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# HEAVY-WATER-MODERATED POWER REACTORS ENGINEERING AND ECONOMIC EVALUATIONS

**Volume I - Summary Report**

by

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## ABSTRACT

Capital investments and the cost of power were estimated for 21 heavy-water-moderated, natural-uranium-fueled power reactor plants, ranging in capacity from 100 to 460 eMW. Comparisons were made of hot and cold moderator reactors and of the relative merits of pressure tube and pressure vessel designs. Reactors cooled with liquid $D_2O$, boiling $D_2O$, $D_2O$ steam, and helium were evaluated. A cold moderator pressure tube reactor cooled with boiling $D_2O$ shows the most economic promise of the $D_2O$-moderated reactor systems studied to date. Reactors of this type have sufficient reactivity to permit satisfactory fuel exposures, but the development of additional technology is a prerequisite for optimum designs.

At capacities of 300 and 400 eMW, the estimated power costs from the current designs of boiling $D_2O$ pressure tube reactor plants are 11.3 and 9.8 mills/kwh, respectively. From liquid-$D_2O$-cooled concepts of comparable capacities the indicated power costs are 7 to 20% higher.

With an active development program, a power cost of 8.0 to 8.5 mills/kwh may be attained in a 300-eMW boiling $D_2O$ reactor plant within the next decade.

A supplementary report, DP-520, records in greater detail the results of the principal engineering studies.

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## HEAVY-WATER-MODERATED POWER REACTORS ENGINEERING AND ECONOMIC EVALUATIONS

### Volume I - Summary Report

### INTRODUCTION

A study of heavy-water-moderated power reactors was undertaken by du Pont in November 1956, at the request of the Atomic Energy Commission (AEC). The inherent neutron economy of a heavy water reactor permits the use of natural uranium fuel. The need for increased attention to this type of fuel was related by the AEC not only to the prospects for achieving economically competitive nuclear power in the United States, but also to our position for helping other nations under the "Atoms for Peace" program.

The experience gained by du Pont in building and operating the heavy water reactors for plutonium production at the Savannah River Plant was cited by the AEC as an important factor in assignment of this study. The study was performed under the existing prime contract AT(07-2)-1 between the AEC and du Pont and was administered by the Savannah River Operations Office of the AEC.

Work done on this study was a joint effort of personnel of the Atomic Energy Division (AED) of the Explosives Department, the Design Division of the Engineering Department, and subcontractors. Assistance in specialized fields was obtained from other Divisions of the Engineering Department. The over-all study was under the direction of the Technical Division of the AED.

At the inception of the du Pont study, the AEC suggested that the work be focused on the technology of reactors using heavy water both as coolant and moderator. It was further suggested that the heavy water coolant be pressurized liquid rather than boiling. These directions were judged to be fully consistent with the primary objective specified by the AEC; i.e., to establish the technology of a 100-eMW power plant having sufficiently modest research and development requirements to permit completion of construction by mid-1962.

The 1962 target date and its attendant restriction on research and development time dominated the course of the investigation until mid-1958, when the AEC relaxed the target date and requested study of the technology and costs of large capacity power plants, including further evaluation of pressure tube reactors. As a result, du Pont broadened its program to include both liquid-cooled and boiling-$D_2O$-cooled pressure tube concepts and undertook an economic survey of $D_2O$-moderated pressure tube and pressure vessel reactor plants at capacities of 100 to 460 net eMW. This survey was completed in mid-1959.

This report summarizes the results of these economic comparisons and the principal data upon which they were based. A companion report (DP-520) records study results in greater detail, including the engineering evaluations that preceded the economic survey. Detailed information on the research and development programs still in progress is not contained in either report. Excluded also is the work on experimental physics, heat transfer burnout, fuel fabrication and testing, and on the Heavy Water Components Test Reactor (HWCTR). The HWCTR is an irradiation test facility that is being built by du Pont at the Savannah River Plant. Progress in these areas, as well as summaries of the engineering and economic evaluations discussed here, has been reported in quarterly progress reports[1-9] and other publications[10-18].

Subsequent to the completion of the studies that are discussed in this report, a further cost evaluation of three of the reactor concepts described herein was made by Sargent & Lundy, Engineers. As part of this evaluation, Sargent & Lundy prepared preliminary designs and cost estimates for reactor plants that were, in general, compatible with the du Pont reactor designs. The results of the Sargent & Lundy evaluation are summarized in DP-480[23], which also reviews the status of the development program (as of March 1960) on $D_2O$-moderated power reactors.

## SUMMARY

Engineering and economic evaluations were made of various concepts of a full-scale $D_2O$-moderated power reactor plant that is fueled with natural uranium metal. On the basis of a preliminary screening of fourteen concepts at a plant capacity of 100 eMW, three concepts having favorable scale-up characteristics were further evaluated at capacities of 200 eMW, 300 eMW, and 400 eMW. These three concepts were: (1) a pressure vessel reactor cooled by liquid $D_2O$, (2) a pressure tube reactor cooled by liquid $D_2O$, and (3) a pressure tube reactor cooled by boiling $D_2O$. The estimated power costs for these concepts are summarized below and in the bar chart on page 10; design data are listed in Table I, and estimates of investment and power costs are presented in more detail in Tables II and III.

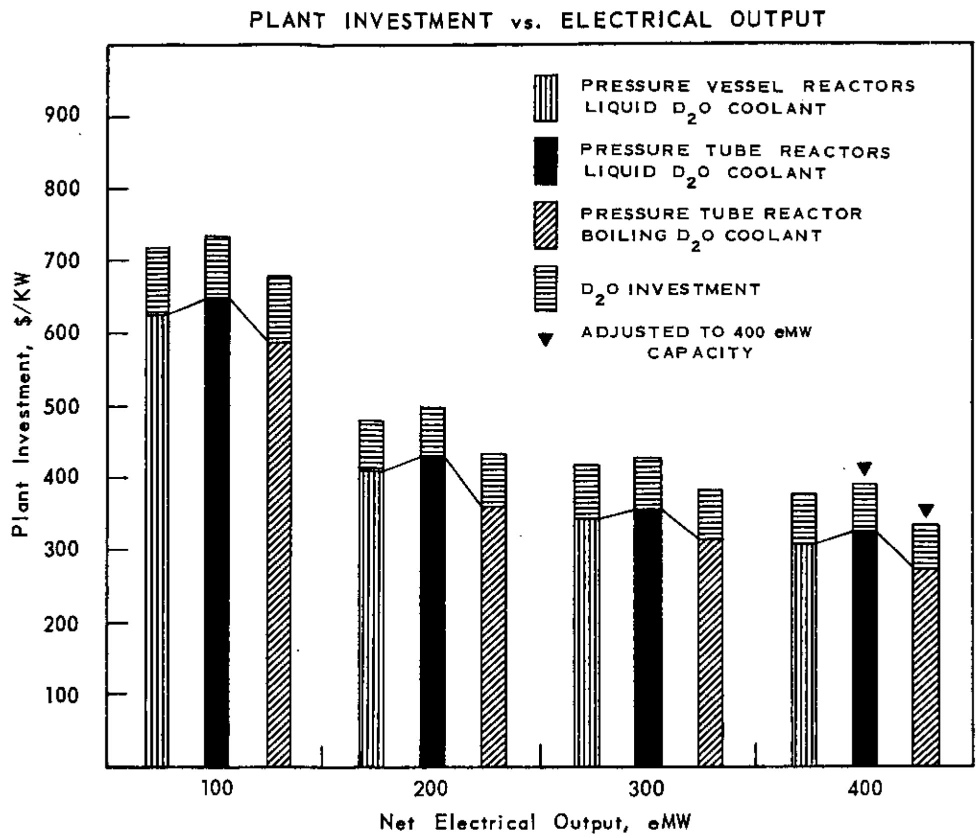
Estimated Power Costs for $D_2O$-Moderated Power Reactors

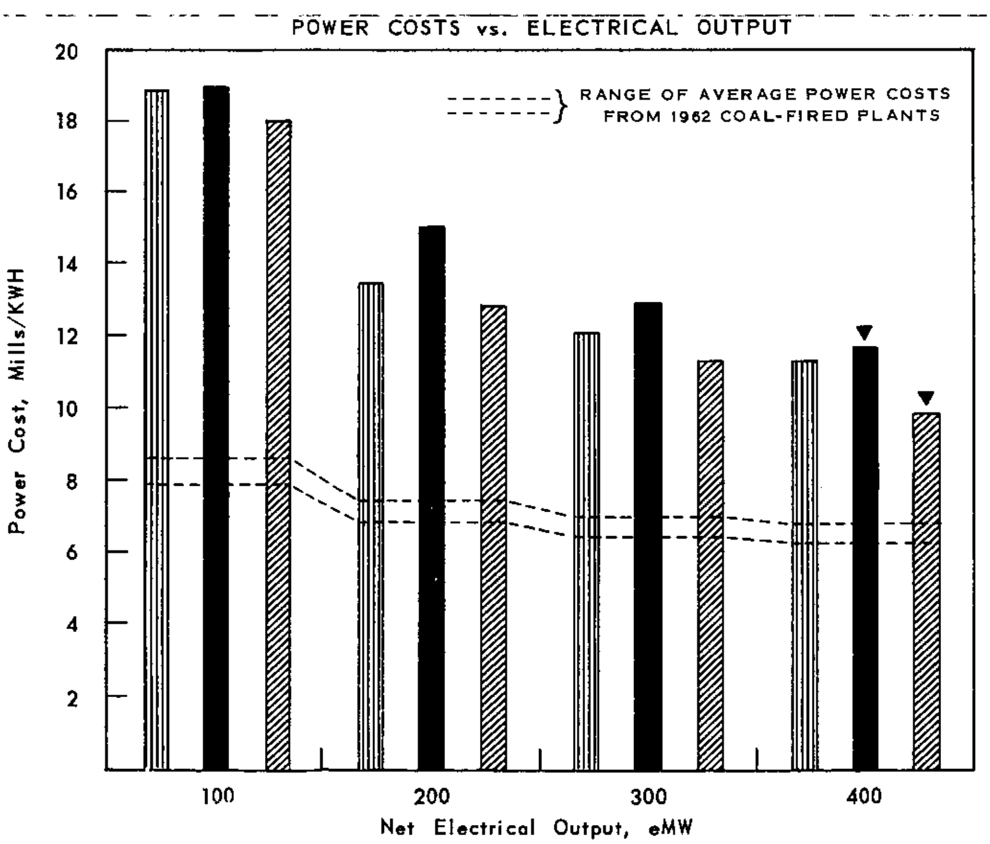
Construction costs are escalated on the basis of plant completion in 1962; plant load factor of 80% assumed

Power Costs, mills/kwh ✓ added

| Plant Capacity, eMW | Pressure Tube Boiling Reactor | Liquid-Cooled Pressure Vessel | Liquid-Cooled Pressure Tube |
|---|---|---|---|
| 100 | 18.0 | 19.0 | 19.1 |
| 200 | 12.8 | 13.5 | 14.9 |
| 300 | 11.3 | 12.1 | 12.9 |
| 400 | 9.8[a] | 11.3 | 11.7[b] |

(a) Adjusted from estimate at 430 eMW
(b) Adjusted from estimate at 460 eMW




INVESTMENTS AND POWER COSTS FOR $D_2O$ - MODERATED NUCLEAR POWER PLANTS

Although uranium metal was postulated as fuel for all reactors in this study, uranium oxide is a feasible alternative. Recent comparisons[23] show that the substitution of oxide fuel increases the total power cost by about one mill/kwh.

Boiling $D_2O$ reactors of the pressure tube type show lower power costs than do the other concepts that were investigated. However, even at high station capacity (400 eMW) the power costs for the boiling reactor are about 50% higher than those for a modern coal-fired plant of the same capacity. The cost of power for all of the concepts is strongly dependent upon plant capacity. The cost drops sharply as capacity is increased from 100 to 200 eMW and more gradually for a further increase in capacity. The decrease in cost with capacity reflects the fact that fixed charges are the dominant factor in the cost of power from all of the $D_2O$-moderated reactors that were examined. At 14% per year, fixed charges on the plant investment range from 56% of the total unit cost of power in the larger capacity plants to about 68% in several of the 100-eMW plants. Fixed charges on the $D_2O$ inventory at 12.5% per year account for an additional 7 to 12% of the total power cost in $D_2O$-cooled reactors.

There is little economic difference between hot and cold moderator reactors. The potential savings in total power cost resulting from the higher nuclear reactivity in a cold moderator reactor are largely dissipated by the cost penalties involved in segregating the moderator and in discarding the heat absorbed therein.

The gas-cooled and $D_2O$-steam-cooled reactor concepts included in this study do not compare favorably with the liquid-$D_2O$-cooled and boiling reactors. The higher reactor investments for the former systems outweigh the lower investment in electrical generation facilities resulting from the improved steam conditions.

The major results of the engineering studies are summarized below:

a. Pressure vessel reactors appear feasible in sizes up to a maximum diameter of about 19 feet with design pressures in the 900 to 1000-psi range. Limiting factors include the size of fabricators' heat-treating facilities and the availability of large diameter flange forgings for vessel closures. The 400-eMW pressure vessel reactor included in this study is sized in accordance with these limitations.

b. Pressure tube reactors can be fabricated in sizes that exceed the diameter limitations of pressure vessel reactors. The feasibility of the pressure tube designs that were studied is dependent on the development of a reliable connection for joining individual Zircaloy pressure tubes to coolant distributors of stainless steel.

c. Engineering studies demonstrated feasible designs for control and safety rod drives and for fuel-handling equipment that can be utilized in $D_2O$-moderated reactors at lattice spacings as small as 6-1/4 inches.

## CONCLUSIONS

1. From an economic standpoint, the most promising $D_2O$-moderated power reactor using natural uranium fuel is a boiling-$D_2O$-cooled pressure tube reactor that operates on a direct steam cycle. However, in the 200 to 400-eMW range, the nuclear power costs from current designs of boiling $D_2O$ reactors are 3 to 5 mills/kwh higher than the average cost of power from modern coal-fired plants of comparable capacity. With further research and development, plus operating experience on prototype units, it is anticipated that part of this cost difference can be eliminated in second- or third-generation plants.

2. For a 300-eMW installation, a power cost of 8.0 to 8.5 mills/kwh may be attainable with a boiling $D_2O$ reactor within the next decade; this cost is some 3 mills/kwh lower than is currently estimated for the same type of reactor. For a 400-eMW plant, the power cost may be reduced to 7.0 to 7.5 mills/kwh. Attainment of these costs is based on (1) a fuel with a 30% lower fabrication cost and capable of an average exposure of at least 6000 MWD/ton, (2) reactor operation at 50% higher power ratings, with the probable inclusion of nuclear superheating, and (3) a 20% reduction in investment requirements.

3. The estimated costs of power from the boiling $D_2O$ reactors are dependent on the success of development programs now under way on these reactors. These programs are designed to furnish additional information on fuel elements, reactor physics, heat transfer burnout, $D_2O$ leakage, hydraulic behavior, reactor stability, and systems analysis.

4. Since none of the 100-eMW $D_2O$-moderated reactors can compete with fossil-fueled plants in the continental USA, their construction can be justified only as prototype units leading to the development and refinement of optimum designs for large capacity plants.

## RECOMMENDATIONS

Continued development effort is necessary if the goal of competitive power from natural uranium in $D_2O$-moderated reactors is to be realized. The development program should include the following:

1. Proof of the feasibility of obtaining high exposure with metallic uranium fuel and improvement of fuel fabrication processes to obtain fuel assemblies of lower cost.

2. A parallel development to reduce the cost of uranium oxide fuel elements.

3. Further study of the nuclear characteristics, heat transfer burnout, stability, and hydrodynamics of boiling $D_2O$ reactors. Design of optimum fuel element and core configurations for both metal and oxide fuels.

4. Development of a reliable Zircaloy-to-stainless-steel joint and continued work on the fabrication of Zircaloy components.

5. Development of reactor concepts including nuclear superheating and possibly using oxide fuel in the high temperature superheater sections.

## DEVELOPMENT PROGRAM

Du Pont's program on $D_2O$-moderated power reactors includes work in most of the recommended areas. The principal activities are as follows:

1. Experimental measurements of the nuclear parameters of natural uranium and of oxide fuel lattices at $D_2O$ temperatures up to 215°C, and their changes with exposure.

2. Development of fabrication processes to lower the cost and improve the quality of Zircaloy-clad fuel elements that contain uranium as metal, oxide, or in alloys.

3. Fabrication of zirconium and Zircaloy components and development of a bonded joint between Zircaloy and stainless steel.

4. Irradiation tests to determine the stability of metallic, oxide, and low alloy uranium fuels under reactor conditions available at SRP, NRU, VBWR, and MTR*. Starting in 1961, exposure in HWCTR of 10-foot-long test elements to the same operating conditions expected in the full-scale power reactors.

5. Fluid flow and mechanical tests on pressure seals, access hole closures, pressure tube connections, fuel element assemblies, safety and control rod mechanisms, charge-discharge machinery, etc.

6. Tests of $D_2O$ leakage rates through pump seals, valve stems, static seals, and nozzle closures.

*SRP, Savannah River Plant; NRU, Chalk River, Canada; VBWR, Boiling Water Reactor, Vallecitos, California; MTR, Materials Testing Reactor, Idaho.

7. Systems analysis of the transient behavior and responses of the boiling $D_2O$ reactor concepts to changes in reactivity, temperature, etc. Study of the hydraulic stability and other characteristics of these concepts.

8. Continued studies at the Engineering Research Laboratories of Columbia University and at the Savannah River Laboratory on heat transfer burnout and two-phase fluid flow in forced convection boiling systems, using configurations and operating conditions applicable to power reactors.

# DISCUSSION

## A. CONTENT OF REPORTS

The results of the du Pont design and economic study on $D_2O$-moderated power reactors, as conducted from November 1956 to mid-1959 are summarized in two companion volumes. This report (Volume I) summarizes the results of the economic studies and includes data and explanatory information that deal directly with the nuclear power plants included in the economic survey.

The Volume II report (DP-520) includes more detailed information on the various reactor concepts and on the results of the engineering studies of the reactors, reactor systems, electrical generation plants, and auxiliary facilities.

## B. STUDY APPROACH

### 1. Basic Reactor Concepts

The initial portions of the du Pont study dealt primarily with liquid-$D_2O$-cooled-and-moderated reactors of the pressure vessel and pressure tube types, since it was felt that these would require the least development effort to meet the original AEC target date for operation in 1962. A power level of 100 eMW was assumed for all concepts, as suggested by the AEC. These reactors were assumed to be fueled with natural metallic uranium in the form of tubular elements clad with Zircaloy-2. Uranium metal was selected as the fuel, in spite of the better irradiation stability and corrosion resistance of the oxide, because of the generally higher reactivity and the potentially lower fabrication cost of metallic fuels.

The initial study was limited to liquid-cooled concepts that did not represent radical departures from current knowledge and which could embody much of the technology that du Pont had already developed in its operation of the Savannah River Plant. These reactor concepts were as follows:

Case 1A. A $D_2O$-cooled pressure vessel reactor moderated with hot $D_2O$. There are no housing tubes surrounding the fuel assemblies; the fuel tubes are in direct contact with the moderator. Saturated steam, which drives the turbine generator, is produced in steam generators by heat transfer between the $D_2O$ coolant and light water.

Case 1B. A $D_2O$-cooled pressure vessel reactor with hot $D_2O$ moderator, similar to Case 1A, except that a Zircaloy housing tube surrounds each fuel assembly to provide higher coolant velocities past the fuel tubes.

Case 1C. A $D_2O$-cooled pressure vessel reactor, similar to Case 1B, except that the $D_2O$ moderator is segregated from the fuel coolant and maintained at about 80°C ("cold" moderator).

Case 1D. A $D_2O$-cooled pressure tube reactor, using cold $D_2O$ as moderator.

