath embrittlement.⁽³⁾ The zirconium hydride platelets ranged in concentration from "nil" to "moderate" and were concentrated near the coolant side of the sheath. The heaviest concentrations that were observed are shown in Figure 6. The predominantly radial orientation of the platelets in the inner sheath in this figure was characteristic of the as-fabricated condition of the sheath tubing. This undesirable orientation is believed to result from a sinking operation on the inner sheath tubing prior to fabrication of the fuel tube. A vacuum annealing treatment was later shown to reduce this tendency toward radial hydriding and was included in the fabrication of subsequent fuel assemblies.

D. DESIGN OF THORIUM TUBES FOR HWCTR IRRADIATION TESTS

As the first step in developing a tubular fuel element of thorium that would be suitable for use in a D₂O-thorium breeder reactor, an HWCTR irradiation test of two thorium metal tubes has been designed and preparations have been made for fabrication of the two tubes. The objective of the test, which is scheduled to start in June 1964, is to evaluate the performance of thorium tubes under irradiation conditions that would be encountered in operation of a liquid-D₂O-cooled-and-moderated breeder reactor operating on an equilibrium thorium-U²³³ fuel cycle. Irradiation data from capsule tests conducted by Argonne National Laboratory⁽⁴⁾ indicate that an exposure of the order of 20,000 MWD/tonne is a reasonable goal for thorium tubes in a D₂O-cooled power

reactor (maximum thorium temperature: $\sim 600^{\circ}\text{C}$). Thorium metal was selected in preference to thorium oxide for the first irradiation tests because (a) the metal offers a higher breeding ratio in a power reactor, (b) limited fabrication experience has already been obtained with thorium metal, and (c) metal of suitable quality for the irradiation tests is on hand.

The thorium tubes, which are to be about 10 feet long, will be clad with Zircaloy-2 by a coextrusion process. Uranium²³⁵ (1.5 wt %) will be used to simulate the U^{233} that would be present in the freshly charged thorium tubes of a breeder reactor. Cross-section dimensions of the tubes and predicted operating conditions in the HWCTR are presented in Table IV. Also shown in this table for comparison purposes are corresponding data for a three-tube thorium assembly designed for use in a full-scale D_2O -thorium breeder. The diameters of the HWCTR tubes are reasonably close to those of the intermediate tube of the three-tube assembly.

The predicted maximum core temperature of the HWCTR tubes is 575°C at the beginning of the test, but this temperature will decrease rapidly as the U^{235} is consumed (see Figure 7). The average maximum temperature over the projected test exposure of 10,000 MWD/tonne will be about 500°C .

III. REACTOR DESIGN AND EVALUATION STUDIES

A. DESIGN OF A D_2O -THORIUM BREEDER REACTOR

It was reported in DP-875 that the Du Pont Engineering Department has initiated an engineering design study of a prototype nuclear power station suitable for demonstration of thorium- U^{233} and U^{238} -plutonium fuel cycles in a D_2O -cooled-and-moderated reactor. Progress during the current report period on the formulation of design data for this reactor is reviewed in the following paragraphs.

1. Reactor Capacity

The power rating of the prototype is determined by selection of a fuel design, a minimum fuel length, a minimum number of fuel positions, and a suitable power per position--each defined by the necessity of meeting the objective of establishing in the prototype the construction and operating costs that typify D_2O -moderated reactors. These considerations indicate that the net electrical output of the prototype should be about 300 MWe. It is thought

essential that the fuel assembly cross section in the prototype should be identical with that in a large reference reactor; the recommended length of the fuel column is 15 feet, which is probably the minimum length in a large-scale reactor.

The number of fuel positions should be sufficient to provide a flat zone that is large enough to demonstrate ripple factors, control rod manipulations required for radial flattening, and fuel management techniques required for radial flattening. Of these three considerations, the control rod manipulation appears to require the largest flattened zone. Figure 8 illustrates schematic layouts of three core sizes that have been considered. A layout with approximately 200 fuel positions (Figure 8a) is recommended for the prototype design study because this layout has a single control position clearly in Gang 1, 8 control positions clearly in Gang 2, and 12 control positions clearly in Gang 3. The minimum that should be considered is a 164-fuel-position core (Figure 8b). Here, one control position is clearly in Gang 1, 4 are clearly in Gang 2 (entirely inside the flat zone), and the other 8 control positions have neighboring fuel positions in both the flat and buckled zones. The 132-fuel-position core (Figure 8c) appears to be too small for a good demonstration of control rod flattening procedures and would have too few fuel positions within a region of uniform control settings to provide good statistical measures of fuel performance and hot spot factors under various fuel management techniques.

The tentative power rating of 300 MWe for the prototype reactor is based on a core with about 200 fuel positions and on the fuel assembly performance that is called for in the reference design of a D_2O -thorium breeder. The latter corresponds to an average $\int k d\theta$ of 29 watts/cm when uranium oxide tubes are used as the fuel.

2. Design Parameters

The preliminary design parameters being employed in the prototype design study are summarized in Table V. All of these data are very preliminary, and it is expected numerous modifications will be made as the design study proceeds and as efforts are made to optimize the designs.

On-line fueling is not being included in the preliminary design study of the prototype, and provision will not be made in the design for future incorporation of this feature. However, the design of the reactor proper will be compatible with on-line refueling. This decision was made in the belief

that on-line refueling is not essential to the objective of demonstrating construction and operation of a reactor that is capable of breeding with thorium. The mechanical, hydraulic, and electronic problems of on-line refueling machines can be solved separately, if needed, without attaching a machine to a reactor. Results from fuel management studies and economic evaluations may show that on-line refueling is advantageous for large (viz., 1000-MWe) reactors. Therefore, the prototype design will not incorporate any principles or unique features that are incompatible with on-line refueling.

3. Control Requirements

A control system with the following characteristics has been specified for preliminary prototype design:

- a. The control system will consist of 29 clusters of rods placed on regular lattice positions as shown in Figure 9.
- b. Each cluster will contain two full-length thorium rods and two partial-length thorium rods, all of 1.0-inch diameter or equivalent cross section. Each cluster will also contain a shim element that makes the cluster "black" to thermal neutrons. This element is envisaged as a boron stainless steel tube, rod group, or cruciform rod.
- c. For scram protection, the shim elements in nine clusters must be capable of being driven or falling into the reactor within two seconds after receipt of a scram signal. This action will result in an estimated 3% decrease in reactivity of the core within 2 seconds.
- d. The shim elements and the regulating rods will be combined into three independently operable gangs, or groups, as follows (see Figure 9):

<u>Gang</u>	<u>No. of Clusters</u>	<u>No. of Scram Elements</u>	<u>No. of Shim Elements</u>	<u>No. of Reg. Rods</u>
1	9	5	4	36
2	12	4	8	48
3	8	-	8	32

The nine shim elements that are employed for scram protection will be withdrawn from the reactor as a separate group. Control Gang 1 comprises the central nine positions, Gang 2 the twelve positions in the second ring, and Gang 3 the outermost eight positions.