A parallel preliminary survey[15] of gas-cooled $D_2O$-moderated power reactors indicated that a helium-cooled system merited further comparison with the liquid-cooled concepts. This system is included in the current evaluations as Case 1G.

Case 2H. Also studied was a $D_2O$-steam-cooled pressure vessel reactor moderated with cold $D_2O$. This reactor would produce superheated $D_2O$ steam at 785 psig and 729°F (387°C).

In June 1958, the AEC relaxed their target date for plant completion in 1962 and requested study of the technology and costs of large nuclear power plants. On the basis of the relaxed target date, the du Pont study was expanded to include the following boiling $D_2O$ concepts:

Case 1J. A boiling-$D_2O$-cooled pressure vessel reactor moderated with hot $D_2O$. Housing tubes surround each fuel element. Saturated $D_2O$ steam from the reactor is piped through a steam separator directly to the turbine generator.

Case 1K. A boiling-$D_2O$-cooled pressure tube reactor moderated with cold $D_2O$. Like Case 1J, dry saturated $D_2O$ steam at 225 psig is piped directly to the turbine generator.

Case 2K. Similar to 1K, but produces saturated steam at 780 psig.

A study of large capacity (200 to 460 eMW) reactor plants of selected types was also started in mid-1958. These types included: (1) liquid-$D_2O$-cooled hot moderator pressure vessels, (2) liquid-$D_2O$-cooled pressure tube reactors, and (3) boiling-$D_2O$-cooled pressure tube reactors.

A substantial portion of the economic results was reported during the progress of the study[9].

## 2. Reactor Physics

The nuclear characteristics of $D_2O$-moderated, natural-uranium-fueled reactor lattices were investigated both theoretically and experimentally at temperatures up to 215°C. The results showed that power reactors fueled with such lattices are feasible from a physics standpoint. The physics measurements facilitated computation of the minimum size of reactor required to obtain a given fuel exposure.

The results of the nuclear physics program have been reported in the quarterly progress reports[1-9] and elsewhere[12-14,17,18], and they are not included in this report.

3. Fuels and Materials

For the liquid-$D_2O$- and boiling-$D_2O$-cooled reactor concepts, tubular uranium fuels alloyed with 2 wt % of zirconium were chosen for initial development. Uranium metal and other low alloys of uranium are being considered as alternative metal fuels.

The feasibility of a potentially low cost coextrusion process for Zircaloy-clad metallic uranium (+ 2 wt % Zr) tubes was demonstrated under a du Pont subcontract to Nuclear Metals, Inc. Numerous corrosion tests of the U - 2 wt % Zr fuel in hot water, including samples with intentional cladding defects, demonstrated a somewhat better corrosion resistance than unalloyed uranium. The stability of these fuel tubes under long exposures to neutron irradiation at high temperatures is being tested by irradiations at SRP and VBWR, and this program will be supplemented by later tests at NRU and in HWCTR.

If metallic fuel tubes should prove unsuitable for power reactor application, uranium oxide elements would be substituted for them. For this reason, a parallel program is in progress on the production of uranium oxide fuels in various forms by potentially low cost methods of mechanical compaction and cladding of oxide powder. At present, the preferred technique involves cold swaging of fused uranium oxide powder between coaxial sheaths of Zircaloy tubing.

Extruded zirconium and Zircaloy housing tubes have been fabricated by the Harvey Aluminum Co. Work is being done at Nuclear Metals, Inc., on the development of a bonded joint between Zircaloy and stainless steel.

4. Heat Transfer Experiments

The Engineering Research Laboratories of Columbia University conducted an experimental study of the heat transfer burnout in water-cooled tubular assemblies of the type designed for the liquid-$D_2O$-cooled reactor concepts. The results of the study were correlated and used to compute the safety factor on heat transfer burnout for the liquid-$D_2O$-cooled 100-eMW power reactor concepts[9,16]. These safety factors ranged from 1.5 to 2.2. A vibration phenomenon that was encountered in some of the burnout experiments was also studied, and the preliminary findings have previously been reported[7,9].

The program at Columbia is currently being extended to include study of heat transfer burnout for the forced circulation of boiling water at conditions applicable to the boiling $D_2O$ reactor concepts.

## 5. Fluid Flow Experiments and Coolant Chemistry

The Savannah River Laboratory performed full-scale flow tests on the fuel element assemblies for the 100-eMW liquid cooled reactor concepts. Their corrosion, erosion, vibration, and pressure drop characteristics were studied[5].

The water quality specified for the power reactor designs was duplicated in some experiments, to determine the corrosive effects of the coolant on fuel element cladding, zirconium conponents, and other structural materials in the system. The lifetime and effectiveness of the resins intended for maintaining the purity of the coolant were also evaluated.

## 6. Design Studies

The design studies initially included a number of 100-eMW liquid-cooled pressure vessel and pressure tube reactor concepts. Later studies included selected concepts at capacities up to 460 eMW. Preliminary reactor designs were prepared, and the various components, such as fuel and housing tube assemblies, control and safety rods, fuel access nozzles, vessel closures, coolant plenums, coolant distributors, etc., were studied in considerable detail. Designs were developed which would avoid or minimize thermal stresses in reactor parts. Calculations were made to define the requirements for internal and external thermal and biological shielding. These designs and the associated studies are described in Volume II (DP-520).

Studies of Zircaloy-2 housing tubes were made to determine: (1) allowable design stress versus temperature, (2) ways of providing thermal insulation, (3) heat leakage to a cold moderator, and (4) reactivity losses to the tube walls. Details are included in Volume II (DP-520).

The basic requirements for instrumentation of power reactors were studied. Equipment was specified for measuring flow, temperature, and fission product activity at each fuel position. Methods were proposed for measuring axial and radial neutron flux variations and reactor power levels.

Preliminary mechanical designs were devised for safety rod, shim rod, and control rod arrangements and their drive mechanisms. A fuel handling scheme was studied to define requirements and feasibility. The results of these studies are described in Volume II (DP-520).

The fabrication feasibility of the pressure tube and pressure vessel reactor concepts was investigated. This part of the study included contacts with representative fabricators to elicit comments on the proposed designs and to determine the feasibility of fabricating pressure vessel reactors in the 400-eMW capacity range. Preliminary information was also obtained on prices and on the time required for fabrication.

Flow diagrams were prepared for typical reactor systems and the associated electrical generation facilities. Piping diagrams and arrangements were prepared for the basic pressure vessel reactor plant (Case 1B). These are shown in Volume II (DP-520).

Vendor contacts were made to determine feasibility and to obtain price information on the reactor coolant pumps and steam generators required for the various reactor plant concepts.

The turbine generator, turbine condenser, feed water heaters, and auxiliary electrical generation facilities were defined. Size and price information was obtained from turbine generator manufacturers for units operating on the proposed steam conditions at capacities of 100 eMW and above.

An over-all power plant arrangement was developed for the basic 100-eMW concept (Case 1B), which included the arrangement of the reactor and associated equipment such as coolant system, steam generators, and fuel handling system, all housed in a containment vessel. The electrical generation equipment was shown installed in a conventional structure.

Auxiliary facilities and service buildings were all included to picture a complete plant (Figures 19 to 23). The required variations in the basic reactor system arrangement for the various reactor concepts were pictured (Figures 24 to 34) where they differ markedly from the basic scheme. The containment vessel designs were examined to determine their suitability for containing an instantaneous release of the energy in the hot $D_2O$ associated with each reactor concept.

Descriptions of the various plant arrangements are given in Section E.

## C. ECONOMIC SURVEY

The economic survey of heavy-water-moderated, natural-uranium-fueled power reactors reported here was completed in mid-1959. During the study the required capital investment and the unit cost of power were estimated for 21 conceptual designs of nuclear power plants ranging in capacity from 100 to 460 net electrical megawatts. The cost figures and the important design features of 17 of these reactor plants are summarized in Tables I, II, and III. Two of the four remaining concepts are variants of Cases 1C and 2H and are described in Sections D-1 and E-11, respectively. The other two concepts were 250-eMW versions of Cases 1B and 1C; both have been superseded. The first phase of this investigation compared various reactor concepts for use in 100-eMW power plants. The second phase of the economic evaluations dealt with plants having capacities greater than 100 eMW, since it was evident from the earlier results and the work done by others that heavy water reactors fueled with natural uranium could approach an economically competitive position only if used as large capacity base load power plants.

1. Method of Cost Estimating

a. Plant Investment

Results on seven of the 17 cases included in this report were shown in earlier quarterly progress reports[7,8]. After a critical review of the original evaluation estimates, which were made on an "intentionally conservative basis"[8], the estimated construction costs of these seven plants were reduced approximately 11.5% from the amounts previously reported. This reduction reflects the current best judgment of the cost of the facilities. Further reductions are believed to be warranted only if they are accomplished by reductions in the scope of the required facilities or by the development of more detailed design data and specifications. All other estimates included in this report were made on this revised basis.

The cost data presented in Tables II and III were derived from several sources. Much information was collected from the du Pont experience in designing, building, and operating the large thermal reactors at the Savannah River Plant. Additional data were gathered from du Pont's extensive experience in purchasing equipment for its commercial chemical plants. Much use was made of information concerning the actual cost of power reactors (e.g., PWR) in the United States. Quotations were obtained from vendors on the cost of key pieces of equipment for the power reactor concepts evaluated in this study.

The estimates of plant investment include an allowance for the development of a 50-acre site that is located east of the Mississippi River and within 1500 feet of water, railroad, public highways, and a power transmission system. The cost of site acquisition is not included. The estimates are based on a normal work week with the use of premium time only as dictated by over-all economy. An allowance is made for anticipated increases in wages and material costs, which would be applicable to plant completion in 1962. The estimates do not include research and development expenses.

The following ground rules affect the plant investments and apply to all the reactor plants:

(1) The ASME Unfired Pressure Vessel Code is used as the design criterion for all pressure vessels as well as pressure tubes.

(2) Containment is provided for the reactor and the primary coolant loop, but not for the turbine generator.

(3) Each plant is provided with facilities comparable to those described in Section E of this report and pictured in Figures 19 through 23.

b. Cost of Power

The following fixed charges were used, as stipulated in a letter dated March 13, 1959, from the Savannah River Operations Office of the AEC:

| | | |
|---|---|---|
| (1) | Annual fixed charges | 14% of plant investment, excluding $D_2O$ costs |
| (2) | Annual $D_2O$ charges | 12.5% of original cost of $28/lb |
| (3) | Annual uranium use charges | 4% of original cost |

A plant load factor of 80% was assumed. Replacement costs for $D_2O$ are based on losing 4% of the $D_2O$ inventory each year by leakage, venting losses, etc. Annual costs for operating and maintenance labor, supervision, technical services, supplies, insurance, etc. were varied as a function of plant capacity.

c. Fuel Costs

The costs of fabricated fuel, as employed in this evaluation, were derived from an earlier estimate of production costs for the coextruded tubular elements that are being developed under a subcontract by Nuclear Metals, Inc. These elements, pictured in Figure 9, consist of uranium metal alloyed with 2 wt % of zirconium. They are clad with 0.015 inch of Zircaloy-2, have outside and inside diameters of 2.06 and 1.47 inches, respectively, and an effective length of 15 feet. The cost of producing this fuel in large quantities, including the natural uranium metal at $40.50/kg, was estimated to be $51.50/kg of uranium.

For reactor concepts that require greater fuel subdivision to satisfy heat transfer requirements (multiple coaxial tubes or twisted ribbons), the fabrication costs were scaled upward to reflect the increased quantity of cladding material and the greater cost per unit weight of uranium for billet preparation, extrusion, heat treatment, inspection, etc. The various tubular fuels range in price from $51.50 to $68/kg uranium, which includes the uranium cost. The comparable cost for twisted ribbons of the same composition was estimated to be $75/kg (Case 1G), while those clad with stainless steel were estimated to cost $65/kg (Case 2H).

Other factors employed in the computation of net fuel costs are listed below:

| | | |
|---|---|---|
| (1) | Shipping charges to reactor plant | $2/kg uranium |
| (2) | Shipping charges to recovery plant | $5/kg uranium |
| (3) | Reprocessing charge | $20/kg uranium |
| (4) | Conversion of U-nitrate to $UF_6$ | $5.60/kg uranium |
| (5) | Credit for plutonium isotopes | $12/gm Pu |
| (6) | Conversion of Pu-nitrate to Pu metal | $1.50/gm Pu |
| (7) | Credit for depleted uranium | AEC schedule of prices |

Fuel inventory costs were based on a 4% use charge for uranium and 12% per annum fixed charges on the fabrication cost of the fuel. The uranium inventory was assumed to include a nine months' supply in fabrication and storage and a six months' supply in reprocessing. No fixed charges were applied to the fabrication cost during the reprocessing period.

2. Layout and Scope of Facilities

In order to establish a basis for cost studies, a conceptual arrangement was made for the buildings and equipment involved in a 100-eMW nuclear power plant, based on a liquid-$D_2O$-cooled-and-moderated pressure vessel reactor. A description of these facilities is included in Section E of this report.

This basic arrangement is illustrated in Figures 19 through 23. The principal buildings shown include the reactor building or containment sphere, the turbine generator building, and the fuel handling building. An aerial view of the relative positions of these buildings is sketched in Figure 19. The facilities for handling the radioactive wastes are not pictured.

a. Reactor Building

Included in the containment vessel are the following facilities:

(1) The reactor with its controls and protective systems

(2) Reactor coolant pumps and piping, steam generators, and steam piping

(3) Moderator and shield cooling systems

(4) Reactor pressurizer vessel (when required) and coolant surge tank

(5) Catalytic recombiner system for $D_2O$ recovery from vented gases

(6) $D_2O$ purification system, consisting of filters, deionizers, and distillation columns. The columns, their drain tanks, and auxiliary equipment are located outside the containment vessel.

(7) A crane with maintenance and cask-handling trolleys

(8) Fuel transfer cask

(9) Biological shielding of the reactor and coolant systems, fuel transfer chutes, etc.

(10) Personnel and equipment air lock, emergency air lock, freight elevator, stairs, ventilation system, sprinkler system, etc.

b. Fuel Handling Building

The fuel handling building includes the following:

(1) Facilities for handling rail and truck shipments

(2) Parts storage, degreasing and assembly facilities, and test and storage areas for new fuel with pertinent equipment

(3) Spent fuel aging basin with cranes, monorails, etc. for transfer to disassembly and to shipping casks

(4) Disassembly equipment

(5) Spent fuel shipping casks and a shielded area for cask loading and transfer to rail cars

(6) Biological shielding as required for personnel protection

c. Turbine Generator Building

The following equipment is included in the turbine generator building:

(1) Turbine generator with exciter, condenser, and auxiliaries

(2) Feed water pumps, heaters, and deaeration equipment

(3) Service crane in turbine bay

(4) Electrical plant facilities in and adjacent to the building, including the main output transformer. The switchyard is not included.

d. Control and Service Building

The upper level includes:

(1) Plant control room with instrument panels and operating consoles

(2) Offices, conference and lunch rooms, and personnel facilities

(3) Health physics facilities, control laboratory, and instrument shop

(4) Tool decontamination and storage

The lower level includes:

(1) A machine shop

(2) Air conditioning equipment for the control room, offices and laboratories. Ventilating equipment for the reactor building, etc.

(3) Air compressors, emergency power equipment, and electrical substation.

e. Auxiliaries and Miscellaneous

Auxiliary items include:

(1) Cooling water pumps and pump house

(2) Water mains and elevated storage tank

(3) Helium storage and compressor

(4) Waste handling and storage facilities and a vent stack

Building services and general facilities include:

(1) Power and lighting distribution

(2) Water treatment and sewage system

(3) Fire protection and telephone system

(4) Heating boiler

(5) Decontamination equipment and equipment and furniture for shops, laboratories, offices, etc.

f. Arrangements for Other Concepts

The basic 100-eMW reactor plant arrangement was found suitable as a basis for housing all of the liquid-cooled 100-eMW reactor concepts.

For the other reactor concepts studied, the sizes and types of containment vessels were varied to fit the desired plant arrangements, with the provision of a building volume adequate to contain any accidental energy realease. Descriptions of the various reactor buildings are given in Section E. Where these differed markedly from the basic case, new arrangements were developed, as shown in Figures 24 to 34.

3. Economic Evaluation of 100-eMW Reactor Plants

Three types of 100-eMW, $D_2O$-moderated power reactors were studied: pressure vessel concepts, moderated with hot or cold $D_2O$; and pressure tube concepts moderated with cold $D_2O$. The reactor coolants included; pressurized liquid $D_2O$, boiling $D_2O$, $D_2O$ steam, and helium gas. Descriptions of these concepts are given in Section E.

Appraisals of the 100-eMW reactor concepts led to the following conclusions:

a. At the estimated total power costs of 18.0 to 20.4 mills/kwh, none of the 100-eMW reactor concepts studied can compete in the United States with fossil-fueled power plants.

For the 100-eMW reactor plants, the over-all investments, including the $D_2O$ inventory, are estimated to be \$649 to \$780/kw (Figure 1 and the following table). These investments are triple those estimated in Section D-3 for modern coal-fired power plants of comparable capacities.

Investments for 100-eMW Power Plants

| | $D_2O$-Cooled Cases | Helium-Cooled, Case 1G | Coal-Fired Plants, 1962 Constr. |
|---|---|---|---|
| Plant investment, \$/kw | 560-671 | 691 | 205-218 |
| $D_2O$ inventory, \$/kw | 81-109 | 52 | - |
| Over-all investment, \$/kw | 649-780 | 743 | 205-218 |

The breakdown of the estimated power costs for the 100-eMW concepts (Table II and Figure 2) shows that the fixed charges on the plant investment at 14% per annum range from 58 to 69% of the totals, with the 12.5% fixed charge on the $D_2O$ inventory accounting for an additional 7 to 11% (gas-cooled Case 1G - 4%).

b. At plant capacities of 100 eMW, pressure vessel reactors with cold moderator have no economic advantage over reactors with hot moderator (Case 1C versus 1B).

c. Increases in the temperature and pressure of the $D_2O$ coolant in 100-eMW cold moderator pressure vessel reactors do not improve their economic status (See Section D-1).

d. Liquid-$D_2O$-cooled pressure tube reactors have no economic advantage over liquid-$D_2O$-cooled pressure vessel reactors of 100-eMW capacity (Case 1D versus 1B). No significant advantage is gained by the pressure tube reactor, even if the price of Zircaloy tubes were lowered from the estimated price of \$50/lb to \$30/lb.

e. At the specific conditions evaluated, gas-cooled and $D_2O$-steam-cooled reactors are less attractive than the 100-eMW liquid-cooled reactors (Cases 1G and 2H versus 1B, 1C, and 1D).

f. At 100-eMW capacity, the most promising boiling-$D_2O$-cooled reactor has a small economic advantage over liquid-cooled or gas-cooled reactors, resulting primarily from a lower plant investment (Case 2K versus 1B, 1C, 1D, and 1G).

g. The only improvement that can effect a sizable reduction in the cost of power from these concepts is a large increase in plant capacity. This conclusion is discussed further in the summary of the second phase of the economic study.

4. Economic Evaluation of Larger Reactor Plants

a. Scope of Survey

The principal objectives of the evaluation of $D_2O$-moderated power reactors in plants of greater than 100-eMW output were as follows:

(1) To determine the relationship between the cost of power and electrical output for the more favorable reactor concepts

(2) To compare the economics of boiling and nonboiling $D_2O$-cooled power reactors

The three reactor types believed most favorable for scale-up to larger capacities are listed in the following table; the plant capacities evaluated are also shown. The design and construction of these reactors should require only modest advances in the existing technology.

Scope of Survey of Large Capacity Power Reactors

| Reactor Type | Type of Construction | $D_2O$ Coolant | $D_2O$ Moderator | Capacity, eMW | | | |
|---|---|---|---|---|---|---|---|
| B | Vessel | Liquid | Hot | 100 | 200 | 300 | 400 |
| D | Tube | Liquid | Cold | 100 | 200 | 300 | 460 |
| K | Tube | Boiling | Cold | 100 | 200 | 300 | 430 |

All of these reactors are fueled with Zircaloy-clad tubes of natural uranium metal. The hot moderator pressure vessel reactors (Type B) use the same $D_2O$ as both moderator and coolant; Figure 10 is a cross section of such a reactor at a capacity of 400 eMW. This 19-foot-diameter vessel exceeds in size any known vessel of its type and crowds the upper limits for construction with existing shop facilities. The manufacture of this type of reactor is discussed in Section D-1 of this report. The specific power rating of this reactor is very high; this is discussed in the next section of this report.

The pressure tube reactors (Types D and K) provide separation of the cold moderator from the hot coolant. Figure 14 is a cross section of an 18.5-foot-diameter large capacity (460 eMW) pressure tube reactor cooled with pressurized liquid $D_2O$. The coolant is distributed to and discharged from the fuel elements through top and bottom plenum chambers. Plenums of this size and complexity have already been constructed. Figure 16 is a cross section of a 430-eMW pressure tube reactor cooled with boiling $D_2O$. This reactor is sized to approximate the 400-eMW capacity of the other large reactors. Individual inlet and discharge piping is used instead of coolant plenum chambers. Descriptions of these two pressure tube concepts are included in Sections E-6 and E-8 of this report.

Gas-cooled reactors were not included in the second phase of the economic survey because their scale-up characteristics (to 400 eMW) do not compare favorably with those of the $D_2O$-cooled reactors. For example, in the 100-eMW liquid-cooled reactors, the tubular fuel elements can readily be subdivided to provide additional heat transfer area. The use of subdivided fuel operating with a higher temperature rise in the coolant provides a means for attaining a marked capacity increase in the liquid-cooled reactors with little effect on their over-all size. By contrast, the fuel elements for the 100-eMW gas-cooled reactors are already finely subdivided, and a very large temperature rise is assumed in the coolant stream.

b. Characteristics of Large Capacity Reactors

The designs of the large capacity power reactors are preliminary and not necessarily the optimum ones that might result from more detailed studies, particularly of fuel configurations, core design, and reactor coolant flows. The predicted performance characteristics of the larger reactors were intentionally made optimistic, to reflect the effect of technical developments expected in the near future.

The larger reactors are all based on the use of concentric tubular fuel elements (2 to 4 tubes per assembly) of Zircaloy-clad metallic uranium, arranged on 6.25 to 9-inch lattice spacings. To facilitate cost comparisons, a 15-foot active core height was specified for all cases, although this dimension may not be optimum for some of the larger cores. The moderator-to-uranium volume ratios for the various concepts range from about 23:1 to 28:1. Average fuel exposures for 100% batch fuel loadings were calculated to be 3200 to 3800 MWD/ton uranium for the liquid-cooled concepts (B and D series) and 3800 to 5000 MWD/ton for the boiling $D_2O$ concepts (K series). In all cases the maximum internal fuel temperatures were calculated to be less than 500°C. In these respects, the larger concepts do not differ markedly from the corresponding 100-eMW designs.

The estimated maximum heat fluxes for the larger liquid-cooled concepts range from 432,000 to 440,000 pcu/(hr)(ft$^2$), except for the 490,000 pcu/(hr)(ft$^2$) value applying to the 400-eMW pressure vessel concept (Case 1B-400). With this exception, the values are similar to those calculated for the 100-eMW cases. In the boiling $D_2O$ concepts (K series), the maximum heat fluxes are estimated to be 200,000 pcu/(hr)(ft$^2$). These fluxes are only slightly higher than the maximum of 194,000 pcu/(hr)(ft$^2$) already attained in EBWR and expected in the Dresden reactor at 125% of rated power.

The larger boiling $D_2O$ reactors are based on the assumption that 30% by weight of the reactor coolant is vaporized in its passage through the fuel assemblies. At the postulated operating conditions, the liquid-vapor mixture at the exit of the fuel assemblies would have an average vapor volume of 92%. The quantitative effects of this high vapor fraction on the nuclear reactivity, heat transfer burnout, and operating stability of forced circulation boiling reactors must still be determined.

Early in this study, the maximum specific power for the uranium metal fuel elements was tentatively limited to 50 MW/ton uranium, and this limit was not exceeded for the 100-eMW reactor concepts. Maximum specific powers for the larger boiling reactors (K series) were estimated at about 40 MW/ton, well below the tentative limit. The larger liquid-cooled pressure tube concepts (D series) show values of about 70 MW/ton, which may not prove excessive.

For the liquid-cooled pressure vessel reactors (B series), the values range still higher, as shown in the following table:

| Case | Max. Specific Power, MW/ton uranium |
|---|---|
| 1B | 36 |
| 1B-200 | 66 |
| 1B-300 | 86 |
| 1B-400 | 104 |

It can be questioned whether or not these higher power levels are attainable, even for a second or third generation design. If not attainable, the larger pressure vessel concepts would have to be rated at lower power levels, thereby increasing the total power cost in the 200 to 300-eMW capacity range by perhaps 10% over the present estimates. The larger boiling reactors would remain first choice from an economic standpoint, but the liquid-cooled pressure tube concepts would then become more attractive than the pressure vessel concepts.

c. Results

In the following discussion, (1) liquid-cooled reactors of the pressure tube and pressure vessel variety are compared, (2) boiling reactors are compared with liquid-cooled reactors, and (3) the plant investments and the power costs are described as functions of plant capacity.

(1) Liquid-$D_2O$-Cooled Power Reactors: Pressure Tubes Versus Pressure Vessels

The following table compares the investment in plant and $D_2O$ and the cost of power from the two types of liquid-$D_2O$-cooled reactors. In Figure 3, these investments are plotted as a function of capacity.

Liquid-$D_2O$-Cooled Reactors
Pressure Vessel Reactors vs. Pressure Tube Reactors

| Plant Capacity, eMW | Reactor Type | Plant Investment, $/kw | $D_2O$ Investment, $/kw | Power Cost, mills/kwh |
|---|---|---|---|---|
| 100 | Pressure Tube | 650 | 81 | 19.1 |
| 100 | Pressure Vessel | 626 | 93 | 19.0 |
| 200 | Pressure Tube | 430 | 68 | 14.9 |
| 200 | Pressure Vessel | 412 | 69 | 13.5 |
| 300 | Pressure Tube | 362 | 66 | 12.9 |
| 300 | Pressure Vessel | 353 | 68 | 12.1 |
| 400 | Pressure Tube | 325[a] | 60[a] | 11.7[a] |
| 400 | Pressure Vessel | 313 | 65 | 11.3 |
| 460 | Pressure Tube | 314 | 56 | 11.1 |

(a)Adjusted from 460-eMW estimate

The previous table and Figure 3 show that the pressure tube reactors are estimated to require about a 4% higher plant investment than the pressure vessel reactors of comparable capacity. The over-all investments, including $D_2O$, are even closer for these two types of reactor plants. Although the comparable investments are not greatly different, the previous table and Figure 6 show a distinct power cost advantage for the larger pressure vessel reactor plants. This results from the lower fuel cycle costs for the pressure vessel reactors.

The mechanical and technical developments required for firm design of these liquid-$D_2O$-cooled reactors are discussed in Section D-1. The construction of either type of reactor is deemed feasible for the sizes considered, although the larger pressure vessels become increasingly difficult to fabricate.

### (2) Liquid-Cooled Versus Boiling-$D_2O$-Cooled Power Reactors

The following table and comparison of Figures 3 and 4 show that boiling-$D_2O$-cooled reactor plants of comparable capacities require lower investments and produce lower cost power than the liquid-$D_2O$-cooled pressure vessel plants. The estimated advantage in plant investment for the boiling reactors over the liquid-cooled plants varies from 6% at 100 eMW to 12% for plants rated at 400 eMW. The lower investments for the boiling reactor plants arise primarily from the elimination of intermediate heat exchangers and from the use of smaller primary coolant circuits. These investment differences, coupled with the higher thermal efficiencies of the boiling reactor plants, result in an estimated power cost advantage which increases from 5% at 100 eMW to 13% in plants of 400-eMW capacity.

Boiling-$D_2O$-Cooled vs. Liquid-$D_2O$-Cooled Reactors

| | Pressure Tube Boiling Reactor | | | Liquid-Cooled Pressure Vessel | | |
|---|---|---|---|---|---|---|
| Plant Cap., eMW | Plant Investment, $/kw | $D_2O$ Investment, $/kw | Power Cost, mills/kwh | Plant Investment, $/kw | $D_2O$ Investment, $/kw | Power Cost, mills/kwh |
| 100 | 588 | 92 | 18.0 | 626 | 93 | 19.0 |
| 200 | 366 | 67 | 12.8 | 412 | 69 | 13.5 |
| 300 | 319 | 63 | 11.3 | 353 | 68 | 12.1 |
| 400 | 275[a] | 60[a] | 9.8[a] | 313 | 65 | 11.3 |
| 430 | 265 | 60 | 9.4 | - | - | - |

(a)Adjusted from 430-eMW estimate

The apparent economic advantage of the boiling-$D_2O$-cooled reactors over the liquid-$D_2O$-cooled reactors can only be achieved through satisfactory solution of the development problems peculiar to the boiling concepts. It should be noted that the design of very large pressure vessels also presents several development problems. The problems associated with the two concepts are discussed in Sections C-5 and D-1 of this report.

It will be shown in a later section (F-2) that the inclusion of nuclear superheating sections in the boiling reactors would further enhance their economic advantage. Inclusion of such facilities in the boiling reactor concepts is deemed much simpler than in the liquid-cooled concepts.

### (3) Effect of Plant Capacity on Investment and Power Cost

The total investment, including $D_2O$, and the unit cost of power from liquid-$D_2O$-cooled and boiling-$D_2O$-cooled reactor plants are plotted as a function of plant capacity in Figures 5 and 6. Figure 5 shows that the total investment in \$/kw for the three types of plants decreases rapidly (about 35%) as capacity increases from 100 to 200 eMW, with a more gradual reduction (about 22%) for a further increase from 200 to 400 eMW.

The curves shown in Figure 6 for the cost of power versus plant capacity for the three reactor types roughly parallel the investment curves. The power costs drop sharply, about 5 mills/kwh, as the plant capacity increases from 100 to 200 eMW; a further increase from 200 to 400 eMW results in a more gradual reduction of some 2 to 3 mills/kwh.

Although the investments and power costs for a 400-eMW boiling $D_2O$ reactor plant are only about one-half of those for a 100-eMW plant, the reactors are not competitive with fossil-fueled plants. The unit investment is nearly twice that estimated for a modern 400-eMW coal-fired plant, and the power cost is about 50% higher (\$335/kw vs. \$174/kw and 9.8 vs. 6.7 mills/kwh, per Section D-3).

## 5. Preferred Reactor Concept

From an economic standpoint, the most promising heavy water, natural uranium reactor is a pressure tube, boiling $D_2O$ reactor operating on a direct steam cycle.*

Although there appears to be little doubt that boiling $D_2O$ reactors are workable, their apparent economic advantage is dependent on satisfactory answers to various problems, some of which are listed on the following page.

* The same conclusion was reached independently by Sargent & Lundy, Engineers, and Nuclear Development Corporation of America in their study of $D_2O$-moderated power reactors.

a. The most important single problem is the development of an adequate low cost fuel element either of natural uranium or of uranium oxide. This problem is common to all $D_2O$-moderated reactors.

b. An analysis is required of the transient response of the boiling $D_2O$ reactor plants to changes in temperature, reactivity, and power load.

c. The development of a reliable Zircaloy-to-stainless steel joint is essential. A metallurgical bond, rather than a mechanical connection, is considered economically desirable to permit restriction of the high cost Zircaloy to the active core region, while maintaining the desired lattice spacings.

d. The work on heat transfer burnout in liquid-cooled fuel assemblies should be extended to include cooling by boiling $D_2O$ at the temperatures, pressures, and vapor fractions postulated for the full-scale reactors. The configurations studied should duplicate or simulate the desired fuel and housing tube assemblies.

e. A further study of the hydraulic stability of the $D_2O$ boilers is required. Associated with this problem is the need for more information on the flow of steam-water mixtures in the selected designs. Methods for assuring a proper flow distribution to each fuel position must be devised and tested.

f. More experimental information is required on the nuclear properties of uranium and uranium oxide lattices cooled by boiling $D_2O$ and the change of these properties with exposure, to permit design of optimum fuel and core configurations.

g. Full-scale hydraulic tests of the fuel assemblies are required to study their pressure drop behavior, as well as their corrosion, erosion, and vibration characteristics.

h. Methods should be explored for chemical treatment of the primary coolant to permit the maximum use of carbon steel equipment.

i. The effects of irradiation on Zircaloy must be further explored to define the limitations of this material for pressure tubes, fuel cladding, and other reactor components.

## D. MAJOR DESIGN ALTERNATIVES

### 1. Comparisons of Pressure Vessel and Pressure Tube Reactors

The $D_2O$-moderated power reactor concepts that are included in this study can all be grouped under the following three basic design classifications:

a. Hot moderator pressure vessel reactors

b. Cold moderator pressure vessel reactors

c. Cold moderator pressure tube reactors

The previous sections have compared the economics of the various reactors. Nuclear and engineering comparisons of the three basic reactor designs are included in this section under the following categories:

a. Nuclear reactivity and fuel exposure

b. Power losses to moderator

c. Reactor coolants

d. Size limitations

e. Operation and control

f. Engineering and mechanical problems

g. Conclusions

a. Nuclear Reactivity and Fuel Exposure

Any $D_2O$-moderated reactor fueled with natural uranium must be large in size to provide adequate nuclear reactivity. For the cases studied, increased lattice spacings will provide a limited additional amount of reactivity from a given core. This reactivity may be used to attain longer fuel exposures and to flatten the power distribution. Although the additional reactivity would lead to lower fuel cycle costs, its attainment requires larger reactors and increased $D_2O$ inventories, with attendant higher fixed charges. An optimum reactor design must therefore be based on an economic balance of the fuel costs and investment requirements.

Because of the present uncertainties in reactivity calculations, it might prove necessary to increase the size of some of the reactors included in this study. The pressure tube reactors could readily be made larger at a modest increase in cost. Enlargement of the pressure vessel reactors would be more costly, particularly for reactors at outputs above 200 eMW.

In the $D_2O$-moderated reactors studied, the reactivity lost through neutron leakage ranges from 3 to 6.5% $k_{eff}$ and varies inversely with the core size. The positioning of control rods or shim rods to flatten the power distribution in the reactor cores is equivalent to a reactivity loss of about 1.5 to 2.5% $k_{eff}$. A reserve of 1.0 to 1.5% $k_{eff}$ must be held in the control rods to override the xenon transients that accompany reductions in power. A further amount of reactivity, about 3.5% $k_{eff}$, must be available to compensate for xenon and samarium poisoning.

Beyond the reactivity requirements just described, reactivity is lost to the temperature coefficients of the moderator and to the parasitic material in the core. These two reactivity losses vary for the three basic types of reactors, leaving differing amounts of excess reactivity available for obtaining long fuel exposures. The following table compares these reactivity losses, the available excess reactivities, and the fuel exposures expected from the $D_2O$ reactors. The figures shown are approximations, but the relative values should hold true.

| Heavy Water Reactors | Hot Moderator Pressure Vessels | Cold Moderator Pressure Vessels | Pressure Tubes |
|---|---|---|---|
| Reactivity losses | | | |
| Temp. coefficients, % $k_{eff}$ | 6-8 | 2-3 | 2-3 |
| Parasitic material in core, % $k_{eff}$ | 1.5 | 1.5 | 2-4 |
| Calandria tubes, (where used), % $k_{eff}$ | - | - | 1-2 |
| Liquid-cooled designs | | | |
| Excess reactivity (hot, poisoned), $k_{eff}$ | 1-2 | 5 | 3-5 |
| Avg. fuel exposure, (batch reloading), MWD/ton | 3500 | 4500 | 3500 |
| Boiling cooled designs | | | |
| Excess reactivity, $k_{eff}$ | - | - | 5-8 |
| Avg. fuel exposure, (batch reloading), MWD/ton | - | - | 4000-5000 |

For the hot moderator concepts, close lattice spacings are required for an optimum design, and this geometry cannot be varied appreciably without having a marked adverse effect on the reactivity. The cold moderator pressure vessel and pressure tube designs permit a somewhat greater latitude, but the lattice spacings may also be limited; a 9.5-in. square spacing is the maximum chosen in this study for the liquid- and boiling-$D_2O$-cooled concepts. For the pressure tube concepts, the core designs require careful study to minimize the use of parasitic materials.

b. Power Losses to Moderator

In the three types of heavy water reactors studied, the heat developed in the moderator by nuclear radiation amounts to about 8% of the reactor thermal power. In the hot moderator concepts, this heat is recovered. In the cold moderator pressure vessel concepts, the losses from heat transfer through the housing tubes and from nuclear radiation, plus possible losses from cross-leakage of coolant and moderator, are expected to consume about 11% of the reactor thermal power. In the cold moderator pressure tube concepts, the losses to the moderator amount to 9 to 13% of the reactor thermal power.

In the present cold moderator designs, all of the heat appearing in the moderator would be lost by heat exchange to the cooling water. Some of this heat loss might be economically recovered by pressurizing the moderator and raising its temperature above 100°C, but this possibility has not been studied. The cold moderator pressure vessel concepts are already designed for operation with a pressurized moderator. In the pressure tube concepts the moderator tanks are operated essentially at atmospheric pressure; the designs could not readily be modified to accommodate higher pressures.

c. Reactor Coolants

The hot moderator pressure vessel concepts are restricted to using $D_2O$ both as moderator and coolant, but it should be possible to operate them with local or bulk boiling in the core. Liquid $D_2O$, boiling $D_2O$, or inert gas can be used as reactor coolants in the cold moderator pressure vessel concepts. In these reactors, it is difficult to eliminate all leakage between the coolant and moderator; this requires that the two fluids be identical or compatible. The maximum coolant conditions in the cold moderator designs are dictated either by the ability of the core materials to withstand higher temperatures or by the pressure limitations of the vessel designs.

The economic effect of increasing the design pressure of the cold moderator pressure vessel reactor, Case 1C, from 950 to 1500 psig was studied. This variant would produce saturated steam at 350 psig (Case 1C, 225 psig). Although the detailed findings are not included in this report, the total power cost was estimated to be 19.4 mills/kwh, 0.4 mills/kwh higher than that estimated for Case 1C. The increased cost resulted from the higher investment in the reactor and associated equipment.

In the pressure tube concepts, complete separation of coolant and moderator is inherent in the designs. This permits a wider selection of reactor coolants, with operation at temperatures limited only by the available materials. The operating pressures are limited primarily by the reactivity lost to the thick-walled pressure tubes.

d. Size Limitations

No exact upper size limit has been established for a pressure tube reactor. The 460-eMW concept shown in Figure 14 includes coolant plenums approximately 18 feet in diameter with numerous penetrations for fuel access, etc., and designed for 1000 psig. Plenum chambers of similar size and complexity have already been built.

Figure 16 illustrates a 430-eMW boiling $D_2O$ pressure tube concept designed for 1000 psig. Individual coolant piping is utilized rather than coolant plenums, which in this case would have to be about 22 feet in diameter. The moderator tank is 21.5 feet in diameter, but this is a low pressure tank that could be assembled at the site.

Field-assembled pressure tube reactors should be feasible for construction in sizes larger than that shown in Figure 16. Transportation limitations and the size of fabricators' facilities are not controlling factors.

The design pressures of the pressure vessel reactors are limited by current fabrication experience and available metal thicknesses to about 1000 psig for the larger sizes and about 1500 psig for the 100-eMW concepts. In addition, the pressure vessel designs are limited in size by existing shop facilities. Shop fabrication is assumed, since lower costs would result, as compared with fabrication at the site.