Rod Withdrawal Rates

The rate of control rod withdrawal has been tentatively set such that a load change of 3% per minute can be accommodated and that the maximum reactivity ramp from control rod withdrawal will be less than 1.0 dollar per minute.

For thorium- U^{233} fuel, the delayed neutron fraction is 0.0035, as compared to 0.0080 for U^{235} - U^{238} . The maximum ramp rate is 0.3% k per minute for withdrawal at 0.5 ft/min of the nine shim elements that are used for scram protection. This is equivalent to about 0.9 dollar per minute for thorium- U^{233} and 0.4 dollar per minute for U^{235} - U^{238} fuel.

The required withdrawal speed of the control rods is not the same for the two fuel loadings. For thorium- U^{233} metal, the speed should be no more than 1 ft/min, so that the reactivity insertion rate is limited to 1.0 dollar per minute. The limit of 1.0 dollar per minute is imposed arbitrarily to protect against the possibility of a startup accident. A thorium metal load has a very small negative power coefficient associated with fuel heating, and the moderator coefficient is not effective because of the very long time constant. In contrast, UO_2 fuel has a strong negative power coefficient that provides inherent protection against startup accidents. With this fuel, the load-following specifications (which require compensation of the power coefficient) place a lower limit on rod withdrawal rate. It is estimated that a withdrawal speed of 3 ft/min will be needed to follow a load change of 3% per minute.

B. CONCEPTUAL DESIGNS OF 1000-MWe REACTORS

Conceptual designs and rough cost estimates were made for 1000-MWe D_2O -moderated power reactors cooled by liquid D_2O , boiling H_2O , or a liquid organic. The objective was to round out the cost optimization program described in earlier

progress reports by extending the data to larger reactors. The designs and costs were developed with the aid of the computer code described in Reference 5. The reactors were not systematically optimized for 1000-MWe reactors, but instead were based on optimization studies for 300- and 500-MWe reactors⁽²⁾.

The salient features of the three 1000-MWe reactors are summarized in Table VI, and estimates of capital and operating costs are presented in Table VII. Computer printout sheets that describe the designs and costs in more detail are presented in the Appendix. The data for the liquid D₂O and boiling H₂O reactors were reported in abbreviated form in DP-875, and are included again in the present report so that information on all three reactors will be available in a single document. The data for the organic-cooled reactor are presented here for the first time.

The energy cost comparison in Table VII is consonant with conclusions drawn previously with respect to the three coolants, namely:

1. The technology of liquid D₂O cooling is farther advanced than that of either boiling H₂O or organic. On this basis, liquid-D₂O-cooled reactors are preferred for early commercialization even though predicted power costs are somewhat lower for the other two coolants.
2. Boiling H₂O does not offer enough potential cost advantage over liquid D₂O cooling to justify the added time and cost that would be necessary for development of boiling H₂O reactors.
3. Organic cooling offers a significant cost advantage on paper opposite liquid D₂O (0.5 mill/kwh at 1000 MWe), but the conceptual design for the organic reactor includes much undeveloped technology. This fact decreases the significance of the indicated cost advantage for organic cooling because cost estimates for systems containing many process unknowns almost invariably prove to be in error on the low side.

IV. USAEC/AECL COOPERATIVE PROGRAM ON D₂O-MODERATED POWER REACTORS

In the past, this series of reports has included periodic reviews of various development projects being executed by Du Pont under the sponsorship of the USAEC/AECL Cooperative Program on D₂O-moderated power reactors. This practice is being discontinued; in the future, these projects will be reported in a new series of monthly reports devoted exclusively to the Cooperative Program. The first report in the new series will cover the work through February 1964. The following current projects will be reported in the new series:

1. Effect of Rod Spacing on Heat Transfer Burnout with Boiling Water.
2. Microprobe Study of Zircaloy Corrosion Films.
3. Irradiation Test of CANDU Fuel Bundles in the HWCTR.
4. Hydride Orientation and Mechanical Properties of Thin-Walled Zirconium Tubing.
5. Use of Sieve Trays to Increase Throughput of GS Process for D₂O Manufacture.

TABLE I

Operating Chronology of HWCTR

Nov. 1-18	Removed failed SOT-7 assembly from liquid loop Startup delayed when newly installed deionizers in loop purification became plugged
Nov. 18	Attained criticality
Nov. 19	Shut down to remove housing tube from liquid loop bayonet Inspection of failed boiling loop bayonet showed housing contributed to failure
Nov. 19-23	Removed housing tube
Nov. 23-24	Attained criticality Made power ascension to 51 MW
Nov. 24-29	Operated at 52-53 MW
Nov. 30	Shut down - feedwater well No. 8 failed
Dec. 1-5	Preparations for first low power physics test
Dec. 5	Conducted low power test #1
Dec. 5-10	Replaced irradiated ring control rods
Dec. 10	Conducted low power test #2
Dec. 10-22	Replaced 24 driver fuel elements, charged new test fuel
Dec. 22	Conducted low power test #3
Dec. 22-29	Prepared for power operation
Dec. 29	Resumed power operation
Dec. 29-31	Power ascension to 26 MW

TABLE II

Operating Summary of HWCTR

	<u>November</u>		<u>December</u>	
Time reactor critical, %	24.3		7.6	
Maximum power, MW	53		26	
Reactor exposure, MWD	<u>Driver</u>	<u>Test</u>	<u>Driver</u>	<u>Test</u>
Month	254	64	13	2
Total accumulated(a)	6268	1460	13	2
D ₂ O losses (100 mol %)				
lb	594		433	
% per year of total inventory(b)	10.2		7.4	

(a) Values in November are accumulated from reactor startup (H-1 cycles); values in December are accumulative since driver replacement (H-2 cycles).

(b) Total inventory of 70,000 lb.