Figure 10 shows a 400-eMW pressure vessel reactor concept that is believed to be the largest size feasible for construction in existing shop facilities. Inquiries to leading fabricators disclosed that the vessel diameter would be limiting. The stress-relieving furnace at one fabricator's shop can accommodate a vessel with an outer diameter of 19 feet. When this limit was applied to the diameter of the shell flanges, the following dimensions resulted for a 900-psig design:

| | |
|---|---|
| Inside diameter of heads, feet | 16 |
| Outside diameter of shell, feet | 18-1/2 |
| Outside diameter of shell flanges, feet | 19 |
| Thickness of top head, inches | 12-1/2 |
| Thickness of bottom head, inches | 7-3/4 |
| Thickness of shell wall, inches | 6 |
| Height, feet | 40 |

The weight of the empty vessel, excluding the internal shielding, was estimated to be 420 tons, which can be handled with the existing cranes during fabrication and subsequent loading for water shipment.

Several vendors can forge the required shell flanges in half rings with equipment currently in operation. The uniformity of physical properties across the forging and welding areas would require further investigation. Hemispherical heads were chosen over ellipsoidal heads because of their lower cost. Rough calculations showed that a thickness of approximately 12 inches would be required for a hemispherical head versus 18 inches for an ellipsoidal one. At thicknesses above 10 to 12 inches, it is increasingly difficult and costly to obtain homogeneous plates or forgings. Photoelastic testing of a model would be required to establish the required thicknesses for hemispherical or ellipsoidal heads, since present methods of stress analysis do not apply for the acute entry angles encountered at the outer fuel nozzles.

e. Operation and Control

Since its moderator temperature is more directly affected by load changes, a hot moderator reactor should be easier to control than a cold moderator reactor. As a result, the self-regulating effects of a strong negative temperature coefficient of reactivity are realized. In a cold moderator reactor, load changes have little effect on the moderator temperature. However, the temperature coefficient of reactivity is slightly negative for a liquid-cooled design.

In the boiling $D_2O$ pressure tube reactors using metal fuel, the positive void coefficient of the coolant might be large enough to overbalance the negative fuel temperature coefficient. If true, these reactors would not be self-stabilizing. Experimental data will be obtained at the Savannah River Laboratory to determine the magnitude of these coefficients.

Fuel element failures in any of the reactor concepts would contaminate the coolant flow with radioactive fission products. In a hot moderator design, the entire volume of $D_2O$ is subject to contamination. Except for possible cross-leakage, the contamination in a cold moderator design would be confined to the smaller volume of the coolant circuits. In a direct-cycle reactor system, contamination of the coolant circuits could readily be transported from the steam separators to the turbines. For such plants, the fuel channel activity monitoring must be able to detect fuel element failures before gross amounts of radioactivity are released.

f. Engineering and Mechanical Problems

(1) General

The design of all the $D_2O$ reactors is influenced by the following considerations:

(a) The high cost of heavy water requires careful attention to system volumes.

(b) All the designs are based on the use of an access nozzle at each fuel position.

(c) All the designs include provisions for replacement of the Zircaloy components.

(2) Pressure Vessel Reactors

For the pressure vessel reactor concepts, a flanged head closure is desirable to facilitate maintenance access. A considerable amount of development and testing would be required prior to the construction of a 13 to 19-foot-diameter flanged connection for internal pressures of

900 to 1000 psig. A similar flanged construction has recently been used for a large power reactor, indicating that the associated problems are not insolvable.

For all the pressure vessel concepts, the numerous head penetrations to accommodate fuel access, control equipment, and instrumentation require the use of unusually thick heads on vessels that are designed for moderate pressures.

The hot moderator pressure vessel concepts do not deviate greatly from reactor designs that have already been built or considered by others. They differ mostly in the use of many closely spaced fuel access nozzles.

The additional problems associated with the cold moderator pressure vessel concepts include the following:

(a) The presence of cold moderator (about 80°C) and high temperature fuel coolant (about 200°C) in the same pressure vessel introduces additional stress problems over those encountered in the hot moderator designs.

Shown in Figure 11 is a typical conceptual arrangement for a 100-eMW cold moderator reactor, in which the cold moderator occupies the midregion of the vessel and hot coolant occupies the two ends. In an area above the moderator level, the vessel wall is in contact only with inert gas. A mathematical analysis showed that radiation heating of the gas-blanketed area would produce high temperature gradients with resulting high thermal stresses in the vessel walls. It was found that the proper placement of a sufficient thickness of internal thermal shielding would alleviate this problem. Details of this study are given in Volume II (DP-520).

(b) In a cold moderator pressure vessel design, a complete separation of the coolant and moderator is desired, although difficult to achieve. In the current designs it was assumed that there would be some cross-leakage.

(c) The cold moderator vessel designs must provide for equalization of the coolant and moderator pressures, to permit the use of thin-walled fuel housing tubes.

(d) Insulated fuel housing tubes are essential to reduce thermal losses to the cold moderator. A study indicated that a double-walled Zircaloy housing tube could be so dimensioned that the thin annular layer of liquid $D_2O$ (or inert gas) between the two tubes would serve as an insulating medium. Methods for fabrication of these tubes are not yet developed; the insulating properties of the final product must be verified.

### (3) Pressure Tube Reactors

Housing tubes with internal insulation are employed in most of the pressure tube reactor concepts; these housing tubes are the pressure tubes that contain the reactor coolant.

For some pressure tube reactor concepts, the pressure tubes are not internally insulated. This alternative construction utilizes a calandria vessel to contain the moderator, with the pressure tubes passing through the calandria tubes. The construction of a reactor calandria is relatively simple. Adequate clearances can readily be provided to accommodate differences in the radial movement of the pressure tubes and the calandria tubes. Inert gas contained in the annular clearance spaces provides an excellent means of thermal insulation. However, the inclusion of a calandria is undesirable from a nuclear standpoint. The walls of the pressure tubes are in direct contact with the hot reactor coolant, and to withstand the pressure at these temperatures, the tube walls become relatively thick. The thick-walled pressure tubes and the calandria tubes both add a considerable amount of parasitic material to the core.

In contrast, a comparable reactor design based on internally insulated pressure tubes utilizes thinner-walled tubes; these introduce less parasitic material. Such tubes would be less difficult to maintain and replace than would the tubes in a calandria.

The pressure tubes and their connections present serious design problems. The specific designs are now based on Zircaloy-2, which has a reasonable mechanical strength and absorbs a minimum of neutrons. The allowable design stresses for Zircaloy-2 pressure tubes were assumed at 25% of the minimum tensile strength for temperatures below 400°C. A typical design stress chosen for an internally insulated pressure tube was 11,250 psi at a metal temperature of 150°C.

It is essential to develop a reliable, leaktight connection between Zircaloy and stainless steel tubing. The need to maintain the close lattice spacings and the economic desirability of restricting the use of high cost Zircaloy to the active core region directed attention to a compact metallurgically bonded joint. An experimental study of bonded joints is under way at Nuclear Metals, Inc.; initial results appear promising[23].

Although partially offset by the reactivity advantage of a cold moderator the capture of neutrons by the heavy-walled pressure tubes (and calandria tubes) is a fundamental disadvantage of the pressure tube reactors. At present, it is necessary to base the pressure tube designs on available materials, such as Zircaloy-2, whose tensile and yield strengths drop sharply with increasing temperatures. There is a great need for alloys having low capture cross sections and more favorable high temperature properties. Their availability would permit use of thinner-walled pressure tubes, with resulting gains in the reactivity from a given core design.

g. Conclusions

From an engineering standpoint, the three basic reactor designs are all considered feasible. However, they differ in the amount of development required prior to design and construction. The pressure vessel reactors have a small economic advantage in total power cost over the pressure tube concepts, when both are liquid-cooled. The pressure tube concepts cooled with boiling $D_2O$ show a distinct economic advantage over the liquid-cooled reactors of both the pressure vessel and pressure tube types.

Only a moderate additional amount of development time and money would be required to permit firm design of the hot moderator pressure vessel reactors at capacities up to about 200 eMW. Further work would be required to develop final designs and fabrication methods for the 300- to 400-eMW concepts.

Optimistically high specific power ratings have been assumed for the 300- and 400-eMW hot moderator pressure vessel concepts. In addition, the uncertainties in the reactivity calculations at a moderator temperature of about 210°C are of such magnitude that the present core designs for the 200- to 400-eMW concepts might require modification to ensure criticality in the hot, poisoned condition. The economic effects of more conservative power ratings and of core modifications for the pressure vessel reactors could readily magnify the economic advantage of the boiling $D_2O$ pressure tube reactor plants.

The reactivity advantage of a cold moderator favors its use in a natural uranium reactor. When a cold moderator replaces a hot moderator in a pressure vessel reactor, additional problems are encountered. The internal structure is complicated by the need to separate and insulate the hot coolant from the cold moderator. Provisions to minimize thermal stresses must be carefully studied. Firm design of the cold moderator concepts would therefore require a greater engineering and development effort than the hot moderator concepts.

Of the three types studied, a cold moderator reactor of the pressure tube type appears to be the most promising for application in large capacity plants. This type is not limited in size and capacity by fabrication and transportation facilities. High temperature liquid, boiling, or gaseous coolants may be used. From an economic standpoint, boiling $D_2O$ is the preferred coolant. High operating pressures do not greatly complicate the design, although the reactivity losses to thick-walled pressure tubes may prove to be limiting. The inclusion of nuclear superheating is less difficult than in a pressure vessel design.

The potentialities of pressure tube reactors can only be attained through a considerable effort to prove the reliability of the pressure tube and its connections, to develop low cost fuel elements and to design optimum core configurations. Much of this work is either programmed or already under way.

## 2. Electrical Generation Plant Economics

### a. General

Although no detailed designs were made for the electrical generation facilities, sufficient studies were made of their requirements to develop reasonable bases from which costs might be estimated. In order to achieve the best economy in power generation, the following plant variables were investigated to determine their effects on investment costs: (1) steam pressure in saturated cycles, (2) the use of superheated steam, (3) direct cycles as opposed to indirect cycles, and (4) condensing pressure.

A study was made of the investment and power costs from conventionally fueled power stations. The same basic premises were employed as those assumed for the $D_2O$-moderated reactor plants, to permit direct cost comparisons.

The term "Electrical Generation Plant" used in this report includes: the turbine generator and its auxiliaries, the condenser and complete cooling water system, the feedwater piping, pumps and feedwater heaters (including extraction piping), main output transformers (but no switchyard), the buildings and auxiliaries normally associated with such facilities, and allocated portions of site development and of certain service facilities. The investments in steam generators for the indirect cycle plants and in steam separators for the direct cycle plants are included in the reactor plant account.

### b. Steam Pressure in Saturated Cycles

The steam pressure available at the turbine throttle in saturated cycles was found to have little effect on the investment cost of the electrical generation facilities, at least within the range of 150 to 800 psig. For comparable electrical outputs, the investment variation was found to be approximately 2%. The estimated investments were based on prices for the major equipment items, obtained from leading manufacturers.

A comparison of the estimated investments shown in Tables II and III for the K Series (780 psig) of direct cycle plants with the B and D Series (150 to 260 psig) of indirect cycle plants indicates a somewhat greater variation in cost. This resulted from the inclusion in the direct cycle plants of extra facilities for handling $D_2O$ steam over those required for indirect cycle operations using light water.

The investments for saturated steam plants are affected by the number of turbine generator units required for a particular plant output. For example, the estimated electrical generation investment for Case 1B-400 using two turbine-generator units is \$137/kw, whereas the investment for the three-turbine-generator Case 1D-460 is \$149/kw, about 9% higher.

c. Superheated Steam Cycles

The use of superheated rather than saturated steam in the turbine cycle would effect a marked reduction in the electrical generation investment for a given output. The investment costs for the 100-eMW gas-cooled (Case 1G) and steam-cooled (Case 2H) reactor concepts reflect this improvement, even though though the latter case is penalized somewhat for direct cycle requirements. The following table shows the investment figures and steam conditions for Cases 1G and 2H compared with the 100-eMW cases which produce saturated steam.

| Net Output, 100 eMW | Electrical Plant Investment, \$/kw | Throttle Pressure, psig |
|---|---|---|
| Helium-cooled, Case 1G | 171 | 1407 (887°F, 475°C) |
| $D_2O$-steam-cooled, Case 2H | 180 | 785 (729°F, 387°C) |
| Liquid-$D_2O$-cooled, Cases 1B, 1C, 1D | 200 to 202 | 152 to 262 (satd.) |
| Boiling-$D_2O$-cooled, Cases 1J, 1K, 2K | 195 to 209 | 225 to 780 (satd.) |

Only two reactor concepts producing superheated steam were included in this study, and these showed no economic advantage in total power cost. Estimated power costs for Cases 1G and 2H are 20.0 and 20.4 mills/kwh, compared to the 18 to 19-mill power estimated for the six 100-eMW saturated steam cases. The high reactor system investments for these two cases more than offset the lower electrical generation investments.

Additional study of reactor concepts including nuclear superheating appears desirable, to seek a reactor system that can realize the advantage of superheat without a serious penalty in reactor cost.

d. Direct vs. Indirect Cycle

Despite the higher investment required for the power generation facilities, the direct cycle used with the boiling $D_2O$ reactors furnishes power at lower cost than the indirect cycle used with the liquid-cooled reactors. The lower power costs result primarily from the lower investments for the direct cycle reactor systems. A major part of the investment saving for the boiling reactors (K series) results from the elimination of steam generators and the use of smaller reactor coolant systems.

The higher investment for the direct cycle electrical generation plant includes; (1) modification to the turbines, (such as special shaft seals to reduce $D_2O$ leakage, and provisions for casing decontamination prior to maintenance), (2) remote operating controls, (3) double tube sheets on the condensers, and (4) facilities for demineralizing the $D_2O$ condensate stream. The total extra investment in such items is small when compared with the investment savings in the reactor systems.

e. Condensing Pressure

During the course of the economic studies, the idea arose that the total power costs for a particular concept might be reduced by condensing at pressures higher than normally used in conventional power plants. It was theorized that the resulting total plant investment would be sufficiently lower to offset the fuel cost increase caused by the loss in thermal efficiency. This did not prove to be correct.

An analysis of power costs was made for each of the twelve concepts shown in Table III at various condensing pressures, with the temperature rise of the cooling water as an additional variable. With 65°F cooling water assumed available, minimum power costs were found to exist for each case when condensing at 1.5 inches of Hg absolute pressure with a water temperature rise of 17.5°F. Further details of this study are given in Volume II (DP-520).

For all the plant estimates reported herein, a condensing pressure of 1.5 inches of Hg absolute and a cooling water temperature rise of 10°F were assumed; this difference from the optimum added about 0.15 to 0.20 mills/kwh to the total power costs.

f. Comparison of Investment with Conventional Facilities

It was difficult to reconcile the estimated investments in the electrical generation facilities for nuclear power plants with those for fossil-fueled plants having the same electrical output. The higher apparent cost of the nuclear facilities was believed to result from factors related to their low thermal efficiency, i.e., volumetric turbine exhaust flow, condensing load, and cooling water requirements. This suggested that the power generation investment for the nuclear stations might better be estimated as a function of thermal input to the turbines, rather than the conventional function of electrical output.

An investigation was made of fossil-fueled plant investments, reported by the Federal Power Commission (FPC)[21]. Appropriate factors were applied to obtain the electrical generation portion of the total investments, and all investment figures were escalated to the same date. These investments were plotted as a function of the estimated plant thermal input. When escalated to a 1962 base, it was found that the line of best fit agreed quite well with the comparable investments estimated for the 17 different nuclear power plant cases included in Tables II and III. Further details of this study are given in Volume II (DP-520).

3. Power Costs from Coal-Fired Plants

To provide a basis for direct comparison of the cost of power from modern USA coal-fired power plants with costs estimated for the heavy-water-moderated nuclear concepts included in this report, use was made of recent studies by Sargent & Lundy, Engineers,[19] and by the General Electric Company[20] of average costs from coal-fired plants. Additional information was extracted from FPC reports[21]. All investment cost data were escalated to a 1962 base, and fixed charges were calculated at 14% per annum and for an 80% plant load factor, the same as assumed for the nuclear facilities.

The following table summarizes the estimated 1962 investment and power cost information derived from the three sources, for capacities ranging from 100 to 400 eMW.

USA Coal-Fired Power Plant Costs
(Averages for 1962 Installations)

| Source | Net Plant Capacity, eMW | Plant Investment, $/kw | Power Cost, mills/kwh |
|---|---|---|---|
| Sargent & Lundy | 100 | 211 | 7.9 |
| (Single unit plants) | 200 | 189 | 7.1 |
| | 325 | 176 | 6.7 |
| Sargent & Lundy | 120 | 213 | 8.2 |
| (Dual unit plants) | 200 | 196 | 7.5 |
| | 400 | 181 | 6.9 |
| General Electric Company | 100 | 205 | 7.9 |
| (Single unit plants) | 200 | 180 | 7.0 |
| | 300 | 165 | 6.6 |
| | 400 | 160 | 6.4 |
| FPC Reports | 100 | 218 | 8.0 |
| (Single and multiple unit | 200 | 194 | 7.2 |
| plants) | 300 | 182 | 6.8 |
| | 400 | 175 | 6.6 |

The 1962 fuel cost estimated by General Electric was $0.31/MM Btu, and this figure was used with their data. A fuel cost of $0.30/MM Btu was used with the Sargent & Lundy and FPC data. Operating and maintenance costs were based on those included in the reference reports.

## E. DESCRIPTION OF NUCLEAR PLANT CONCEPTS

### 1. General

The over-all nuclear power plant arrangements are based on a layout made for a 100-eMW liquid-$D_2O$-cooled pressure vessel reactor plant and pictured in Figures 19 to 23. The scope of facilities included in this plant has been listed in the earlier section (C-2) on economics. A description of the major items is included in the following section, as they apply to the 100-eMW hot moderator pressure vessel concept selected as the base case (1B).

The other nuclear plants included in the study are described in Sections E3 to E11, which deal primarily with the differences from the basic plant concept, as dictated by the variations in the plant capacity and the type of reactor.

### 2. Basic 100-eMW Hot Moderator Pressure Vessel Reactor Plant

#### a. Reactor Building

A spherical container was selected for the reactor building in preference to either vertical or horizontal cylinders. When comparisons were made, the proportions of a sphere were found best suited for the desired equipment arrangement. The size of the container was dictated more by the layout than by the volumetric and pressure considerations related to its containment function.

The design of the reactor building shown in Figures 19 to 23 is based on a 100-eMW cold moderator reactor in general accordance with Case 1C but little difference would be noted in a design for the 100-eMW hot moderator version, Case 1B. However, in cases where the internal pressure developed by a major accident is the limiting design criterion, the greater stored thermal energy in a hot moderator reactor system would require about a 30% thicker wall for a sphere of the same diameter.

Preliminary studies showed that the 180-foot-diameter sphere selected in this study requires a wall thickness of at least 3/4 inch (of A-201-B steel) for stability under outside loading. Calculations indicated that this thickness is adequate to contain the maximum credible accident of either a hot moderator or cold moderator 100-eMW reactor system.

The "maximum credible accident" assumes a 100% release of the thermal energy in the $D_2O$ coolant and moderator with no heat absorption by shielding or structure. Additional energy from chemical reactions of 25% of the active core plus 25% of the Zircaloy cladding and housing tubes adjacent thereto might result in a short time pressure peak exceeding the design pressure, but lower than the test pressure. This arbitrarily chosen figure of a "25% reaction" is believed to be quite conservative. No attempt was made to determine peak pressures which might result from very rapid (explosive) energy releases. The containment sphere houses (a) the reactor, (b) the coolant circulating system of four 15,000-gpm pump loops with eight steam generators, totaling 32,700 $ft^2$ of heat transfer area, (c) the surge tank, (d) the $D_2O$ liquid and gas purification systems, and (e) the service crane. The $D_2O$ drain tanks and distillation columns are immediately adjacent to, but outside of, the sphere. The lowest point of the sphere is approximately 45 feet below grade. The four coolant loops are segregated from each other by compartmentation and by shielding. This permits limited access for maintenance of an idle loop while the other loops are in operation.

A revolving bridge crane of 120-ton capacity is provided above the reactor. The crane is equipped with a trolley for maintenance work and a cask trolley for fuel charging and discharging. New and spent fuel is handled by means of a manually controlled cask that passes through the shielded hatches to and from the fuel handling building which is located adjacent to the sphere.

Personnel access into the sphere is provided through an air lock that is situated at the principal operating level, 45 feet above grade. The outer shell of the air lock is cylindrical with the ends closed by flat bulkheads. In each of these bulkheads there is a hinged door, 6 feet high by 7 feet wide, that is sealed against a rubber gasket by a mechanical latching mechanism. Small pieces of equipment, such as pumps, motors, and valves, can be handled through the personnel air lock without interrupting reactor operation. Larger pieces, such as steam generators, are handled only during shutdown and pass through a large, bolted and seal-welded access door, also at the 45-foot level. One or more emergency exit air locks are provided, as indicated in Figure 21. In all instances, the doors are interlocked to assure pressure equalization on either side of the bulkhead before unlatching.

b. Reactor

The reactor vessel for Case 1B is pictured in Figure 7. It is 13 feet, 7 inches internal diameter and about 31 feet long, designed for a pressure of 710 psig. The vessel wall is 3-3/8 inches thick, and the thickness of the heads is 9-7/8 inches for the top and 5-1/8 inches for the bottom head. The material of construction is carbon steel (SA-212-B), lined with a 1/4 inch thickness of weld-deposited stainless steel cladding. Heavy water enters the reactor through four nozzles in the vessel wall immediately above the bottom shield. In passing upward through the core, the water surrounds the fuel housing tubes and functions as the moderator. The $D_2O$ reverses direction and enters the housing tubes through slots below the top shield and flows downward through the fuel to serve as coolant. The moderator is hot; its temperature averages 207°C, and the operating pressure is about 525 psig.

The reactor core contains 340 fuel assemblies, each consisting of a single Zircaloy-clad fuel tube of uranium alloyed with 2 wt % of zirconium and surrounded by a Zircaloy housing tube. This U-Zr alloy is assumed for all cases, though frequently termed "metallic uranium". Figure 8 pictures a typical fuel and housing tube assembly, and Figure 9 shows sectional details. The uranium inventory in the reactor is about 30 tons. The $D_2O$ inventory in the entire system is about 165 tons.

A 1-foot-thick radial and axial heavy water reflector surrounds the core of the reactor. Internal thermal shielding plus a limited amount of biological shielding are included at top and bottom and outside the radial reflector. The top and bottom shields provide thermal protection for the vessel heads and, when the reactor is shut down, serve as biological shields for access to the top and bottom heads and to the equipment mounted on them. Each shield is approximately 2.5 feet deep, over-all, and the volume composition is one-half stainless steel and one-half heavy water. Structural rigidity is provided by tubes at each fuel and control position which are welded to the top and bottom plates. The interstices are filled with Raschig rings or other particulate forms of stainless steel. The top shield serves as the support grid for the fuel assemblies. The tubes of the bottom shield engage with the lower end of the fuel housing tubes and conduct coolant into the plenum between the shield and the bottom head of the reactor vessel.

Spiral muffs in the tubes of top and bottom shield permit water flow but prevent radiation leakage.

The shielding outside the reactor consists of concrete thick enough to prevent induction of radioactivity in surrounding facilities, and to permit human access to these facilities during reactor shutdowns.

Monitoring is provided for the temperature, flow, and activity of the coolant effluent from each fuel assembly. The control system consists of twelve shim rods and seven clusters of small control rods, all located at lattice positions. In addition, nineteen safety rods are provided at interstitial locations.

The reactor is arranged for bottom entry of the control rods and safety rods. The safety rods are normally positioned above the core to permit them to fall by gravity in the event of a reactor scram. Thimbles, which project about 6 feet above the top head, house the upper ends of the safety rods when the rods are in a raised position.

A nozzle is provided in the top head at each fuel position to permit fuel replacement without disturbing the head joint. Removal of the top head is necessary only for the replacement of fuel housing tubes and the guide thimbles for the control rods and safety rods.

The total thermal power of the reactor is 440 MW, which is converted, via an indirect saturated steam cycle, into a net electrical output of 100 MW at an over-all thermal efficiency of about 23%. About 1,600,000 lb/hr of saturated steam are produced at a temperature of 185°C and a pressure of about 155 psig by heat exchange with the $D_2O$ coolant in steam generators that are located in each of the four coolant loops.

If all the fuel is discharged from the reactor at one time, the average fuel exposure is calculated to be about 3250 MWD/ton.

A flow diagram and heat balance for this reactor and for its power generation system are shown in Volume II (DP-520).

### c. Reactor Coolant System

Heat is removed from the reactor by pumping a total of 60,000 gpm of liquid $D_2O$ by four parallel circuits through the reactor to the tubes in eight steam generators (two per circuit). Horizontal centrifugal pumps are employed, fitted with shaft seals and provided with means for leak collection. On failure of the primary power supply, flywheels on each pump shaft assure a gradual slowdown of the pumps during the interval before the emergency power is effective. Emergency power is also available for cooling the reactor during shutdowns.

The steam generators are vertical, cylindrical units with U-tube heat exchange surfaces of stainless steel construction. Internal steam separators are included in the upper part of each vessel. Downcomers and internal baffling provide for natural liquid circulation on the steaming side.

### d. Reactor Auxiliary Systems

Auxiliary systems include the reactor pressurizing system, the facilities for accommodating $D_2O$ volume changes in the primary system, and the $D_2O$ purification facilities. Helium gas rather than vapor pressurization was chosen. The need to recombine and recover dissociated $D_2O$ gases was an important factor in this choice. A gas blanket in the top of the reactor displaces an expensive volume of $D_2O$, an additional advantage of inert gas pressurizing. Recovery of deuterium gas from the helium blanket requires a cooler, moisture separator, preheater, catalytic recombiner, aftercooler, moisture separator, and a return pump and compressor. A purge stream from the recombining cycle is passed through adsorbers to recover $D_2O$ and is then vented to a stack. Tritium in the purge stream is diluted to a safe concentration for disposal by discharging the ventilation fans into the same stack.

Ionic purity of the $D_2O$ is maintained by withdrawing a stream from the primary cooling circuits and passing it through a cooler, a mixed resin deionizer, and a filter. Most of the purified stream is returned immediately to the reactor system by a catch tank, pump, and preheater.

A small portion of cool deionized $D_2O$ is pumped to a head tank as source of sealing fluid for the primary coolant pump seals. The remainder of the $D_2O$ from the deionizer is fed to a distillation train that removes $H_2O$ to keep the $D_2O$ content of the system at 99.75 mol %. Bottoms from the carbon steel distillation train are returned to the deionizer feed line. The overhead product, approximately 80 mol % $D_2O$, is returned to a $D_2O$ production facility for reprocessing.

e. Turbine Generator Building and Equipment

The turbine generator building, shown in plan in Figure 20, is a steel-framed "Transite"-enclosed structure, approximately 90 feet wide by 160 feet long, with a 70-foot-high turbine bay. This building houses the turbine generator, condenser, feedwater pumps and five stages of feedwater heaters, water treatment facilities, and other auxiliary equipment. A crane is provided for servicing this equipment. , delete

A single turbine generator is assumed. The turbine is tentatively specified as an 1800 rpm, tandem compound, double-flow unit with 43-inch final stage blades. Interstage moisture separation is required.

f. Fuel Handling Building

Although the fuel handling building is not included in Figures 19 to 23, a schematic plan view is shown in Figure 25. It is visualized as a steel-framed "Transite" building, approximately 250 feet long and 75 feet wide. Access is provided for truck and railroad shipments, with suitable loading and unloading facilities. The building houses areas for new fuel storage, cleaning, assembly and testing, and includes a 30-foot-deep storage basin for spent fuel. This basin communicates with the reactor sphere, as indicated in Figure 21. Suitable cranes, monorails, and minimum requirements for spent-fuel transfer casks are provided in the fuel handling building.

g. Control and Service Building

The control and service building is shown in Figures 20 and 22 as a two-level steel-framed "Transite" structure, 72 feet by 160 feet in plan, located adjacent to the reactor sphere. The lower level houses a machine shop, air conditioning and ventilating equipment, air compressors, emergency power equipment, and an electrical substation.

The upper level of the building contains the control room with operating console, offices, conference room, health physics facilities, control laboratory, instrument shop, tool cleaning and storage, lunch room, and personnel facilities. An enclosed passageway connects the upper level to the personnel air lock entrance of the containment vessel.

h. Auxiliaries and Miscellaneous

Various auxiliaries are included, such as pump house and pumps, elevated water storage tank, helium storage and compressor, waste handling and storage, a vent stack, and the electrical facilities, including the main output transformer.

Building services and general facilities are included, such as power and lighting distribution, sewage system, fire protection, telephone system, heating boiler, decontamination equipment; also the shop, laboratory, and health physics equipment and furniture. Site development includes grading, landscaping, fencing, paving, storm sewers, water mains, and gate house.

3. Large Capacity Hot Moderator Pressure Vessel Reactor Plants

a. Reactor Building

For the 200- to 400-eMW pressure vessel reactors (Cases 1B-200 to 1B-400), it was found that the pressure and volume considerations for containing the energy release from a maximum credible accident outweighed equipment arrangement factors in the selection of a suitable containment vessel.

Figures 24 to 26 show plans and a section of a 240-foot-diameter spherical containment vessel required for housing the 400-eMW hot moderator pressure vessel reactor pictured in Figure 10, along with its six-loop coolant circulating system. This includes six 30,000 gpm pumps in parallel and twelve steam generators, two to a loop. The heat transfer area of the twelve steam generators totals 104,000 $ft^2$ (vs. 32,700 $ft^2$ for Case 1B).

The other equipment and features of this reactor building are similar to those described for the basic 100-eMW case.

For Case 1B-300, the reactor system is housed in a 220-foot-diameter sphere, with the arrangement similar to the 400-eMW case. Four, instead of six, 30,000-gpm primary coolant pumps are required. Eight steam generators with a total area of 73,000 $ft^2$ are included.

For Case 1B-200, the 400-eMW reactor building is scaled down to a 200-foot-diameter sphere. Four 20,000 gpm primary coolant pumps are used, plus eight steam generators with a total area of 49,000 $ft^2$.

b. Reactor

The large capacity pressure vessel reactors are based on the 400-eMW concept shown in Figure 10. This design is an extension and refinement of the 100-eMW design in Figure 7, and is intended to show the maximum size of pressure vessel reactor that is feasible for fabrication with existing shop facilities. Hemispherical, rather than ellipsoidal, heads were selected to reduce the cost and to hold the metal thickness of the top head to a feasible maximum of about 12 inches. An inlet plenum is shown which provides means for distribution of the moderator flow across the reactor core area.

The reactor is arranged for top entry of control rods, shim rods, and safety rods. All are located on lattice positions to limit the required head thickness. An individual nozzle provides access to each fuel assembly.

The power ratings for the 200- to 400-eMW pressure vessels were intentionally chosen at optimistic levels (particularly so for 1B-400) to determine the economic effect of pushing the pressure vessel designs well beyond the power output expected from initial installations. Each fuel assembly consists of two concentric fuel tubes which provide the additional heat transfer area required to prevent burnout. Thinner fuel sections are used to limit the maximum fuel temperatures.

The 200- and 300-eMW reactor concepts are also patterned on Figure 10, though scaled down for their smaller capacities. The following table lists some of the differences between the larger reactor concepts.

| Case | 1B-200 | 1B-300 | 1B-400 |
|---|---|---|---|
| Core diameter, ft | 12 | 13 | 14 |
| Shell ID at core, ft | 14.4 | 16.5 | 17.5 |
| Over-all length, ft | 34.3 | 38.5 | 40.3 |
| Design pressure, psig | 1000 | 1000 | 900 |

These reactors would operate at an average moderator temperature of 213°C, permitting an average fuel exposure of about 3600 MWD/ton for 100% batch reloading. Saturated steam at 170 psig would be fed to the turbine throttle, resulting in an over-all thermal efficiency of 23.4%.

c. Turbine Generator Building

For Case 1B-200 the turbine generator is somewhat larger than for Case 1B. In turn, the turbine building is 20 feet wider, or 110 feet wide by 160 feet long.

The 300- and 400-eMW cases each require the installation of two turbine generator units which are housed in turbine buildings 126 feet wide by 200 feet long.

The service crane and the auxiliary equipment are scaled up as required.

### d. Other Facilities

In general, most of the other facilities are similar or identical to those for the base Case 1B. The principal exceptions are the pump house and pumps, plus the cooling water mains, which are sized for the particular capacity.

## 4. Cold Moderator 100-eMW Pressure Vessel Reactor Plant

### a. Reactor Building

The reactor building shown in Figures 19 to 23 and described for the base case (1B) actually pictured an arrangement for the cold moderator pressure vessel concept, Case 1C. The primary difference between the two arrangements is the inclusion for Case 1C of separate pump circuits and heat exchangers for cooling the moderator.

As in the base case, the equipment arrangement dictated the size and selection of the particular containment vessel.

### b. Reactor

The 100-eMW liquid-cooled cold moderator pressure vessel reactor chosen for evaluation as Case 1C is shown in Figure 11. In this particular concept the vessel walls are exposed in adjacent areas to hot coolant, cold blanket gas, and the cold moderator. A study of the temperature gradients along the reactor shell disclosed that radiation heating of the vessel wall in the gas-blanketed area would give rise to very severe bending stresses. It was shown that the inclusion of suitably placed internal thermal shielding would alleviate this problem. Details of this study are included in Volume II (DP-520).

The reactor vessel is 43 feet 6 inches in over-all height, and has an inside diameter of 13 feet 2 inches. It is constructed of carbon steel (SA-212-B) lined with a 1/4-inch thickness of weld-deposited stainless steel cladding and weighs approximately 200 tons, exclusive of internal shields. The minimum wall thickness is about 4-1/2 inches. The top head is about 12 inches thick; the bottom head is 6 inches thick. Both heads include numerous penetrations for fuel access nozzles, instrument pins, control rods, and safety rods.

A total coolant flow of 60,000 gpm enters through four 18-inch nozzles above the top shield, passes through a perforated distributor, and enters the fuel housing tubes which are suspended in sleeves that pass through the top shield. The coolant emerges from the housing tubes below the bottom shield and exits through four 18-inch nozzles.. The moderator flow totals 8900 gpm and enters through four 6-inch nozzles just above the lower shield, passes upward through the core, and leaves the reactor through nozzles located below the top shield. Flexible metal seals connect the top and bottom shields to the reactor wall to prevent crossflow between the coolant and the moderator.

The arrangement shown in Figure 11 is based upon bottom entry of control and safety rods, similar to the base case (1B). Sufficient height is provided in the vessel to position the safety rods above the core during normal operation, thus permitting them to fall by gravity for emergency shutdown.

The 310 fuel tubes are identical to those used for the base case, but the housing tubes include internal insulation to reduce heat losses to the moderator. A thin-walled Zircaloy liner tube is inserted in each housing tube to provide a thin annular stagnant gas layer as the actual insulating medium. Individual nozzles are provided in the top head to permit charging and discharging of fuel. Replacement of the fuel housing tubes and other parts of the core requires removal of the top head.

The head flange is locked to the shell by interrupted buttress threads that require only a fractional turn of the head to open. Sealing is effected by a stuffing box that has soft packing and accessible gland bolts which permit tightening while the reactor is pressurized. This design represents one of several investigated as alternatives to the conventional bolted flange.

The reactor contains two gas-filled regions; one is above the moderator and the other above the coolant in the top head. Although both regions are at essentially the same pressure, the moderator blanket will be at a lower temperature and will contain less vapor than the coolant blanket. The insulating annuli of the fuel housing tubes can therefore be vented into the moderator gas blanket without incurring condensation in the annuli and the consequent loss of insulating effect.

The cold moderator pressure vessel is designed for 950 psig and operates at 730 psig with a coolant temperature of about 250°C. The average moderator temperature is 80°C.

The four coolant loops remove the reactor heat by exchange to boiling light water in the steam generators. These produce 225-psig saturated steam, as measured at the turbine throttle, versus 152-psig steam for the basic hot moderator case (1B). The gross steam cycle efficiency for Case 1C is therefore higher, but this advantage is overbalanced by the 11% unrecovered loss of reactor power to the cold moderator. This requires a reactor operating power of 460 thermal MW for Case 1C versus 440 MW for Case 1B. The resulting over-all thermal efficiency is about 22% versus 23% for the base case.

The average fuel exposure is calculated to be 4500 MWD/ton for Case 1C (Case 1B = 3250 MWD/ton), which reduces the fuel costs. It was shown in the economic section (C-3) that the higher investments required for the cold moderator case offset these lower fuel costs.

c. Other Facilities

Aside from the equipment housed in the reactor building, the facilities for the cold moderator case are nearly identical with those for the base case. The pump house includes additional pumping capacity to provide water for the moderator coolant circuits.

5. Liquid-Cooled 100-eMW Pressure Tube Reactor Plant

a. Reactor Building

The reactor building and the equipment arrangement would be essentially the same as that shown for the cold moderator pressure vessel (Case 1C).

b. Reactor

The 100-eMW liquid-cooled pressure tube reactor concept evaluated as Case 1D is shown in Figure 13. In this concept, the cold moderator is contained in a calandria tank which provides a complete separation from the hot reactor coolant. The annular gas spaces between the calandria tubes and the pressure tubes are an efficient means for thermal insulation of the fuel assemblies. From a nuclear standpoint, the use of a calandria is undesirable; its tubes absorb an appreciable fraction of the slow neutrons and leak a significant number of fast neutrons by streaming. The Case-1D reactor is characterized by top and bottom plenums for coolant distribution, by an aluminum calandria, and by packing gland seals between the pressure tubes and the plenum tubes. Lifting of the top plenum by internal pressure effects is prevented by tension in the pressure tubes, which is developed against shoulders in the plenum tubes. Other features of this concept are described as follows:

(1) Plenum Chambers

Each plenum is approximately 12 feet 9 inches in diameter and 18 inches deep, constructed of 2-1/2-inch-thick stainless steel plate. The pressure tubes housing the fuel assemblies terminate in tubular sleeves in each plenum. These plenum sleeves are stainless steel and have a 3/4-inch minimum wall thickness. Individual fuel access nozzles are included in the top plenum. Each plenum is connected to four 18-inch coolant pipes. The over-all height of the assembled reactor is about 30 feet.

(2) Shields

The top and bottom shields are external to the calandria. These shields are of stainless steel plate-and-tube construction, filled with stainless steel Raschig rings or other shapes which occupy approximately 50% of the shield volume; the remainder is filled with light water. The annular thermal shield is external and consists of a closed tank that contains metal plates and light water. The water from the top and bottom shields and the annular tank is pumped through external heat exchangers for heat removal.

(3) Calandria

The 12-foot 10-inch ID aluminum calandria is of closed construction and is supported by the bottom shield. Moderator flows at 6700 gpm and an average temperature of 80°C upward through the tank and out into a gas-blanketed surge tank where any dissociated gases are removed. From the surge tank, the moderator is pumped through a cooler back to the calandria.

(4) Gas Enclosure

The spaces between the plenums, shields, calandria, and in the annuli around the pressure tubes are filled with an inert gas (e.g., helium) which may be monitored to detect moderator leakage. Escape of the gas to the atmosphere is prevented by a steel sheath which lines the inside of the concrete shield and is attached to the top and bottom plenum chambers by means of flexible metal seal strips.