TABLE III

Test Fuel Irradiation Data
November-December 1963(a)

Reactor power 53 MW (November)
26 MW (December)
Coolant pressure 1200 psig
Coolant inlet temperature 183.5°C (November)
Moderator outlet temperature 200°C

Position	Element Number	Fuel Type	Fuel Assembly Description	Starting Date	Discharged	Maximum Nominal Conditions									Maximum Exposure, MWD/ton U(c),	
						Assembly Power(b), MW	Specific Power(c), MW/ton U	Heat Flux, pcu/(hr)(ft ²)	Outlet Temp., °C	Surface Temp., °C	Core-Clad Temp., °C	Core Temp., °C	k/dθ, watts/cm	Attained	Planned	
37	CANDU	Oxide rod	Five 19-rod bundles of natural UO ₂ pellets	10-5-62	-	1.36	32	173,000	221	230	257	-	35.5	4520	9,000	
38	SOT-6-2	Oxide tube	Seven 14" long 2.5" OD tubes of natural UO ₂	12-29-63	-	(d)	(d)	(d)	(d)	(d)	(d)	-	(d)	(d)	5,000	
39	2ETWO-2	Metal tube	Unalloyed, 2.1% enriched 2" OD single tube	5-19-63	11-30-63	1.38	97.5	565,000	203	279	424	507	-	6610	8,000	
40	SOT-1-2	Oxide tube	Seven 14" long tubes of 1.5% enriched UO ₂ (e)	10-5-62	-	0.61	65	324,000	193	244	338	-	25.7	11,390	23,000	
42	2ETWO-3	Metal tube	Same as position 39	6-11-63	11-30-63	1.46	103	598,000	204	281	435	521	-	6420	10,000	
42	OT-1-4	Oxide tube	Same as position 55	12-29-63(f)	-	(d)	(d)	(d)	(d)	(d)	(d)	-	(d)	4030	20,000	
55	OT-1-2	Oxide tube	Single 1.5% enriched UO ₂ vibratory and swaged tube	10-3-63(g)	-	0.82	65	332,000	197	246	346	-	26.4	9020	20,000	
56	SOT-1-3	Oxide tube	Same as position 40(e)	1-6-63	11-30-63	0.60	65	319,000	193	246	336	-	25.3	9220	8,000	
56	RMT-1-2	Metal tube	Unalloyed, natural uranium 60-mil Zircaloy clad tube	12-29-63	-	(d)	(d)	(d)	(d)	(d)	(d)	(d)	-	(d)	6,000	
57	SMT-1-2	Metal tube	Ten 11-1/4" alloyed (Fe,Al) natural uranium tubes	5-19-63	-	0.64	36.5	311,000	219	305(h)	377	441	-	2410	8,000	
58	SOT-1-4	Oxide tube	Same as position 40(e)	7-13-63	-	0.82	89	436,000	197	265	391	-	34.7	5015	12,000	
59	OT-1-7	Oxide tube	Same as position 55	7-13-63	-	1.04	82	420,000	201	266	391	-	33.6	4685	20,000	
60	SMT-1-3	Metal tube	Five 11-1/4" alloyed (Fe,Al,Si) natural uranium tubes	7-13-63	-	0.56	45.5	390,000	214	305(h)	394	474	-	2415	8,000	

(a) Data taken 11-26-63; exposures as of 12-31-63.

(b) "Flow-ΔT" power calculation; does not include moderator heating (gamma and neutron absorption).

(c) These values are based on an assembly power of 1.09 times "Flow-ΔT" power to include moderator heating.

(d) Operation in December for only one day at reduced power level did not produce significant data for newly installed elements.

(e) Originally contained eight tubes. Top tube replaced with dummy fuel piece after vibration damage was observed.

(f) Irradiation testing began 1-6-63; was interrupted on 4-3-63 in favor of another element; recommenced 12-29-63.

(g) Irradiation testing began 10-5-62; was terminated on 6-20-63 because of vibration damage; recommenced 10-3-63.

(h) Temperature limited by surface boiling.

(i) Exposures and specific powers are expressed in terms of 2000-pound tons.

TABLE IV

Thorium Fuel Dimensions and
Operating Conditions for HWCTR Tests

	Reference Fuel Design For 1000-MWe D ₂ O-Thorium Breeder			HWCTR Test	
	Outer	Inter	Inner		
<u>Dimensions, inches</u>					
Fuel OD (clad)	3.661	2.560	1.272		2.540
ID (clad)	3.208	1.988	0.665		1.830
Core thickness	0.187	0.246	0.264		0.295
Length (clad)	184	184	184		118
Cladding thickness	0.020	0.020	0.020		0.030
<u>Operating Conditions</u>					
Coolant inlet temp., °C	264			Start of Cycle	Avg. for 10,000 MWD/ Tonne Exposure
Max. specific power, (a) MW/tonne	60	50	35	180	180
Max. core temp., °C	440	460	460	65	53
Max. surface temp., (b,c) °C	320	320	320	575	500
Max. heat flux, (c) pcu/(hr)(ft ²)	299,000	326,000	360,000	280	260
Minimum BOSF (d)	2.0			550,000	448,000
Enrichment, wt %	1.5 U ²³³			2.2	2.8
				1.5 U ²³⁵	-

- (a) Specific power shown in the table is based on heat generation in the fuel. Total fission heat is about 8% greater than tabulated values.
- (b) Core and surface temperature calculations do not include hot spot factors.
- (c) In HWCTR the maximum surface temperature and heat flux will occur on the inner surface of the tubes. The maximum temperature and heat flux on the outer surface will be about 15°C and 20% lower, respectively, than the tabulated values for the inner surface.
- (d) Calculations of burnout safety factor include an assumed over-all hot spot factor of 0.7, based on experience with similar geometries in the HWCTR.

TABLE V

Description of 300-MWe Prototype
of D₂O-Moderated Power Reactor

Fuel	Th metal (or UO ₂)
Initial enrichment	1.5% U ²³³ (or 1.2% U ²³⁵)
Fuel geometry	3 concentric tubes
Lattice pitch	10 in. square
No. of fuel positions	192
No. of control positions	29
No. of blanket positions	72
Core diameter	13.5 ft
Core length	15 ft
Reactor coolant	Liquid D ₂ O
No. of coolant loops	3 or 4
Coolant piping material	Carbon steel
Pressure tube material	Zr - 2.5% Nb (insulated internally)
Coolant pressure	1700 psi
Coolant inlet temp.	264°C
Coolant outlet temp.	304°C
Max. fuel temp. of average flat zone assembly	460°C (fk dθ 29 watts/cm)
Max. sheath temp.	330°C
Max. heat flux of average flat zone assembly	360,000 pcu/(hr)(ft ²)
Avg. fuel exposure	At least 10,000 MWD/tonne
Throttle steam pressure (saturated)	570 psia
Reactor thermal power	1023 MW
Gross electrical output	321 MW
Net electrical output	300 MW
D ₂ O inventory	290 tons
Fuel inventory	29.3 tonnes Th (23.1 tonnes U)

TABLE VI

Design Features of
1000-MWe D₂O-Moderated Reactors

See Appendix for detailed data.