(5) Control and Safety Rods

Control rods enter the reactor core from the bottom through sleeves in the bottom plenum and pass through tubes in the calandria. Cooling of the rods is necessary in this design because of their separation from the reactor fluids. Safety rods enter through the top plenum and also pass through calandria tubes. The safety rod actuators are mounted above the reactor and must be removed periodically for fuel charging and discharging operations.

The 225 fuel tubes are identical to those used in the base case (1B). Each fuel tube is assembled in a Zircaloy-2 pressure tube fitted with stainless steel ends that extend through the top and bottom shields to attachments in the coolant plenums. As discussed in an earlier section (D-1), the Zircaloy-to-stainless-steel joints are a major design problem for any of the pressure tube concepts. The pressure tubes in this concept are not internally insulated; the gas annuli around them reduce the heat loss to the cold moderator.

The plenums and pressure tubes are designed for 1000-psig internal pressure and are operated at 800 psig and a coolant temperature of about 250°C. The total coolant flow of 60,000 gpm is pumped through four loops to steam generators.

Saturated steam produced in the steam generators is delivered to the turbine throttle at 262 psig (Case 1B - 152 psig). The calculated gross steam cycle efficiency is about 27% versus 24% for the base case. About 9% of the reactor power is lost to the cold moderator. The resulting over-all thermal efficiency of 23% is nearly the same as that calculated for the hot moderator base case.

This pressure tube concept is based on a 7.8-inch triangular lattice spacing as compared with the 6.5-inch spacing for the pressure vessel concepts (Case 1B and 1C). Mechanical considerations and nuclear requirements both contributed to the selection of this lattice pattern.

The average fuel exposure for the pressure tube case is calculated at 3500 MWD/ton versus 4500 MWD/ton for the cold moderator pressure vessel (Case 1C). This difference arises from the different lattice geometry and from the parasitic absorption by the housing and calandria tubes.

c. Other Facilities

The facilities outside the reactor building essentially duplicate those for the cold moderator pressure vessel concept, Case 1C.

6. Large Capacity Liquid-Cooled Pressure Tube Reactor Plants

a. Reactor Building

The larger pressure tube reactors (Cases 1D-200 to 1D-460) are housed in flat-bottomed, vertical, cylindrical containment vessels having hemispherical top enclosures. For Cases 1D-200 and 1D-300, each vessel is 175 feet in diameter and the cylindrical portion is 150 feet high; the over-all height is 237-1/2 feet. For Case 1D-460, the diameter is 180 feet and the over-all height is 240 feet.

Unlike the larger hot moderator pressure vessel concepts, the energy release during a maximum credible accident in the liquid-$D_2O$-cooled pressure tube reactor plants was not the governing factor in the selection of the type of containment vessel. The desired equipment arrangement was more readily accommodated in a vertical cylindrical vessel than in a spherical unit.

The volume of hot, pressurized $D_2O$ in these pressure tube reactors is much less than is encountered with the hot moderator concepts at comparable outputs. As a result, calculations showed that these cylindrical shapes would provide adequate containment of any accidental energy release. Plate requirements for the required design pressures do not exceed the 1.25-inch thickness permitted by the ASME UPV Code without stress relief after welding.

The reactor building arrangement for Case 1D-460 is shown in Figures 27 to 29. The facilities included are similar to those described for the basic arrangement (Case 1B) but increased in size and number of units, as required for this capacity. The arrangements for Cases 1D-200 and 1D-300 are similar in character with the appropriate size variations.

b. Reactor

The larger liquid-cooled pressure tube reactors are based on the 460-eMW concept shown in Figure 14. This design utilizes top and bottom coolant plenums connected by the pressure tubes. The bottom plenum is hung from the pressure tubes, thus keeping them in tension. Each plenum chamber is approximately 18 feet 9 inches ID by 18 inches deep and is constructed of 2-1/2-inch stainless steel plate. Six coolant connections are provided to each plenum; 20-inch diameter to the top inlet plenum and 24-inch diameter to the bottom outlet plenum. The pressure tubes terminate in tubular sleeves in each plenum.

The top and bottom shields each consist of ten 1-inch-thick horizontal stainless steel plates, spaced apart and submerged in the moderator to provide cooling. The annular thermal shield is externally located in a separately supported closed tank, similar to the 100-eMW concept (Case 1D).

The cold moderator enters through six 12-inch connections into an inner open top tank which surrounds the core. The moderator overflows from this tank into a concentric outer tank provided with six 16-inch pipe outlets. The bottom shield is included in the inner tank; the top shield is located above the inner tank but below the moderator level. Like the 100-eMW concept, a sealed gas enclosure is provided around the reactor and the external shield tank and between the top and bottom plenums.

Each fuel assembly consists of three coaxial Zircaloy-clad uranium metal tubes, assembled in a Zircaloy pressure tube. The pressure tubes are in direct contact with the cold moderator and include internal liners of thin Zircaloy tubing. The narrow annular spaces between the liners and the pressure tubes contain stagnant layers of $D_2O$, which provide thermal insulation to reduce heat losses to the moderator.

The control and safety rods enter through the top plenum and are also contained in pressure tubes in direct contact with the moderator. The rod actuators are located at the top and are removable to permit fuel handling operations. Individual fuel access nozzles are included in the top plenum and extend upward through external biological shielding to the operating level.

Smaller versions of the 460-eMW concept were evaluated for the 200- and 300-eMW cases. For all three cases, the plenums are designed for 1000-psig internal pressure and operate at approximately 800 psig with a coolant temperature of about 250°C. The average moderator temperature is 80°C for each case.

Each of the three concepts is based on a 9.5-inch triangular lattice spacing, selected from a combination of mechanical and nuclear considerations. The calculated average fuel exposures for 100% batch reloading range from 3200 to 3800 MWD/ton.

Each coolant system includes steam generators which deliver 170-psig saturated steam to the turbine throttle. The gross steam cycle efficiencies are calculated at about 25%, but the loss of 13% of the reactor power to the cold moderator reduces the over-all thermal efficiencies to about 20.5%.

The following table lists several of the differences in the 200-, 300-, and 460-eMW reactor concepts.

| Case | 1D-200 | 1D-300 | 1D-460 |
|---|---|---|---|
| No. of fuel assemblies | 166 | 250 | 330 |
| Core diameter, ft | 11.4 | 13.8 | 15.8 |
| Reactor tank OD, ft | 14.1 | 16.5 | 18.6 |
| Coolant loops | 4 | 4 | 6 |
| Total coolant flow, gpm | 80,000 | 120,000 | 180,000 |
| Moderator flow, gpm | 22,000 | 33,500 | 51,000 |

c. Turbine Generator Building

For the large capacity pressure tube reactors, the turbine generator facilities vary as follows:

| Case | 1D-200 | 1D-300 | 1D-460 |
|---|---|---|---|
| No. of turbine units | 1 | 2 | 3 |
| Size of turbine building, ft | 160 x 110 | 200 x 126 | 220 x 126 |

The scale-up with capacity includes not only the turbine generators but the condensers, feedwater pumps and heaters, the service crane, and the auxiliary equipment.

d. Other Facilities

The principal additional changes with capacity are associated with the pump house and cooling water system. Most of the plant auxiliaries are similar or identical to the base case (1B).

### 7. Boiling $D_2O$ 100-eMW Pressure Tube Reactor Plants

#### a. Reactor Building

The building arrangement proposed for the boiling $D_2O$ reactors is shown in Figures 30 and 31. The reactor and associated equipment are housed in a 175-foot-diameter vertical, cylindrical containment vessel with a flat bottom and a hemispherical top. Height of the straight side is 50 feet; over-all height is 137-1/2 feet.

The steam generators required for the liquid-cooled concepts are omitted for the direct cycle boiling $D_2O$ reactors. In their place, centrifugal steam separators are included to dry the steam ahead of the turbine generators.

The presence of fewer equipment items in the reactor building permitted an arrangement on three floor levels as compared with the four levels required for the liquid-cooled concepts. The vertical height of the arrangement was lessened by two factors: (1) all control mechanisms are located on top of the reactor, and (2) the absence of steam generators and other large, heavy equipment associated with the reactor eliminated the need for a permanently installed crane. For fuel transfer operations, the unloading cask moves on tracks, rather than being carried by a crane.

The conservative assumption was made that all the condensed $D_2O$ that is recycled to the reactor would require filtration and demineralization. Equipment for this purpose is included in a shielded area inside the reactor building. An additional catalytic recombiner is provided to recover $D_2O$ from noncondensibles ejected from the turbine condenser.

Coolant pumps provide forced circulation from the steam separators to the reactor. The purified $D_2O$ from the demineralizers is fed to the suction side of these pumps. A separate moderator cooling system is included, although not pictured in this arrangement.

The size and type of containment vessel was selected to suit the desired equipment arrangement, but the volume and design pressure were deemed adequate for containment of the maximum credible accident.

#### b. Reactor

Two 100-eMW pressure tube boiling reactors were evaluated. Case 2K is a smaller version of the Case 1K-430 concept shown in Figure 16; this is described in the later section on the large capacity boiling reactors.

The Case 1K concept is shown in Figure 15. Each of the 175 fuel assemblies consists of three coaxial fuel tubes fabricated from Zircaloy-clad metallic uranium fuel. The individual assemblies are each installed in an aluminum pressure tube of the bayonet type. An internal Zircaloy liner tube provides a stagnant liquid $D_2O$ annulus for thermal insulation. This construction lowers the pressure tube wall temperatures enough to permit the use of aluminum for the 200°C coolant temperature assumed for this particular concept.

Subcooled liquid $D_2O$ enters through a top plenum distributor and travels downward through the center channel of each fuel assembly. At the lower end of each pressure tube, the coolant reverses direction and about 10% by weight is vaporized in passing upward through the surrounding fuel channels. The resulting mixture of $D_2O$ liquid and vapor is discharged through individual piping connections and flow restrictors to ring headers leading to the steam separators. A 9-inch square lattice pattern was selected, rather than a triangular one, to provide maximum-width lanes between fuel positions for the individual coolant outlet piping.

The bayonet pressure tubes are submerged in the cold moderator which is contained in an open-top tank. The use of bayonet-type tubes eliminates bottom penetrations in the reactor, leading to a simpler design of the reactor and its shielding.

The bottom and radial thermal shields are contained in a larger tank that encloses the moderator tank. The top shield is a horizontal plenum-type tank penetrated by sleeves at the fuel and control positions. The bottom and radial shields consist of spaced metal plates; the top shield contains stainless steel Raschig rings. Both types are cooled with light water. A sealed gas enclosure is provided around the reactor and the shield tanks.

The pressure tubes and coolant inlet plenum are designed for 300 psig and operate at about 250 psig with a coolant temperature of about 200°C. The moderator temperature averages 80°C. The mixture of $D_2O$ liquid and steam flows from the reactor tubes to four centrifugal steam separators operating in parallel. These deliver saturated $D_2O$ steam directly to the turbine, at a throttle pressure of 225 psig.

To provide maximum subcooling and protection against pump cavitation, no feedwater heaters are used for this concept. The resulting gross steam cycle efficiency of 24%, combined with the loss of 13% of the reactor power to the cold moderator, reduces the over-all thermal efficiency to 19.6%. The reactor thermal power becomes 510 MW, relatively high for a 100-eMW concept.

c. Turbine Generator Building

It was assumed that the steam separators in the reactor building would reduce the radioactive carryover sufficiently to eliminate the need for shielding the steam piping, the turbine, and the associated equipment. Therefore, the installation is similar to the basic 100-eMW case (1B).

A principal difference is the use of $D_2O$ steam on the steam ejector and the inclusion of a closed ejector condenser to recover $D_2O$. The noncondensibles from the ejector system are piped to a separate recombiner located in the reactor building.

d. Other Facilities

The other plant facilities and auxiliaries are mostly identical to the base case (1B).

8. Large Capacity Boiling $D_2O$ Pressure Tube Reactor Plants

a. Reactor Building

For the 200- to 430-eMW boiling pressure tube reactor plants, the equipment arrangement is the same as described for the 100-eMW boiling $D_2O$ reactor (Figures 30 and 31). For Case 1K-200, the reactor building is identical in size to Case 1K. For Cases 1K-300 and 1K-430, the building diameter was increased from 175 to 180 feet and the over-all height from 137-1/2 to 140 feet.

The building dimensions are those required for arrangement purposes, but they were determined to be adequate for containing the maximum credible accident.

b. Reactor

The boiling $D_2O$-cooled pressure tube reactor chosen for Case 1K-430 is shown in Figure 16. Smaller reactors of similar construction were evaluated for Cases 2K, 1K-200, and 1K-300.

Each fuel assembly consists of three or four coaxial fuel tubes, constructed of Zircaloy-clad metallic uranium fuel. These assemblies are each enclosed by a Zircaloy pressure tube, internally insulated by means of a thin liner of Zircaloy tubing. The actual insulating medium is a thin annular layer of stagnant liquid $D_2O$.

The pressure tubes are assumed to have stainless steel ends bonded to the Zircaloy. These assemblies extend vertically through the moderator tank; their walls are in direct contact with the cold moderator. Individual inlet and outlet piping connections provide for coolant flow upward through each pressure tube. A square lattice spacing is used, to provide maximum-width pipe lanes from each pressure tube to the coolant headers.

The top of each pressure tube extends through biological shielding, ending in a nozzle closure for fuel access. The control and safety rods are top entry, with removable actuators to prevent interference with fuel handling operations.

The moderator tank is of low pressure design. The moderator flow enters near the bottom through four inlets to a flow distribution chamber inside the tank and rises through a series of perforated, spaced, horizontal stainless steel plates which constitute the bottom thermal shield. Near the top of the moderator tank, a similar series of submerged horizontal plates serves as the top thermal shield. The heated moderator flows through a top collection chamber to the moderator cooling circuit.

The radial thermal shields are vertically arranged, spaced plates set into an external tank and provided with light water cooling.

In rising through the pressure tubes, the subcooled reactor coolant at about 800 psig is heated from 237 to 270°C and about 30% by weight is vaporized. The resulting mixture of liquid and vapor passes through the steam separators to produce dry, saturated steam at a turbine throttle pressure of 780 psig. A single stage of regenerative feedwater heating is used, resulting in a gross steam cycle efficiency of 30%. This, combined with a 13% loss of reactor power to the cold moderator, results in an over-all thermal efficiency of 24.7%.

The description given in the previous paragraphs may be applied to the 100- to 430-eMW cases. The following table lists information applying to the particular capacities.

| Case | 2K | 1K-200 | 1K-300 | 1K-430 |
|---|---|---|---|---|
| Fuel tubes/assembly | 3 | 4 | 4 | 4 |
| Fuel assemblies | 185 | 257 | 362 | 475 |
| Lattice spacing, in. | 8.5 | 8.5 | 8.5 | 9.0 |
| Core diameter, ft | 10.6 | 13.1 | 15.5 | 19.2 |
| Core length, ft | 15 | 15 | 15 | 15 |
| Reactor tank, OD, ft | 12.6 | 15.1 | 17.5 | 21.6 |
| Coolant flow, gpm | 11,000 | 21,000 | 29,000 | 40,000 |
| Moderator flow, gpm | 8,800 | 18,500 | 28,000 | 40,000 |
| Avg. fuel exposure, MWD/ton | 4,200 | 3,800 | 4,000 | 5,000 |

A plant flow diagram typical of this series of boiling reactors and based on Case 2K is shown in Volume II (DP-520).

c. Turbine Generator Building

For the large-capacity boiling reactors, the turbine generator facilities vary as follows:

| Case | 2K | 1K-200 | 1K-300 | 1K-430 |
|---|---|---|---|---|
| No. of turbine units | 1 | 1 | 2 | 2 |
| Size of turbine building, ft | 160 x 90 | 160 x 110 | 200 x 126 | 200 x 126 |

The facilities for Case 2K are similar to those required for the basic case (1B). For the larger capacities, the turbine generators and associated equipment plus the building and its facilities are all scaled up as required.

d. Other Facilities

Additional capacity is included in the pump house and cooling water systems for the large capacity plants. Most of the plant auxiliaries remain similar or identical to those for the base case.

9. Boiling $D_2O$ 100-eMW Pressure Vessel Reactor Plant

a. Reactor Building

The reactor building is the same as that described for the 100-eMW boiling $D_2O$ pressure tube plant, Case 1K, except that a separate moderator-cooling circuit is not required.

b. Reactor

The 100-eMW boiling $D_2O$ pressure vessel reactor, Case 1J, is a hot moderator concept, illustrated in Figure 12. The vessel is 14 feet 9 inches ID by 35 feet over-all length, with welded closures for the top and bottom heads. The design pressure is 300 psig. The bottom head and lower portion of the shell are 1-3/4-inch-thick steel plate (SA-212-B). The upper portion of the shell is penetrated by four inlet and four outlet nozzles for coolant flow. The top head includes individual fuel access nozzles and control and safety rod penetrations. Plate thicknesses in these areas are 4-1/8 inches. The entire vessel is lined with a 1/4 inch thickness of weld-deposited stainless steel cladding.

The total coolant flow of 28,700 gpm of liquid $D_2O$ is pumped into the reactor at 187°C and enters through a distribution plenum above the core and serves first as hot moderator as it flows downward between the fuel housing tubes. Below the core, the liquid reverses direction and flows from the moderator area through openings into each housing tube. On flowing upward past the fuel assemblies, the coolant is heated to 203°C and about 10% by weight is vaporized. The resulting liquid-vapor mixture passes from the reactor to centrifugal steam separators which deliver dry saturated steam to the turbine throttle at 225 psig.

The radial and thermal shields are internal and consist of spaced stainless steel plates which surround the core and reflector areas. The top and bottom biological shielding is external to the vessel.

Each of the 356 fuel assemblies consists of two coaxial fuel tubes placed in a thin-walled Zircaloy-2 housing tube. The fuel is metallic uranium, clad with Zircaloy-2. The average fuel exposure is calculated to be 3500 MWD/ton for 100% batch reloading.

Like Case 1K, no feedwater heaters are employed. The gross steam cycle efficiency is 24%; the over-all thermal efficiency is 22.5%.

c. Other Facilities

The turbine generator building and the equipment included are identical with the comparable facilities described for the 100-eMW boiling reactor, Case 1K. Plant auxiliaries and other facilities are identical to the base case (1B).

10. Helium-Cooled 100-eMW Reactor Plant

a. Reactor Building

The helium-cooled reactor plant includes four large steam generators, circulating gas blowers, and large diameter coolant piping. A 200-foot-diameter sphere was chosen to house this reactor system, based on the equipment size and arrangement. This sphere is considerably larger than the size needed to contain a maximum credible accident.

b. Reactor

The helium-cooled reactor concept (Case 1G) and the associated facilities have previously been described[15]. For completeness, portions of this description are included in the following paragraphs.

A conceptual arrangement for a helium-cooled pressure vessel reactor is shown in Figure 17. Gas-cooled pressure vessel reactors offer some advantages over the pressure tube types, especially if the reactor is small or of medium size. The more important advantages are: (a) the elimination of numerous gas seals that must operate at high temperature and moderate pressure differentials (up to 400 psi), (b) the elimination of heavy-walled pressure tubes within the reactor core, and (c) the reduction of pressure drop in the system by the elimination of coolant plenums or individual coolant piping for each fuel element.

The liquid-cooled cold moderator pressure vessel concepts require careful analysis and design to avoid excessive thermal stresses in the reactor shell, resulting from the wide difference between the temperatures of the coolant and the moderator. In a gas-cooled concept, the coolant gas can readily be used as an insulating medium to minimize thermal gradients and the resulting bending stresses in the vessel wall. S added

Features of the reactor arrangement presented in Figure 17 are as follows:

(1) The moderator is at low temperature and is isolated from the coolant gas within the reactor. However, the $D_2O$ is maintained at the same pressure as the coolant gas by equalization in an external pressurizer vessel, to eliminate the need for heavy-walled fuel housing tubes.

(2) The heavy water moderator is contained within a calandria and is further isolated from the walls of the pressure vessel and all the gas coolant passages by annuli filled with stagnant or low velocity gas. This insulation minimizes thermal stresses in the reactor shell and reduces heat losses from the hot coolant to the cold moderator. The outer walls of the calandria are formed by the bottom shield, the annular thermal shield, and the top shield; all are fabricated of stainless steel. The calandria tubes are Zircaloy.

(3) The heavy water that circulates through the annular shields also circulates through the moderator space. This eliminates many possible causes of thermal stresses and minimizes the number of welds that must remain leaktight. The top and bottom axial shields are cooled by separate $H_2O$ circuits.

(4) The top head of the vessel is designed for removal when fuel replacement is necessary. This minimizes the number of openings required in the top head. Removal of the top head is considered feasible because fuel cycles are long, the inlet helium temperatures and pressures are moderate, and the probability of fuel element failure is reduced when using an inert coolant.

(5) The pressure vessel of the reactor is fabricated from carbon steel (SA-212-B) without stainless steel cladding. This is considered feasible for helium service.

The reactor vessel is 16.5-foot ID by 43-foot over-all length, designed for a pressure of 450 psig. The minimum shell thickness is about 5 inches, the top head is 2.5 inches thick and the bottom head is 6.5 inches thick.

Each of the 174 fuel assemblies consists of 136 twisted ribbons of thin Zircaloy-clad metallic uranium, totaling over 550 lb of uranium per assembly. The helium coolant flow of 1,530,000 lb/hr enters the tops of the fuel housing tubes at about 400 psig and 225°C and leaves through the bottom head at 511°C.

From the reactor the hot coolant flows through four parallel steam generators, across banks of finned steel tubing arranged in superheater, evaporator, and economizer sections. The prime area, or tubular heat transfer area, totals 35,000 $ft^2$. Circulating gas blowers recycle the coolant to the reactor.

The steam generators produce steam at turbine throttle conditions of 1407 psig with 300°F (167°C) of superheat. The calculated gross steam cycle efficiency is 37.6%. When combined with an 11% loss of reactor power to the cold moderator, the resulting over-all thermal efficiency is 31.4%.

A simplified flow diagram of the plant was shown previously[15] and is repeated in Volume II (DP-520).

### c. Turbine Generator Building

The turbine generator building is the same size as in the base case (1B). The turbine, the condenser, and the steam piping are all smaller in size, as brought about by the improved steam conditions.

### d. Other Facilities

The amount of cooling water is less than that required for the liquid-cooled 100-eMW concepts, which reduces the capacity of the water pumping and distribution facilities below that specified for Case 1B. Auxiliaries and other facilities are nearly all identical with the base case.

## 11. $D_2O$-Steam-Cooled 100-eMW Reactor Plant

### a. Reactor Building

Equipment arrangement requirements led to the selection of a 200-foot-diameter sphere to house the reactor system. Containment of the maximum credible accident would not require so large a vessel.

### b. Reactor

A preliminary study was made of a 100-eMW cold moderator pressure vessel reactor that is cooled with superheated $D_2O$ steam. A schematic arrangement for this concept (Case 2H) is shown in Figure 18. The major advantages of this type of reactor are as follows:

(1) The massive boilers that are usually required in a gas-cooled reactor system are eliminated.

(2) Superheated steam can be produced in a direct cycle at a pressure that permits its use in a turbine generator plant of conventional modern design. This results in an over-all thermal efficiency higher than that expected in the liquid cooled and boiling $D_2O$ concepts.

Each fuel assembly for Case 2H consists of 31 twisted ribbons of natural uranium metal, each clad with a 0.007-inch thickness of stainless steel; each bundle of ribbons is contained in a double-walled Zircaloy housing tube. The cold moderator is insulated from the hot coolant by helium contained in the annulus between the two walls of each housing tube. A separate cooling system maintains the moderator at an average temperature of about 80°C. The nuclear lattice is contained in a mild steel (SA-212-B) pressure vessel clad internally with a 1/4-inch thickness of weld-deposited stainless steel. The reactor vessel is 18 feet in internal diameter and about 52 feet in length and is designed for a pressure of 900 psig.

Heavy water steam at about 800 psig cools the fuel. The steam enters the reactor slightly superheated, and it is cooled and desuperheated by contact with cascading liquid $D_2O$ as it rises through the perforated plates used in the bottom thermal shield. On passing upward through the coolant passages of the fuel assemblies, it is superheated to about 387°C at 785 psig. This amounts to about 117°C (210°F) of superheat.

About 16% by weight of the hot steam is fed to the turbine. The turbine condensate is reheated to 221°C in five stages of feed water heaters and is pumped to the bottom of the reactor where it serves as a reservoir of liquid $D_2O$. The heat capacity of this large holdup of liquid $D_2O$ contributes to the stability of the system. The remaining 84% of the superheated steam is recycled to the reactor by gas blowers. Enroute it passes through venturi sections where the steam is cooled to within a few degrees of saturation temperature by the injection of liquid $D_2O$ drawn from the bottom of the reactor vessel.

The temperature of the effluent steam from the hottest fuel position is about 427°C. The maximum temperature of the uranium metal is about 625°C. For this preliminary design, the fuel inventory is 71 tons and the $D_2O$ inventory is 195 tons. The gas blowers consume about 4000 horsepower. The over-all thermal efficiency is 28.6% which includes loss of 11% of the reactor power to the cold moderator. An average fuel exposure of 3600 MWD/ton is expected for 100% batch reloading.

Although the work on the steam-cooled reactor was preliminary in nature, some general conclusions can be drawn. With the postulated reactor materials, the reactor core must be about 15 to 16 feet in loaded diameter, in order to attain the necessary geometric buckling for operation. The major problem concerning the feasibility of this reactor concept, as in the helium-cooled reactor (Case 1G), involves the high temperature behavior of uranium metal. It is not yet known whether a serious distortion of the uranium fuel ribbons will occur during extended periods of irradiation at the reactor conditions.

For Case 2H it is assumed that the turbine will not be seriously contaminated by radioactive carryover. On this premise, the power generation equipment is unshielded and located in a conventional building outside the containment vessel.

It is also assumed that the water chemistry can be controlled to permit use of carbon steel in both the primary coolant circuit and in the power cycle. As noted previously, the reactor vessel is clad internally with stainless steel.

As indicated in Figure 18, helium or other inert gas is introduced to the coolant loops after reactor shutdowns. This provides a circulating medium for shutdown cooling and for use during startup, prior to the generation of a sufficient volume of $D_2O$ steam.

c. Turbine Generator Building

The turbine generator building is the same as provided in the base case (1B). The better steam conditions for Case 2H permit use of a smaller, less costly turbine generator system.

d. Other Facilities

Less cooling water is required than for Case 1B, but the other facilities duplicate those for the base case.

e. Alternative Building Arrangement

For Case 2H it was assumed that the turbine generator and the associated equipment can be housed in a conventional structure, omitting any radiation shielding. An alternative plant arrangement was studied, on the basis of the more conservative assumption that the turbine generator would become sufficiently radioactive to require its location in the containment vessel in a limited access area.

This plant arrangement, shown in Figures 32 to 34, is housed in a 200-foot-diameter vertical, cylindrical vessel with hemispherical top and ellipsoidal bottom. The over-all height is 275 feet. The equipment arrangement in the containment vessel provides three principal operating levels: at grade, at -50 feet, and at -75 feet. A single crane serves both for fuel handling operations and for maintenance requirements. Unlike Case 2H, it is assumed that stainless steel construction is required for the primary coolant system.

The other principal buildings are located adjacent to the containment vessel in an arrangement differing from the basic case (1B).

The total plant investment for this alternative is estimated to be about 17% higher than for Case 2H; the estimated power cost is some 11% higher, totaling 22.6 mills/kwh.

## F. STATUS AND POTENTIAL OF $D_2O$-MODERATED REACTORS

### 1. Technological Status

From a technological standpoint, the preferred pressure tube boilers are not developed to the same degree as the liquid-cooled concepts, especially those based on pressure vessel reactors. As pointed out in Section C-5, knowledge is incomplete or lacking on a number of design and operating aspects of the boiling $D_2O$ reactors. Information is needed on topics such as: (1) nuclear physics, (2) hydraulic behavior, (3) boiling heat transfer burnout, (4) operating stability and transient response to operating changes, and (5) effects of irradiation, temperature, and corrosion on the fuel assemblies. Additional data on fuel endurance are equally important for the other metal-fueled reactors.

The development of a dependable Zircaloy-to-stainless-steel joint and the fabrication of insulated Zircaloy housing tubes are major problems common to all the pressure tube reactor concepts. A low cost process for fabrication of the fuel elements is greatly needed, but this can be said for every concept.

An intensive experimental program should be able to supply sufficient information to permit firm design of the pressure tube boiling reactors and to predict their operating behavior. Du Pont's future program, as outlined previously, is expected to develop much of the required basic knowledge. Additional information will become available from the Sargent & Lundy and Nuclear Development Corp. developmental programs in this field. Related work by others on pressure tube reactors will supply further answers.

### 2. Future Potential

The economic results presented in this report are based on the current knowledge of nuclear power plants, a field which has been actively developing over a period of only five to ten years. These results are being compared with the costs of power from today's fossil-fueled plants - costs that have been reduced through technological improvements over a period of perhaps fifty years. Therefore, it should not be surprising that nuclear power, based on 1959 designs, is not competitive in the USA.

It is impossible to foresee all the various improvements to the nuclear plants that will result from the next five to ten years of development and operating experience. However, enough information is available for a preliminary evaluation of the economic effect of several probable improvements.

The future potential of a 300-eMW pressure tube boiling reactor plant was studied briefly to determine the variations in power costs resulting from: (a) operation at higher power levels, (b) longer fuel life, (c) lower cost Zircaloy, (d) lower cost fuel fabrication, and (e) use of nuclear superheat. The 300-eMW capacity was selected for two reasons: (1) recent installations of fossil-fueled base-load stations in the USA approach this capacity, and (2) 300 eMW is about the maximum capacity expected available in the near future from a single-shaft turbine generator unit operating on saturated steam at the postulated throttle conditions.

a. Effect of Higher Power Levels

Case 1K-300 is based on a maximum specific power of 38 MW/ton uranium and a maximum heat flux of 200,000 pcu/(hr)($ft^2$). It is possible that a 50% increase in the power rating can be realized after experience is gained from the operation of a prototype unit. It is estimated that this single development would reduce the 300-eMW reactor plant investment by some 8 to 10% and the $D_2O$ inventory by about 15%. These two factors would reduce the total power cost about 0.5 mill/kwh.

b. Effect of Longer Fuel Life

The estimated average fuel exposure for Case 1K-300 is 4000 MWD/ton for 100% batch reloading. If it is assumed that one-third of the fuel is recharged per cycle, with suitable repositioning in the reactor, the average fuel exposure should be increased to about 6000 MWD/ton. On this basis, the fuel cost for a 300-eMW boiling $D_2O$ reactor would be reduced by about 0.9 mill/kwh, or from 2.5 to 1.6 mills/kwh.

Driggers and St. John[12] have shown the effect on fuel exposure of using a so-called "continuous" recharging scheme. This scheme assumes that single fuel assemblies would be recharged at regular time intervals with no interruption of the reactor operation.

If such a "continuous" recharging scheme were employed, the average fuel exposure for Case 1K-300 should amount to about 7500 MWD/ton. The estimated fuel cost would then be about 1.25 mills/kwh, approximately 0.35 mill/kwh less than the fuel cost for the previous scheme of recharging one-third of the core per cycle. This difference of 0.35 mill is equivalent to the fixed charges on a plant investment of $5.25 million. However, the additional investment in the equipment required for a continuous recharging scheme could amount to several million dollars. The attractiveness of continuous recharging would then be based primarily on the easier attainment of a high plant load factor.

An optimum core and fuel element design based on better knowledge of the reactor physics of the boiling reactors may result in a greater excess reactivity than the 5.3% figure calculated for Case 1K-300. An increase in the available reactivity would permit a higher average fuel exposure for any recharging scheme. For example, a 1K-300 core design with 7% excess reactivity is estimated to permit an average fuel exposure of 4700 MWD/ton for 100% batch reloading, and the corresponding fuel cost would be about 2.0 mills/kwh (Case 1K-300 = 4000 MWD/ton and 2.5 mills/kwh).

All these variations have assumed that the proposed metallic uranium fuels will satisfactorily withstand irradiation exposures of 6000 to 8000 MWD/ton. This requires confirmation by test irradiations at comparable reactor conditions.

### c. Effect of Lower Cost Zircaloy

The current estimates have assumed a $50/lb purchase price for the Zircaloy-2 tubing used for housing and insulating tubes and for fuel cladding. If this purchase price were reduced to $30/lb, the equivalent reduction in the total power cost for Case 1K-300, operated on 100% batch reloading, would be about 0.2 mill/kwh (split almost evenly between the fixed charges on the plant investment and the cost of fuel).

### d. Effect of Lower Cost Fuel Fabrication

If it is assumed that the fabrication cost, exclusive of Zircaloy, of the 1K-300 tubular fuel elements can be reduced by one-third, their fabrication would then cost about $12/kg uranium. The equivalent reduction in power cost for Case 1K-300 would amount to another 0.2 mill/kwh for 100% batch reloading.

### e. Cumulative Effect on Preferred Concept

For comparative purposes, the total power cost was estimated for a 300-eMW pressure tube boiling $D_2O$ reactor plant producing 780 psig saturated steam, similar to Case 1K-300, but making use of several of the probable future improvements discussed in the previous sections. For identification, this is termed Case X.

## Case X

Basic Assumptions

300-eMW boiling $D_2O$ pressure tube reactor

Saturated steam at 780 psig to turbine

Maximum specific power, 60 MW/ton

Average fuel exposure, 6000 MWD/ton

Zircaloy-2 tubing at $30/lb

Fuel fabrication cost, $12/kg uranium (exclusive of Zircaloy)

The fixed charges on plant and $D_2O$ investments, the $D_2O$ losses, and the other cost factors were those assumed in Section C-1.

I was the economics section.

| Power Cost | mills/kwh |
|---|---|
| Fixed charges, plant | 6.1 |
| $D_2O$ (fixed charges plus losses) | 1.3 |
| Fuel costs | 1.3 |
| Operation and maintenance | 0.9 |
| Total power cost | 9.6 |

### f. Effect of Nuclear Superheat (Case Y)

To date, the du Pont study has not dealt extensively with reactor concepts which include nuclear superheat. Case 2H is a 100-eMW $D_2O$ steam-cooled concept to produce superheated steam, but it does not appear attractive from an economic standpoint. The reactor system investment is relatively high, of a magnitude which offsets the lower investment for a power generation system operating on superheated steam.

Information available from other reactor plant concepts made it possible to obtain an approximation of the investments and fuel costs for a 300-eMW boiling $D_2O$ pressure tube reactor plant, including nuclear superheat and operating on a direct cycle. This is identified as Case Y.

A number of assumptions were made to define the reactor system. The reactor core was visualized as having two zones. Zone I would be loaded with Case 1K-300 fuel assemblies and would vaporize 30% by weight of the liquid $D_2O$ feed (approximately 30,000 gpm). The liquid-vapor mixture would leave Zone I at about 1050 psig and 550°F (288°C) and would flow to steam separators. The feedwater ($D_2O$), heated to 470°F (243°C), would be mixed with the liquid $D_2O$ returned from the steam separators, thus subcooling the mixture to about 540°F (282°C). Circulating pumps would boost the pressure of the liquid to 1100 psig for introduction to Zone I.

Zone II would be loaded with twisted ribbon elements of the type used for Case 2H. The saturated $D_2O$ steam from the steam separators would pass through Zone II, where it would be superheated to 700°F and delivered to the turbine throttle at 1000 psig. For these steam conditions, the gross steam cycle efficiency would be about 35%. Only one turbine generator unit would be required.

For Zone I, the maximum specific power was assumed to be 60 MW/ton uranium (1K-300 = 38 MW/ton). For Zone II, the maximum specific power was assumed to be 11 MW/ton, the same as for Case 2H. It was assumed that the Zone II assemblies would occupy the central area of the core, on about a 12-inch square lattice spacing. The Zone I assemblies would surround Zone II, on an 8.5-inch square lattice spacing.

The over-all core size would approximate that for Case 1K-300, and it was assumed that the dimensions and arrangement for the 1K-300 reactor would generally apply. An exception would be the provision of separate inlet and outlet headers for Zones I and II. In addition, the design pressure of the headers, piping, and pressure tubes would be increased from 900 to 1300 psig.

For the fuel cost calculations, it was assumed that one-third of the Zone I fuel would be recharged per cycle for an average exposure of 6000 MWD/ton. Zone II fuel would be recharged on a 100% batch basis at an assumed average exposure of 3600 MWD/ton. Zircaloy tubing was assumed to cost $30/lb. The fabrication costs of the fuel, exclusive of Zircaloy, were assumed to be one-third less than those estimated for Case 1K-300 (Zone I fuel) and for Case 2H (Zone II fuel). The resulting total plant investment estimated for the 300-eMW boiling reactor with integral nuclear superheat (Case Y) is considerably less than that estimated for Case 1K-300. This difference results almost entirely from the effect of the improved steam conditions on the electrical generation investment.

Tabulated below are the estimated power costs for the three 300-eMW boiling $D_2O$ reactor plants: (1) Case 1K-300, (2) Case X, a boiling reactor producing saturated steam, but based on the same general assumptions as Case Y, and (3) Case Y, a boiling reactor with nuclear superheat.

| | Case 1K-300 | Case X 300 eMW Satd. Steam | Case Y 300 eMW Plus Nucl. Superheat |
|---|---|---|---|
| Fixed charges, plant (14%) | 6.4 | 6.1 | 5.6 |
| $D_2O$ (fixed charges plus losses) (16.5%) | 1.5 | 1.3 | 1.4 |
| Fuel costs | 2.5 | 1.3 | 1.3 |
| Operation and maintenance | 0.9 | 0.9 | 0.9 |
| Total power cost, mills/kwh | 11.3 | 9.6 | 9.2 |

Comparison of the three cases shows that the use of nuclear superheating in itself accounts for a reduction of about 0.5 mill/kwh in the fixed charges on the plant investment. Fuel costs and other charges are approximately equal for the saturated and superheated steam concepts.

g. Future Nuclear Power Costs

The plant investments for the 300-eMW cases shown above are all assumed to require similar containment, auxiliaries, general facilities, etc. Future operations of prototype units are expected to uncover additional savings, mainly in the form of lower plant investments. It might reasonably be assumed that the plant investments for second or third generation plants would be some 20% below the current estimates. If this proved correct, the cost of power from the two "improved" 300-eMW boiling $D_2O$ reactor plants (Cases X and Y) would then be in the range of 8.0 to 8.5 mills/kwh. The attainment of these lower costs is greatly dependent on the availability of lower cost fuel assemblies that can be exposed for at least 6000 MWD/ton.

Although 8.0 to 8.5 mills/kwh power does not compete with the estimated 1962 average costs from modern coal-fired plants, it might become attractive in some areas of the USA, for plants installed some 5 to 10 years hence.

It must be emphasized that power costs of 8.0 to 8.5 mills/kwh from 300-eMW boiling $D_2O$ reactors are not believed to be attainable from the 1959 plant designs. Areas for improvement have been roughly evaluated to show the economic effect of future developments. The power cost of 8.0 to 8.5 mills/kwh may prove too optimistic, but at this writing it does not appear impossible to achieve.