Coolant	<u>Liquid D₂O</u>	<u>Boiling H₂O</u>	<u>Organic</u>
Fuel material	Uranium Oxide	Uranium Oxide	Uranium Carbide
Fuel cladding	Zircaloy-2	Zircaloy-2	Sintered Aluminum Product
Fuel geometry	← Concentric Tubes →		
Pressure tube material	← Zircaloy →		
Coolant design press., psia	1975	1750	310
Lattice pitch, inches	10.0	9.0	8.0
Number of fuel positions	489	874	730
U ²³⁵ enrichment, wt %	1.2	1.2	1.2
Max. power per fuel position, MW	9.1	4.0	5.2
Max. specific power, MW/tonne U	90	22	40
Max. heat flux, pcu/(hr)(ft ²)	435,000	180,000	293,000
Type of steam cycle	Indirect	Direct	Indirect
Throttle steam temperature and pressure, °C and psia	240/495	312/1470	358/492
Gross turbine efficiency, %	29.7	35.8	32.5
D ₂ O inventory, tonnes	600	370	290

TABLE VII

Estimated Power Costs for 1000-MWe D₂O Reactors

Private Financing; 0.8 Load Factor

Coolant Costs ^(a)	Liquid D ₂ O		Boiling H ₂ O		Organic Liquid	
	10 ⁶ \$	mills/kwh	10 ⁶ \$	mills/kwh	10 ⁶ \$	mills/kwh
Reactor and primary system	29.5	0.61	25.5	0.53	23.7	0.49
Reactor bldg. and auxiliaries	18.7	0.38	17.8	0.37	16.5	0.34
Turbine plant	51.1	1.05	54.2	1.12	46.5	0.96
Indirect costs ^(b)	<u>47.4</u>	<u>0.98</u>	<u>46.6</u>	<u>0.97</u>	<u>41.5</u>	<u>0.86</u>
Total const. cost	146.7	3.02	144.1	2.99	128.2	2.65
D ₂ O (at \$20/lb)	26.5	0.49	16.4	0.30	12.9	0.24
Operating costs ^(c)		0.43		0.36		0.49
Fuel cycle costs ^(d,e)		<u>0.53</u>		<u>0.68</u>		<u>0.61</u>
Total energy cost		4.47		4.33		3.99

(a) Fixed charges on capital are 14.5%/yr for depreciating capital and 13.0%/yr for nondepreciating capital.

(b) Indirect costs are computed by the accounting procedure outlined in the AEC Cost Evaluation Handbook.⁽⁶⁾

(c) Includes D₂O losses at 2%/yr of the D₂O inventory.

(d) See Appendix for details of fuel cycle costs. U²³⁵ price was obtained from the AEC price schedule in Ref. 6. Reprocessing costs were computed in accordance with data in Ref. 6. Pu net credit was assigned at \$8/g. The U²³⁵ use charge was computed at 4-3/4%/yr.

(e) All fuel cycle costs were computed on the basis of continuous on-line refueling. The capital cost of on-line refueling equipment would add an estimated 0.2 mill/kwh to the unit capital costs in this table for all three reactor concepts.

FIG. 1 OPERATING POWER OF HWCTR

FIG. 2 HEAVY WATER QUALITY IN HWCTR

FIG. 3 COMPONENTS FOR BOTTOM FITTING OF
EMPTY HOUSING IN HWCTR BAYONET

FIG. 4 DAMAGE TO INSIDE SURFACE OF HWCTR BAYONET

FIG. 5 HOUSING RIB THAT PENETRATED
BOTTOM OF HWCTR BAYONET

FIG. 6 TRANSVERSE SECTIONS OF IRRADIATED ZIRCALOY SHEATH TUBING
(Tube Z - 257A of Assembly SOT - 2 - 3)

FIG. 7 EFFECT OF EXPOSURE ON CORE TEMPERATURE OF THORIUM TUBES
Predicted Conditions for HWCTR Tests

FIG. 8 CORE LAYOUTS

FIG. 9 CONTROL SYSTEM FOR D₂O-THORIUM PROTOTYPE

APPENDIX

COMPUTER PRINTOUT SHEETS FOR 1000-MWe D₂O-MODERATED REACTORS

	Organic	Liquid D ₂ O	Boiling H ₂ O
LATTICE PITCH IN INCHES	0.80000E 01	0.10000E 02	0.90000E 01
SYSTEM PRESSURE PSIA	0.25000E 03	0.16980E 04	0.15000E 04
DESIGN PRESSURE PSIA	0.31050E 03	0.19757E 04	0.17500E 04
DESIGN TEMPERATURE DG C	0.38000E 03	0.32000E 03	
CLAD THICKNESS IN MILS	0.20000E 02	0.20000E 02	0.20000E 02
WEIGHT OF FUEL LB PER FOOT	0.27000E 02	0.22000E 02	0.40000E 02
INLET TEMP DG C	0.28000E 03	0.26400E 03	0.30000E 03
MAX SUBCHANL OUTLET TEMP DG C	0.38000E 03	0.30400E 03	
NUMBER OF TUBES	3	3	3
MODERATOR TEMPERATURE DG C	0.80000E 02	0.80000E 02	0.80000E 02
OUTER CHANNEL IN MILS	0.10000E 03	0.18000E 03	0.12500E 03
FUEL LENGTH IN INCHES	0.18000E 03	0.18000E 03	0.18000E 03
FUEL DENSITY PER CENT THEOR-O.		0.92000E 02	0.92000E 02
U 235 CONTENT PER CENT	0.11850E 01	0.11850E 01	0.11850E 01
H2O IN MODERATOR PER CENT	0.30000E-00	0.25000E-00	0.25000E-00
LINER THICKNESS IN MILS	0.30000E 02	0.30000E 02	0.20000E 02
DEAD SPACE IN MILS	0.12000E 03	0.60000E 02	0.60000E 02
SURFACE TEMP LIMIT DG C	0.47000E 03	0.40000E 03	
FUEL TEMP LIMIT DG C	0.10000E 04	0.20000E 04	
BOSF LIMIT-O.		0.10000E 01	
OUTLET SATURATION TEMPERATURE DG C			0.31340E 03
MAXIMUM STEAM QUALITY PERCENT			0.30000E 02
FUEL ASSEMBLY EDIT			
MAXIMUM POWER MW	0.40590E 01	0.71804E 01	0.31000E 01
POWER TO MODERATOR MW	0.20663E-02	0.40255E-02	0.40000E-02
REACTOR OUTLET TEMPERATURE DEG C	0.38000E 03	0.30400E 03	
MAXIMUM FLOW, GPM AT TIN	0.32173E 03	0.63978E 03	0.15000E 03
MAXIMUM SUBCHANNEL VELOCITY FT/SEC	0.41677E 02	0.38210E 02	0.50000E 02
PRESSURE DROP PSI	0.76199E 02	0.31321E 02	0.40000E 02
MAXIMUM SURFACE TEMPERATURE DEG C	0.47002E 03	0.33379E 03	0.32500E 03
MAXIMUM FUEL TEMPERATURE DEG C	0.60690E 03	0.20000E 04	0.18000E 04
MAXIMUM HEAT FLUX PCU/HR/SQ FT	0.29282E 06	0.43532E 06	0.18000E 06
MINIMUM BOSF	0.20405E 01	0.30192E 01	0.20000E 01
PHI1	0.16433E 01	0.13995E 01	
PHI2	0.11955E 01	0.11351E 01	
PHI3	0.10000E 01	0.10000E 01	
AXIAL PHI MAX/PHI AVG	0.13988E 01	0.13988E 01	0.14000E 01
INTEGRAL OF K(T) WATTS/CM		0.38428E 02	0.25000E 02
MAX OUTLET STEAM QUALITY PERCENT			0.30000E 02
HOT CLEAN LATTICE PARAMETERS			
CELL SIGMA A	0.81871E-02	0.50472E-02	1.00000E-03
D X SIGMA F	0.99653E-01	0.95958E-01	1.00000E-01
ETA	0.15180E 01	0.15170E 01	0.13000E 01
EPSILON	0.10319E 01	0.10200E 01	0.10300E 01
RES ESCAPE PROBABILITY	0.84823E 00	0.90230E 00	0.90000E 00
THERMAL UTILIZATION	0.95709E 00	0.95542E 00	0.90000E 00
K INFINITY	0.12716E 01	0.13340E 01	0.12260E 01
L SQUARED	0.10350E 03	0.17593E 03	0.60000E 02
TAU	0.14591E 03	0.15363E 03	0.14000E 03
M SQUARED	0.24941E 03	0.32956E 03	0.20000E 03
B SQUARED	0.99423E-03	0.92124E-03	0.11300E-02
CALANDRIA			
OD INCHES	0.36973E 01	0.46016E 01	0.49000E 01
ID INCHES	0.36373E 01	0.45416E 01	0.48600E 01
PRESSURE TUBE			
OD INCHES	0.33973E 01	0.44216E 01	0.47400E 01
ID INCHES	0.33348E 01	0.40064E 01	0.43400E 01
FUEL TUBES-CLAD DIAMETERS			
NO. 1	OD INCHES 0.31348E 01	0.36464E 01	0.40900E 01
	ID INCHES 0.25542E 01	0.31452E 01	0.32800E 01
NO. 2	OD INCHES 0.22234E 01	0.25458E 01	0.28800E 01
	ID INCHES 0.14582E 01	0.19221E 01	0.18400E 01
NO. 3	OD INCHES 0.11252E 01	0.12777E 01	0.14400E 01
	ID INCHES 0.33496E-00	0.61061E 00	0.42300E-00

	Organic	Liquid D ₂ O	Boiling H ₂ O
Pile 1			
THERMAL POWER MW	1700	2000	1500
MODERATOR POWER MW	69	82	63
MAX TO AVE IN TUBES	1.2	1.1	1.2
MAX SP PWR MW/TONNE U	40	90	22
AVE SP PWR MW/TONNE U	13	32	7
MAX TO AVE SPEC PWR	2.9	2.8	3.0
COOLANT FLOW GPM	.1348E 06	.1783E 06	.7267E 05
OUTER REFL DIMNS IN			
	H 228.0	228.0	228.0
	R 145.1	149.4	173.3
CORE RADIUS IN	125.1	129.4	153.3
NO OF FUEL POSITIONS	730	489	874
NO OF CONTROL POSITIONS	37	37	37
NO OF SAFETY POSITIONS	40	40	40
D2O INVENTORY LB	.5317E 06	.5945E 06	.7461E 06
COOLANT LB	.1797E 05	.2890E 05	.3589E 05
U INVENTORY TONNES	127.8	64.5	209.7
THROUGHPUT TAYR U	41.3	46.1	47.8
EXPOSURE MWD/T U	12506	13175	9558
K IN POISON	0.045	0.045	0.044
K IN CONTROL	0.010	0.010	0.010
INITIAL EXCESS K	0.217	0.248	0.172
SPENT FUEL ASSAY			
GM 25/KG U	3.274	2.247	3.909
GM 49/KG U	3.233	2.856	2.645
GM 40/KG U	1.630	1.253	0.885
GM 41/KG U	0.420	0.297	0.184
SHIELD FLUX RADIAL	.1188E 14	.2119E 14	.4137E 13
VERTICAL	.2031E 14	.3736E 14	.8521E 13
Pile 2			
INITIAL EXCESS K	0.198	0.225	0.160
EXPOSURE MWD/T U	18703	24026	17089
THROUGHPUT TAYR U	27.6	25.3	26.7
SPENT FUEL ASSAY			
GM 25/KG U	1.534	0.006	1.152
GM 49/KG U	3.103	2.965	2.950
GM 40/KG U	2.482	2.343	1.649
GM 41/KG U	0.629	0.603	0.417
Pile 3			
THERMAL POWER MW	3230	3600	3000
MODERATOR POWER MW	130	146	123
MAX SP PWR MW/TONNE U	40	90	22
AVE SP PWR MW/TONNE U	26	58	14
MAX TO AVE SPEC PWR	1.5	1.6	1.5
BUCKLED ZONE TURNOVER	0.39	0.33	0.35
COOLANT FLOW GPM	.2562E 06	.3210E 06	.1454E 06
FLAT ZONE RADIUS IN	93.4	90.3	117.6
EXPOSURE MWD/T U	16514	21087	15658
THROUGHPUT TAYR U	59.4	51.9	58.3
SHIELD FLUX RADIAL	.3612E 14	.5795E 14	.1417E 14
VERTICAL	.3454E 14	.5981E 14	.1524E 14
FLAT ZONE			
AXIAL MAX/AVG PHI	1.09	1.10	1.08
EXPOSURE MWD/T U	18885	23934	16949
SPENT FUEL ASSAY			
GM 25/KG U	1.497	0.021	1.183
GM 49/KG U	3.098	2.966	2.949
GM 40/KG U	2.502	2.334	1.635
GM 41/KG U	0.634	0.600	0.413
BUCKLED ZONE			
RADIAL MAX/AVG PHI	1.22	1.27	1.24
AXIAL MAX/AVG PHI	1.33	1.33	1.33
EXPOSURE MWD/T U	13587	18375	13559
SPENT FUEL ASSAY			
GM 25/KG U	2.889	0.887	2.124
GM 49/KG U	3.231	2.958	2.877
GM 40/KG U	1.795	1.777	1.292
GM 41/KG U	0.463	0.448	0.312

	<u>Organic</u>	<u>Liquid D₂O</u>	<u>Boiling H₂O</u>
FUEL ASSEMBLY - OPERATING CONDITIONS			
MAXIMUM POWER MW	0.52205E 01	0.90963E 01	0.40364E 01
MAXIMUM FLOW, GPM AT TIN	0.41384E 03	0.81058E 03	0.19537E 03
MAXIMUM SUBCHANNEL VELOCITY FT/SEC	0.53573E 02	0.48405E 02	0.65123E 02
PRESSURE DROP PSI	0.12606E 03	0.50201E 02	0.67856E 02
MAXIMUM SURFACE TEMPERATURE DEG C	0.46775E 03	0.33340E 03	0.32500E 03
MAXIMUM FUEL TEMPERATURE DEG C	0.60683E 03	0.20017E 04	0.18000E 04
MAXIMUM HEAT FLUX PCU/HR/SQ FT	0.29555E 06	0.43436E 06	0.18000E 06
MINIMUM BOPF	0.18179E 01	0.30430E 01	0.20000E 01
MINIMUM LATTICE PITCH INCHES	0.77785E 01	0.10021E 02	0.93799E 01
NEUTRON HEIGHT INCHES	0.22251E 03	0.22251E 03	0.22251E 03
ASSEMBLY HEIGHT INCHES	0.18000E 03	0.18000E 03	0.18000E 03
FLATTENED HEIGHT INCHES	0.95754E 02	0.87055E 02	0.10262E 03
AXIAL PHI MAX/PHI AVG	0.10876E 01	0.11041E 01	0.10752E 01
INTEGRAL OF K(T) WATTS/CM		0.38322E 02	0.25000E 02

SHIELD DESIGN

SHIELD THICKNESS	IN			
RADIAL THERMAL		0.10146E 02	0.11366E 02	0.78927E 01
TOP THERMAL		0.16776E 02	0.18008E 02	0.15010E 02
BOTTOM THERMAL		0.16776E 02	0.18008E 02	0.15010E 02
RADIAL BIOLOGICAL		0.11400E 03	0.11400E 03	0.11400E 03
SHIELD HEAT LOAD	BTU/HR			
RADIAL THERMAL		0.14333E 06	0.22614E 06	0.73181E 05
TOP THERMAL		0.29228E 06	0.52583E 06	0.18972E 06
BOTTOM THERMAL		0.29228E 06	0.52583E 06	0.18972E 06

PRIMARY COOLANT PIPING DESIGN

NOMINAL PIPE SIZE	INCHES	0.36000E 02
DIRECT COST	DOLLARS	0.17750E 07
ORGANIC INVENTORY	LBS	0.83563E 06
PRESSURE DROP	FT	0.20553E 02
FLOW VELOCITY	FT/SEC	0.23479E 02

CONTAINMENT VESSEL DESIGN

RADIUS	FEET	0.11921E 03	0.11802E 03	0.11260E 03
HEIGHT	FEET	0.10867E 03	0.12050E 03	0.11980E 03
WALL THICKNESS	INCHES	0.62500E 00	0.14866E 01	0.14868E 01
TOP HEAD THICKNESS	INCHES	0.50000E 00	0.74291E 00	0.74300E 00
PRESSURE	PSIG		0.17308E 02	0.18144E 02

ORGANIC DECOMPOSITION RATE	LBS/HR	0.74461E 03
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TURBINE DESIGN

FEEDWATER TEMPERATURE	DEG F	0.38239E 03	0.38688E 03	0.51572E 03
THROTTLE TEMPERATURE	DEG F	0.67699E 03	Sat.	Sat.
DEGREES OF SUPERHEAT	DEG F	0.21224E 03		
THROTTLE PRESSURE	PSIA	0.49187E 03	0.49455E 03	0.14700E 04
GROSS TURBINE EFFICIENCY	PERCENT	0.32493E 02	0.29725E 02	0.35800E 02
GROSS ELECTRICAL OUTPUT	MW	0.10600E 04	0.10844E 04	0.10824E 04
POWER USED BY AUXILIARIES	MW	0.61370E 02	0.82784E 02	0.84041E 02
REACTOR FISSION POWER	MW	0.33608E 04	0.37470E 04	0.31243E 04
NET SYSTEM EFFICIENCY	PERCENT	0.29714E 02	0.26731E 02	0.31954E 02
LOAD FACTOR	PERCENT	0.80000E 02	0.80000E 02	0.80000E 02
INPUT POWER TO TURBINE	MW			0.30234E 04

STEAM GENERATOR DESIGN		Organic	Liquid D ₂ O	Boiling H ₂ O
D2O VELOCITY	FT/SEC		0.14160E 02	
HEAT TRANSFER AREA	SQ FT		0.22707E 06	
LENGTH OF TUBES	FT		0.28412E 02	
NUMBER OF TUBES			0.60994E 05	
DIAMETER	INCHES		0.10275E 03	
PRESSURE ON STEAM SIDE	PSIG		0.50985E 03	
STEAM TEMPERATURE	DEG C		0.24442E 03	
INPUT POWER TO STEAM GENERATOR	MW		0.36481E 04	
H2O INVENTORY	LB		0.19477E 05	
D2O INVENTORY	LB		0.16467E 06	
INPUT POWER	MW	0.32622E 04		
ANNUAL COST	\$/YR	0.16669E 07		
TOTAL COST	\$	0.65659E 07		
ORGANIC INVENTORY	LBS	0.33428E 06		
PRESSURE DROP	FT	0.55790E 02		
EQUIV. STEAM PIPING DIA.	FT	0.55222E 01		
PRESSURE DROP IN PIPING	PSI	0.10272E 02		
ANNUAL COST OF PIPING	\$/YR	0.69783E 05		
SUPERHEATER				
NUMBER OF U-TUBES		0.22352E 05		
LENGTH OF U-TUBES	FT	0.30933E 02		
HEAT TRANSFER AREA	SQ FT	0.11317E 06		
ORGANIC INLET TEMP.	DEG C	0.38000E 03		
ORGANIC OUTLET TEMP.	DEG C	0.36619E 03		
STEAM OUTLET TEMP.	DEG C	0.35844E 03		
SHELL DIAMETER	FT	0.72230E 01		
PRESSURE DROP	FT	0.98737E 01		
COST	\$/SQ FT	0.15055E 02		
ANNUAL COST	\$/YR	0.37389E 06		
BOILER				
NUMBER OF U-TUBES		0.43058E 05		
LENGTH OF U-TUBES	FT	0.28000E 02		
HEAT TRANSFER AREA	SQ FT	0.19733E 06		
STEAM PRESSURE	PSIA	0.51755E 03		
STEAM TEMPERATURE	DEG C	0.24335E 03		
ORGANIC OUTLET TEMP.	DEG C	0.29016E 03		
SHELL DIAMETER	FT	0.64726E 01		
PRESSURE DROP	FT	0.34663E 02		
COST	\$/SQ FT	0.19988E 02		
ANNUAL COST	\$/YR	0.73753E 06		
ECONOMIZER				
NUMBER OF U-TUBES		0.21747E 05		
LENGTH OF U-TUBES	FT	0.12000E 02		
HEAT TRANSFER AREA	SQ FT	0.42713E 05		
ORGANIC OUTLET TEMP.	DEG C	0.28000E 03		
H2O INLET TEMP.	DEG C	0.19466E 03		
SHELL DIAMETER	FT	0.65039E 01		
PRESSURE DROP	FT	0.11254E 02		
COST	\$/SQ FT	0.21495E 02		
ANNUAL COST	\$/YR	0.48574E 06		
FUEL CYCLE COSTS				
BUCKLED ZONE				
FUEL EXPOSURE	MWD/TONNE	0.13587E 05	0.18375E 05	0.13559E 05
THROUGHPUT	TONNES/YR	0.26590E 02	0.26574E 02	0.22183E 02
FUEL PREPARATION AND SHIPPING	\$/KG	0.48190E 01	0.88899E 01	0.88899E 01
FUEL FABRICATION	\$/KG	0.13358E 02	0.95021E 01	0.53789E 01
URANIUM DEPLETION	\$/KG	0.66095E 02	0.66095E 02	0.66095E 02
NET CREDIT FOR REPROCESSING	\$/KG	0.18477E 02	0.16026E 02	0.10385E 02
BURNUP	\$/KG	0.47618E 02	0.50069E 02	0.55710E 02
USE CHARGE	\$/KG	0.93692E 01	0.66520E 01	0.16345E 02
TOTAL FUEL COST	\$/KG	0.75164E 02	0.75113E 02	0.86325E 02
FEAT ZONE				
FUEL EXPOSURE	MWD/TONNE	0.18885E 05	0.23935E 05	0.16950E 05
THROUGHPUT	TONNES/YR	0.32834E 02	0.25312E 02	0.36078E 02
FUEL PREPARATION AND SHIPPING	\$/KG	0.48190E 01	0.88899E 01	0.88899E 01
FUEL FABRICATION	\$/KG	0.13358E 02	0.95021E 01	0.53789E 01
URANIUM DEPLETION	\$/KG	0.66095E 02	0.66095E 02	0.66095E 02
NET CREDIT FOR REPROCESSING	\$/KG	0.24458E 02	0.21776E 02	0.14520E 02
BURNUP	\$/KG	0.41637E 02	0.44319E 02	0.51575E 02
USE CHARGE	\$/KG	0.88723E 01	0.59548E 01	0.13697E 02
TOTAL FUEL COST	\$/KG	0.68686E 02	0.68666E 02	0.79541E 02

PILE AVERAGE

		<u>Organic</u>	<u>Liquid D₂O</u>	<u>Boiling H₂O</u>
TOTAL FUEL COST	\$/KG	0.71585E 02	0.71968E 02	0.82124E 02
FUEL EXPOSURE	MWD/TONNE	0.16515E 05	0.21087E 05	0.15659E 05
ANNUAL FUEL COST	\$/YR	0.42539E 07	0.37342E 07	0.47846E 07
TOTAL FUEL COST	MILLS/KWHR	0.60784E 00	0.53198E 00	0.68386E 00

D2O INVENTORY		LB		
TANK, NOT CORE AND REFLECTOR		0.	0.	0.
PRESSURE TUBE EXTENSIONS			0.54188E 05	
PIGTAILS			0.13160E 06	
COOLANT HEADERS			0.44934E 05	
PRIMARY COOLANT PIPING			0.16051E 06	
PRIMARY COOLANT PUMPS			0.23793E 05	
STEAM SEPARATORS				
TURBINE				
MODERATOR HX SYSTEM		0.43660E 05	0.51490E 05	0.40000E 05
MISCELLANEOUS		0.70000E 05	0.70000E 05	0.70000E 05
CORE- MOD, COOLANT, AND REFL		0.53167E 06	0.59446E 06	0.71023E 06
STEAM GENERATOR			0.16467E 06	
PRESSURIZER VESSEL			0.24344E 05	

PRESSURE DROPS		FT		
PIGTAILS			0.12373E 03	0.94051E 02
PRESSURE TUBE EXTENSIONS		0.49631E 02	0.12938E 03	0.10457E 02
COOLANT HEADERS			0.10421E 02	0.91779E 02
PRIMARY COOLANT PIPING		0.20553E 02	0.15994E 03	0.44172E 02
FUEL ASSEMBLY		0.31807E 03	0.13558E 03	0.20023E 03
FUEL ASSEMBLY ORIFICING		0.	0.	0.20023E 03
STEAM GENERATOR		0.55790E 02	0.41670E 02	
PLENUM CHAMBERS		0.11390E 03		

ORGANIC INVENTORY		LB
PRESSURE TUBE EXTENSIONS		0.44360E 05
PLENUM CHAMBERS		0.10451E 06
PRIMARY COOLANT PIPING		0.83563E 06
PRIMARY COOLANT PUMPS		0.17084E 05
STEAM GENERATOR		0.33428E 06

REACTOR COSTS		DOLLARS		
TOP THERMAL SHIELD		0.53248E 06	0.82995E 06	0.10421E 07
BOTTOM THERMAL SHIELD		0.51908E 06	0.80780E 06	0.10199E 07
RADIAL THERMAL SHIELD		0.57902E 06	0.73701E 06	0.57159E 06
RADIAL BIOLOGICAL SHIELD		0.64049E 05	0.66129E 05	0.71244E 05
SHIELD COOLING		0.65400E 05	0.73593E 05	0.60340E 05
CALANDRIA		0.42862E 06	0.37807E 06	0.58525E 06
REACTOR ENCLOSURE		0.71507E 05	0.72979E 05	0.78401E 05
PRESSURE TUBES		0.11950E 07	0.24009E 07	0.44307E 07
PRESSURE TUBE HARDWARE		0.20591E 06	0.23947E 06	0.46179E 06
PRESSURE TUBE EXTENSIONS		0.86419E 06	0.73966E 06	0.14115E 07
PIGTAILS			0.10432E 07	0.29724E 06
COOLANT HEADERS			0.32563E 06	0.72867E 06
SAFETY RODS		0.57400E 06	0.61848E 06	0.61848E 06
CONTROL RODS		0.15392E 07	0.16421E 07	0.16421E 07
COOLANT MONITORING INSTR		0.27551E 07	0.12903E 07	0.14516E 07
NUCLEAR INSTRUMENTATION		0.10000E 06	0.10000E 06	0.10000E 06
FUEL CHARGING MACHINE		0.16000E 07	0.16000E 07	0.16000E 07
PRIMARY COOLANT PIPING		0.17750E 07	0.41899E 07	0.40298E 07
PRIMARY COOLANT PUMPS		0.25940E 07	0.51101E 07	0.24329E 07
PRESSURIZER VESSEL			0.31512E 06	
THERMAL INSULATION		0.42108E 05	0.32051E 05	0.37033E 05
PRIMARY COOLANT INSTR		0.90000E 06	0.60000E 06	0.20000E 06
STEAM SEPARATORS				0.26368E 07
PLENUM CHAMBERS		0.70019E 06		
STEAM GENERATOR COST	DOLLARS	0.65659E 07	0.61542E 07	
TURBINE COST	DOLLARS	0.46529E 08	0.51080E 08	0.54234E 08

AUXILIARY COSTS	DOLLARS	Organic	Liquid D ₂ O	Boiling H ₂ O
MODERATOR HEAT EXCHANGER	0.37342E	06	0.43143E	06
0.34584E				06
PIPING FOR MOD HEAT EXCHANGER	0.67708E	05	0.73371E	05
0.64837E				05
MODERATOR STORAGE TANK	0.61611E	05	0.65474E	05
0.81967E				05
MODERATOR PURIFICATION SYSTEM	0.16500E	06	0.16500E	06
0.16500E				06
MODERATOR PUMPS	0.51962E	05	0.59401E	05
0.47456E				05
COOLANT MAKEUP SYSTEM	0.55000E	05	0.11800E	06
0.11800E				06
COOLANT PURIFICATION SYSTEM	0.45829E	05	0.24649E	06
0.21808E				06
MODERATOR MAKEUP SYSTEM	0.55000E	05	0.55000E	05
0.55000E				05
D2O DISTILLATION SYSTEM	0.31000E	06	0.31000E	06
0.31000E				06
OFF GAS RECOMBINATION SYSTEM	0.50000E	06	0.50000E	06
0.50000E				06
LIQUID POISON SYSTEM	0.21000E	06	0.21000E	06
0.21000E				06
INTERNAL STRUCTURES	0.22552E	07	0.27816E	07
0.23442E				07
SHUTDOWN COOLERS	0.84000E	05	0.	0.36407E
0.36407E				06
HEATING AND AIR CONDITIONING	0.23415E	06	0.31336E	06
0.18481E				06
WASTE DISPOSAL	0.80000E	06	0.73000E	06
0.73000E				06
REACTOR BUILDING CRANE	0.70042E	05	0.11600E	06
0.11372E				06
COOLANT STORAGE TANK	0.21382E	06	0.73155E	05
0.58918E				05
LAND AND LAND RIGHTS	0.36000E	06	0.36000E	06
0.36000E				06
ACCESS ROADS	0.55000E	06	0.55000E	06
0.55000E				06
MISC STRUCTURES AND SYSTEMS	0.28900E	07	0.28300E	07
0.28300E				07
EXTERNAL FUEL HANDLING	0.22000E	07	0.22000E	07
0.22000E				07
WASTE GAS HANDLING SYSTEM	0.11500E	06		
STEAM TRACING SYSTEM	0.11000E	06		
COOLANT PARTICULATE REMOVAL SYSTEM	0.88000E	05		
ORG DEGAS AND PRESS SYSTEM	0.15601E	06		
ORG WASTE DISPOSAL SYSTEM	0.86297E	05		
CONTAINMENT VESSEL	0.18385E	07	0.38047E	07
0.35587E				07
CONT VESSEL SUBSTRUCTURE	0.17387E	07	0.16903E	07
0.14857E				07
CONTAINMENT VESSEL EXTERNALS	0.37811E	06	0.40826E	06
0.38226E				06
SHADOW SHIELDING	0.47830E	06	0.52654E	06
0.49930E				06
ANNUAL COSTS	\$/YR			
FUEL INVENTORY CHARGES	0.		0.	0.
D2O LOSSES	0.64533E	05	0.52799E	06
0.82000E				05
ORGANIC MAKEUP	0.88710E	06		
OPERATING CHARGES	0.21300E	07	0.21300E	07
0.21300E				07
INSURANCE	0.35787E	06	0.36944E	06
0.35070E				06
ECONOMIC SUMMARY				
I CAPITAL INVESTMENT				
INVESTMENT IN \$				
DIRECT LABOR AND MATERIAL				
REACTOR AND PR CL SYSTEM	0.23671E	08	0.29367E	08
0.25508E				08
TURBINE PLANT	0.46529E	08	0.51080E	08
0.54234E				08
AUXILIARY FACILITIES	0.16482E	08	0.18618E	08
0.17778E				08
INDIRECT CONSTRUCTION	0.41468E	08	0.47354E	08
0.46610E				08
TOTAL CAPITAL COSTS	0.12815E	09	0.14642E	09
0.14413E				09
D2O INVENTORY CHARGES	0.12907E	08	0.26400E	08
0.164 E				08
ORGANIC INVENTORY CHARGES	0.22710E	06		
ANNUAL COST \$/YR				
DIRECT LABOR AND MATERIAL				
REACTOR AND PR CL SYSTEM	0.34323E	07	0.42582E	07
0.36986E				07
TURBINE PLANT	0.67467E	07	0.74066E	07
0.78639E				07
AUXILIARY FACILITIES	0.23899E	07	0.26996E	07
0.25778E				07
INDIRECT CONSTRUCTION	0.60128E	07	0.68664E	07
0.67584E				07
TOTAL CAPITAL COSTS	0.18582E	08	0.21231E	08
0.20899E				08
D2O INVENTORY CHARGES	0.16779E	07	0.34320E	07
0.2132 E				07
ORGANIC INVENTORY CHARGES	0.29523E	05		
ENERGY COST MILLS/KWH				
DIRECT LABOR AND MATERIAL				
REACTOR AND PR CL SYSTEM	0.49044E-00		0.60664E	00
0.52864E				00
TURBINE PLANT	0.96404E	00	0.10552E	01
0.11240E				01
AUXILIARY FACILITIES	0.34149E-00		0.38460E-00	
0.36845E-00				
INDIRECT CONSTRUCTION	0.85917E	00	0.97822E	00
0.96598E				00
TOTAL CAPITAL COSTS	0.26551E	01	0.30246E	01
0.29871E				01
D2O INVENTORY CHARGES	0.23975E-00		0.48893E-00	
0.30486E-00				
ORGANIC INVENTORY CHARGES	0.42185E-02			

ECONOMIC SUMMARY	<u>Organic</u>	<u>Liquid D₂O</u>	<u>Boiling H₂O</u>
II OPERATING EXPENSES			
ANNUAL COST \$/YR			
OPERATING CHARGES	0.21300E 07	0.21300E 07	0.21300E 07
D2O LOSSES	0.64533E 05	0.52799E 06	0.082 E 06
INSURANCE	0.35787E 06	0.36944E 06	0.35070E 06
FUEL INVENTORY CHARGES	0.	0.	0.
ORGANIC MAKEUP	0.88710E 06		
TOTAL OPERATING COSTS	0.34395E 07	0.30274E 07	0.25627E 07
ENERGY COST MILLS/KWH			
OPERATING CHARGES	0.30436E-00	0.30345E-00	0.30444E-00
D2O LOSSES	0.92211E-02	0.75220E-01	0.011 E-01
INSURANCE	0.51136E-01	0.52633E-01	0.50126E-01
FUEL INVENTORY CHARGES	0.	0.	0.
ORGANIC MAKEUP	0.12676E-00		
TOTAL OPERATING COSTS	0.49147E-00	0.43130E-00	0.36626E-00
III FUEL CYCLE COSTS			
ANNUAL COST \$/YR	0.42539E 07	0.37342E 07	0.47846E 07
ENERGY COST MILLS/KWH	0.60784E 00	0.53198E 00	0.68386E 00
NET ELECTRICAL OUTPUT MWE	0.99863E 03	0.10016E 04	0.99835E 03
TOTAL ENERGY COST MILLS/KWH	0.39984E 01	0.44759E 01	0.43421E 01

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