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TABLE I

PLANT CHARACTERISTICS OF $D_2O$-MODERATED POWER REACTORS
FUELED WITH NATURAL URANIUM

| | CASE 1B | CASE 1B-200 | CASE 1B-300 | CASE 1B-400 | CASE 1D | CASE 1D-200 | CASE 1D-300 |
|---|---|---|---|---|---|---|---|
| **GENERAL** | | | | | | | |
| 1. Net Electrical Output, MW | 100 | 200 | 300 | 400 | 100 | 200 | 300 |
| 2. Coolant | Liquid $D_2O$ | Liquid $D_2O$ | Liquid $D_2O$ | Liquid $D_2O$ | Liquid $D_2O$ | Liquid $D_2O$ | Liquid $D_2O$ |
| 3. Reactor Type | Pressure Vessel Hot Moderator | Pressure Vessel Hot Moderator | Pressure Vessel Hot Moderator | Pressure Vessel Hot Moderator | Pressure Tube Cold Moderator | Pressure Tube Cold Moderator | Pressure Tube Cold Moderator |
| 4. Fuel Enrichment | Natural U | Natural U | Natural U | Natural U | Natural U | Natural U | Natural U |
| 5. Core Inventory, tons Uranium | 29.2 | 30.0 | 35.2 | 39.0 | 19.4 | 32.0 | 48.0 |
| 6. $D_2O$ Inventory, tons | 165 | 247 | 362 | 467 | 145 | 241 | 354 |
| 7. Over-all Thermal Efficiency, % | 22.7 | 23.4 | 23.4 | 23.3 | 23.0 | 20.4 | 20.4 |
| **REACTOR** | | | | | | | |
| 1. Gross Thermal Power, MW | 440 | 855 | 1280 | 1720 | 435 | 980 | 1470 |
| 2. Fuel Configuration | 1 Tube | 2 Concentric Tubes | 2 Concentric Tubes | 2 Concentric Tubes | 1 Tube | 3 Concentric Tubes | 3 Concentric Tubes |
| 3. No. of Fuel Assemblies | 340 | 390 | 507 | 396 | 225 | 166 | 250 |
| 4. Lattice Spacing, in. | 6.5 Hex. | 6.25 Hex. | 6.25 Hex. | 7.25 Hex. | 7.8 Hex. | 9.5 Hex. | 9.5 Hex. |
| 5. Core Diameter, ft. | 10.5 | 12 | 13 | 14 | 10.8 | 11.4 | 13.8 |
| 6. Core Height, ft. | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| 7. Moderator/Uranium Vol. Ratio | 25.0 | 25.3 | 28.0 | 26.5 | 34.8 | 22.9 | 22.9 |
| 8. Avg. Moderator Temp., °C | 207 | 213 | 213 | 213 | 80 | 80 | 80 |
| 9. Reactor Power to Moderator, % | 8 | 8 | 8 | 8 | 9 | 13 | 13 |
| 10. Max. Heat Flux, pcu/(hr.)(ft²) | 418,000 | 432,000 | 440,000 | 490,000 | 480,000 | 440,000 | 440,000 |
| 11. Gross Avg./Max. Heat Flux | 0.43 | 0.43 | 0.43 | 0.43 | 0.54 | 0.43 | 0.43 |
| 12. Max. Specific Power, MW/ton U | 36 | 66 | 86 | 104 | 42 | 71 | 70 |
| 13. Max. Fuel Temp., °C | 470 | <500 | <500 | <500 | 531 | <500 | <500 |
| 14. Hot Excess k | 0.0104 | 0.012 | 0.012 | 0.008 | 0.057 | 0.027 | 0.038 |
| 15. Avg. Fuel Exposure, MWD/ton U | 3250 | 3600 | 3600 | 3500 | 3500 | 3200 | 3500 |
| 16. Vaporization, % by wt. | - | - | - | - | - | - | - |
| 17. Inlet Pressure, psig | 524 | 783 | 783 | 705 | 800 | 783 | 783 |
| 18. Design Pressure, psig | 710 | 1000 | 1000 | 900 | 1000 | 1000 | 1000 |
| 19. External Diameter, ft. | 14.4 | 15.3 | 17.5 | 18.5 | 12.8 | 14.1 | 16.5 |
| **FUEL ASSEMBLY** | | | | | | | |
| 1. Fuel Material | U + 2 wt % Zr | U + 2 wt % Zr | U + 2 wt % Zr | U + 2 wt % Zr | U + 2 wt % Zr | U + 2 wt.% Zr | U + 2 wt % Zr |
| 2. Cladding Material | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 |
| 3. Housing & Insulating Tubes | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 |
| 4. Calandria Tubes | None | None | None | None | Aluminum | None | None |
| 5. Calandria Tube OD, in. | - | - | - | - | 4.46 | - | - |
| 6. Calandria Tube ID, in. | - | - | - | - | 4.36 | - | - |
| 7. Housing Tube OD, in. | 2.96 | 2.60 | 2.90 | 3.70 | 3.31 | 4.71 | 4.71 |
| 8. Housing Tube ID, in. | 2.90 | 2.54 | 2.84 | 3.64 | 2.90 | 4.33 | 4.33 |
| 9. Insulating Tube OD, in. | None | None | None | None | None | 4.21 | 4.21 |
| 10. Insulating Tube ID, in. | - | - | - | - | - | 4.15 | 4.15 |
| 11. Cladding Thickness, in. | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 |
| 12. Fuel Tube #1 Clad OD, in. | 2.06 | 2.14 | 2.35 | 3.18 | 2.06 | 3.72 | 3.72 |
| 13. Fuel Tube #1 Clad ID, in. | 1.47 | 1.78 | 2.05 | 2.90 | 1.47 | 3.35 | 3.35 |
| 14. Fuel Tube #2 Clad OD, in. | - | 1.07 | 1.17 | 2.08 | - | 2.48 | 2.48 |
| 15. Fuel Tube #2 Clad ID, in. | - | 0.71 | 0.87 | 1.80 | - | 2.12 | 2.12 |
| 16. Fuel Tube #3 Clad OD, in. | - | - | - | - | - | 1.24 | 1.24 |
| 17. Fuel Tube #3 Clad ID, in. | - | - | - | - | - | 0.88 | 0.88 |
| 18. Fuel Tube #4 Clad OD, in. | - | - | - | - | - | - | - |
| 19. Fuel Tube #4 Clad ID, in. | - | - | - | - | - | - | - |
| **PRIMARY COOLING SYSTEM** | | | | | | | |
| 1. Flow to Reactor-Liquid, gpm | 60,000 | 80,000 | 120,000 | 180,000 | 60,000 | 80,000 | 120,000 |
| Gas or Vapor, lb/hr | - | - | - | - | - | - | - |
| 2. No. of Cooling Loops | 4 | 4 | 4 | 6 | 4 | 4 | 4 |
| 3. Temp. Entering Reactor, °C | 206 | 212 | 212 | 212 | 230 | 212 | 212 |
| 4. Temp. Leaving Reactor, °C | 233 | 250 | 250 | 247 | 255 | 250 | 250 |
| 5. Over-all Pressure Drop, psi | 60 | 80 | 80 | 80 | 88 | 80 | 80 |
| 6. Area of Steam Generators, ft² | 32,700 | 49,000 | 73,100 | 104,000 | 29,800 | 49,000 | 73,100 |
| 7. Construction Material, Cooling System | SST | SST | SST | SST | SST | SST | SST |
| **ELECTRICAL GENERATION PLANT** | | | | | | | |
| 1. Steam to Turbine Throttle, lb/hr | $1.6 \times 10^6$ | $3.2 \times 10^6$ | $4.8 \times 10^6$ | $6.4 \times 10^6$ | $1.5 \times 10^6$ | $3.2 \times 10^6$ | $4.8 \times 10^6$ |
| 2. Turbine Throttle Pressure, psig | 152 (Satd) | 170 (Satd) | 170 (Satd) | 170 (Satd) | 262 (Satd) | 170 (Satd) | 170 (Satd) |
| 3. No. of Turbines | 1 | 1 | 2 | 2 | 1 | 1 | 2 |
| 4. Gross Steam Cycle Efficiency, % | 24.1 | 24.8 | 24.8 | 24.8 | 26.8 | 24.8 | 24.8 |
| 5. Gross Electrical Output, MW | 106 | 212 | 318 | 425 | 106 | 212 | 318 |

Notes:
1. Each reactor includes 1 ft of radial and 1 ft of axial reflector.
2. Fuel exposures are based on 100% batch reloading.
3. One ton = 2,000 lb.
4. For nuclear parameters and additional detail, see Tables I and II, Vol. II

* Prime area of finned heat transfer surface.

| CASE 1D-460 | CASE 2K | CASE 1X-200 | CASE 1X-300 | CASE 1X-430 | CASE 1C | CASE 1J | CASE 1K | CASE 1G | CASE 2H |
|---|---|---|---|---|---|---|---|---|---|
| 460 | 100 | 200 | 300 | 430 | 100 | 100 | 100 | 100 | 100 |
| Liquid $D_2O$ | Boiling $D_2O$ | Boiling $D_2O$ | Boiling $D_2O$ | Boiling $D_2O$ | Liquid $D_2O$ | Boiling $D_2O$ | Boiling $D_2O$ | Helium Gas | $D_2O$ Steam |
| Pressure Tube Cold Moderator | Pressure Tube Cold Moderator | Pressure Tube Cold Moderator | Pressure Tube Cold Moderator | Pressure Tube Cold Moderator | Pressure Vessel Cold Moderator | Pressure Vessel Hot Moderator | Pressure Tube Cold Moderator | Pressure Vessel Cold Moderator | Pressure Vessel Cold Moderator |
| Natural U | Natural U | Natural U | Natural U | Natural U | Natural U | Natural U | Natural U | Natural U | Natural U |
| 62.0 | 30.8 | 45.3 | 63.8 | 89.0 | 26.6 | 28.4 | 27.2 | 48.4 | 71 |
| 458 | 164 | 240 | 340 | 460 | 184 | 195 | 158 | 93 | 195 |
| 20.7 | 24.7 | 24.7 | 24.6 | 24.7 | 21.7 | 22.5 | 19.6 | 31.4 | 28.6 |
| 2220 | 405 | 810 | 1220 | 1740 | 460 | 445 | 510 | 318 | 350 |
| 3 Concentric Tubes | 3 Concentric Tubes | 4 Concentric Tubes | 4 Concentric Tubes | 4 Concentric Tubes | 1 Tube | 2 Concentric Tubes | 3 Concentric Tubes | Twisted Ribbons | Twisted Ribbons |
| 330 | 185 | 257 | 362 | 475 | 310 | 356 | 175 | 174 | 174 |
| 9.5 Hex. | 8.5 Sq. | 8.5 Sq. | 8.5 Sq. | 9.0 Sq. | 6.5 Hex. | 7 Hex. | 9 Sq. | 12 Hex. | 13 Hex. |
| 15.8 | 10.6 | 13.1 | 15.5 | 19.2 | 10 | 11.8 | 11.8 | 13.8 | 15 |
| 15 | 15 | 5 | 15 | 15 | 15 | 15 | 15 | 13.8 | 16 |
| 22.9 | 24.7 | 22.8 | 22.8 | 24.2 | 25.0 | 30.7 | 29.4 | 18.4 | 18.8 |
| 80 | 80 | 80 | 80 | 80 | 80 | 188 | 80 | 80 | 80 |
| 13 | 13 | 13 | 13 | 13 | 11 | 8 | 13 | 11 | 11 |
| 440,000 | 200,000 | 200,000 | 200,000 | 200,000 | 415,000 | 180,000 | 185,000 | 35,500 | 99,300 |
| 0.50 | 0.45 | 0.45 | 0.50 | 0.50 | 0.50 | 0.45 | 0.45 | 0.45 | 0.45 |
| 70 | 29 | 40 | 38 | 39 | 36 | 35 | 42 | 15 | 11 |
| <500 | <400 | <400 | <400 | <400 | 498 | <350 | <350 | 648 | 625 |
| 0.044 | 0.060 | 0.045 | 0.053 | 0.077 | 0.053 | 0.024 | 0.023 | 0.022 | 0.016 |
| 3800 | 4200 | 3800 | 4000 | 5000 | 4500 | 3500 | 3000 | 3000 | 3600 |
| - | 30 | 30 | 30 | 30 | - | 10 | 10 | - | - |
| 823 | 815 | 815 | 815 | 815 | 731 | 255 | 250 | 400 | 791 |
| 1000 | 900 | 900 | 900 | 900 | 950 | 300 | 300 | 450 | 900 |
| 18.6 | 12.6 | 15.1 | 17.5 | 21.6 | 13.9 | 15.4 | 13.8 | 17.3 | 18.9 |
| U + 2 wt % Zr | U + 2 wt % Zr | U + 2 wt % Zr | U + 2 wt % Zr | U + 2 wt % Zr | U + 2 wt % Zr | U + 2 wt % Zr | U + 2 wt % Zr | U + 2 wt % Zr | U + 2 wt % Zr |
| Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | SST |
| Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Zircaloy-2 | Housg. Aluminum | Zircaloy-2 | Zircaloy-2 |
| None | None | None | None | None | None | None | Insula. Zirc.-2 | Zircaloy-2 | Zircaloy-2 |
| - | - | - | - | - | - | - | - | 7.085 | 6.00 |
| - | - | - | - | - | - | - | - | 6.985 | 5.90 |
| 4.71 | 3.49 | 3.84 | 3.84 | 3.94 | 3.22 | 2.96 | 4.79 | 6.785 | 5.70 |
| 4.33 | 3.23 | 3.54 | 3.54 | 3.65 | 3.16 | 2.90 | 4.56 | 6.685 | 5.60 |
| 4.21 | 3.11 | 3.42 | 3.42 | 3.53 | 2.96 | None | 4.44 | None | None |
| 4.15 | 3.05 | 3.36 | 3.36 | 3.47 | 2.90 | - | 4.38 | - | - |
| 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.015 | 0.010 | 0.007 |
| 3.72 | 2.83 | 3.11 | 3.11 | 3.22 | 2.06 | 2.60 | 3.98 | - | - |
| 3.35 | 2.43 | 2.80 | 2.80 | 2.90 | 1.47 | 2.30 | 3.72 | - | - |
| 2.48 | 1.99 | 2.44 | 2.44 | 2.52 | - | 1.40 | 3.02 | - | - |
| 2.12 | 1.59 | 2.12 | 2.12 | 2.20 | - | 1.10 | 2.76 | - | - |
| 1.24 | 1.15 | 1.76 | 1.76 | 1.82 | - | - | 2.06 | - | - |
| 0.88 | 0.75 | 1.45 | 1.45 | 1.50 | - | - | 1.80 | - | - |
| - | - | 1.09 | 1.09 | 1.12 | Clad Ribbon Width, in. | | | 0.508 | 0.875 |
| - | - | 0.77 | 0.77 | 0.80 | Clad Ribbon Thickness, in. | | | 0.090 | 0.264 |
| | | | | | No. of Ribbons Per Fuel Assembly | | | 136 | 31 |
| 180,000 | 11,000 | 21,000 | 29,000 | 40,000 | 60,000 | 28,700 | 30,000 | - | - |
| - | - | - | - | - | - | - | - | $1.53 \times 10^6$ | $6.95 \times 10^6$ |
| 6 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| 212 | 237 | 237 | 237 | 237 | 223 | 187 | 188 | 225 | 272 |
| 252 | 270 | 270 | 270 | 270 | 248 | 203 | 203 | 511 | 387 |
| 80 | 50 | 50 | 50 | 50 | 60 | 60 | 60 | 2.7 | 8 |
| 116,000 | None | None | None | None | 30,600 | None | None | 33,100 * | None |
| SST | Steel | Steel | Steel | Steel | SST | Steel | Steel | Steel | Steel |
| $7.5 \times 10^6$ | $1.3 \times 10^6$ | $2.6 \times 10^6$ | $3.9 \times 10^6$ | $5.5 \times 10^6$ | $1.5 \times 10^6$ | $1.5 \times 10^6$ | $1.5 \times 10^6$ | $1.0 \times 10^6$ | $1.1 \times 10^6$ |
| 170 (Satd) | 780 (Satd) | 780 (Satd) | 780 (Satd) | 780 (Satd) | 225 (Satd) | 225 (Satd) | 225 (Satd) | 1407 (887°F) | 785 (729°F) |
| 3 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 |
| 24.8 | 30.0 | 30.0 | 30.0 | 30.0 | 26.0 | 24.0 | 24.0 | 37.6 | 34.5 |
| 480 | 106 | 212 | 318 | 454 | 106 | 106 | 106 | 106 | 107 |

TABLE II
ECONOMIC SURVEY OF 100 eMW $D_2O$-MODERATED POWER REACTORS FUELED WITH NATURAL URANIUM

| | CASE 1B | CASE 1D | CASE 2K |
|---|---|---|---|
| GENERAL | | | |
| 1. Net Electrical Output, MW | 100 | 100 | 100 |
| 2. Coolant | Liquid $D_2O$ | Liquid $D_2O$ | Boiling $D_2O$ |
| 3. Reactor Type | Pressure Vessel Hot Moderator | Pressure Tube Cold Moderator | Pressure Tube Cold Moderator |
| PLANT COST ESTIMATE, MILLIONS OF DOLLARS | | | |
| REACTOR PLANT | | | |
| 1. Site Development | 1.1 | 1.1 | 1.0 |
| 2. Fuel Handling | 3.0 | 3.0 | 3.0 |
| 3. Reactor Bldg. & Containment | 12.2 | 12.1 | 10.8 |
| 4. Reactor | 4.6 | 6.1 | 4.8 |
| 5. Coolant System | 6.6 | 7.4 | 2.9 |
| 6. Moderator System | - | 0.5 | 1.0 |
| 7. Control & Protective System | 6.1 | 5.9 | 5.4 |
| 8. Purification & Waste Systems | 2.6 | 2.6 | 2.7 |
| 9. Fuel Charging & Discharging | 2.7 | 2.7 | 2.8 |
| 10. Control & Service Building | 2.0 | 2.0 | 2.0 |
| 11. Building Services | 1.2 | 1.2 | 1.1 |
| 12. General Facilities | 0.4 | 0.4 | 0.4 |
| REACTOR PLANT TOTAL | 42.5 | 45.0 | 37.9 |
| ELECTRICAL GENERATION PLANT | | | |
| 13. Site Development | 0.5 | 0.5 | 0.5 |
| 14. Pump House | 3.2 | 3.2 | 2.8 |
| 15. Turbine Building | 1.0 | 1.0 | 1.0 |
| 16. Generating Equipment | 13.4 | 13.3 | 14.5 |
| 17. Electrical Facilities | 1.5 | 1.5 | 1.5 |
| 18. Building Services | 0.5 | 0.5 | 0.6 |
| ELECTRICAL GENERATION TOTAL | 20.1 | 20.0 | 20.9 |
| TOTAL PLANT | 62.6 | 65.0 | 58.8 |
| $D_2O$ INVENTORY, MILLIONS OF DOLLARS | 9.3 | 8.1 | 9.2 |
| POWER COST, MILLS/kwh | | | |
| 1. Fixed Charges, Plant (14%) | 12.5 | 13.0 | 11.8 |
| 2. Fixed Charges, $D_2O$ (12.5%) | 1.7 | 1.4 | 1.6 |
| 3. Fuel Costs | 2.5 | 2.4 | 2.3 |
| 4. $D_2O$ Losses (4% Per Year) | 0.5 | 0.5 | 0.5 |
| 5. Operating, Maintenance Labor, Supplies | 1.8 | 1.8 | 1.8 |
| TOTAL POWER COST | 19.0 | 19.1 | 18.0 |

Notes:
1. Turbine Plant containment and shielding are assumed not required.
2. Credit is taken for recovery of Pu and U-235 from spent fuel.
3. Cost estimates include escalation to plant completion in 1962.
4. A plant load factor of 80% is assumed.
5. Research and development costs are not included.
6. For additional assumptions, see Discussion, Section C.

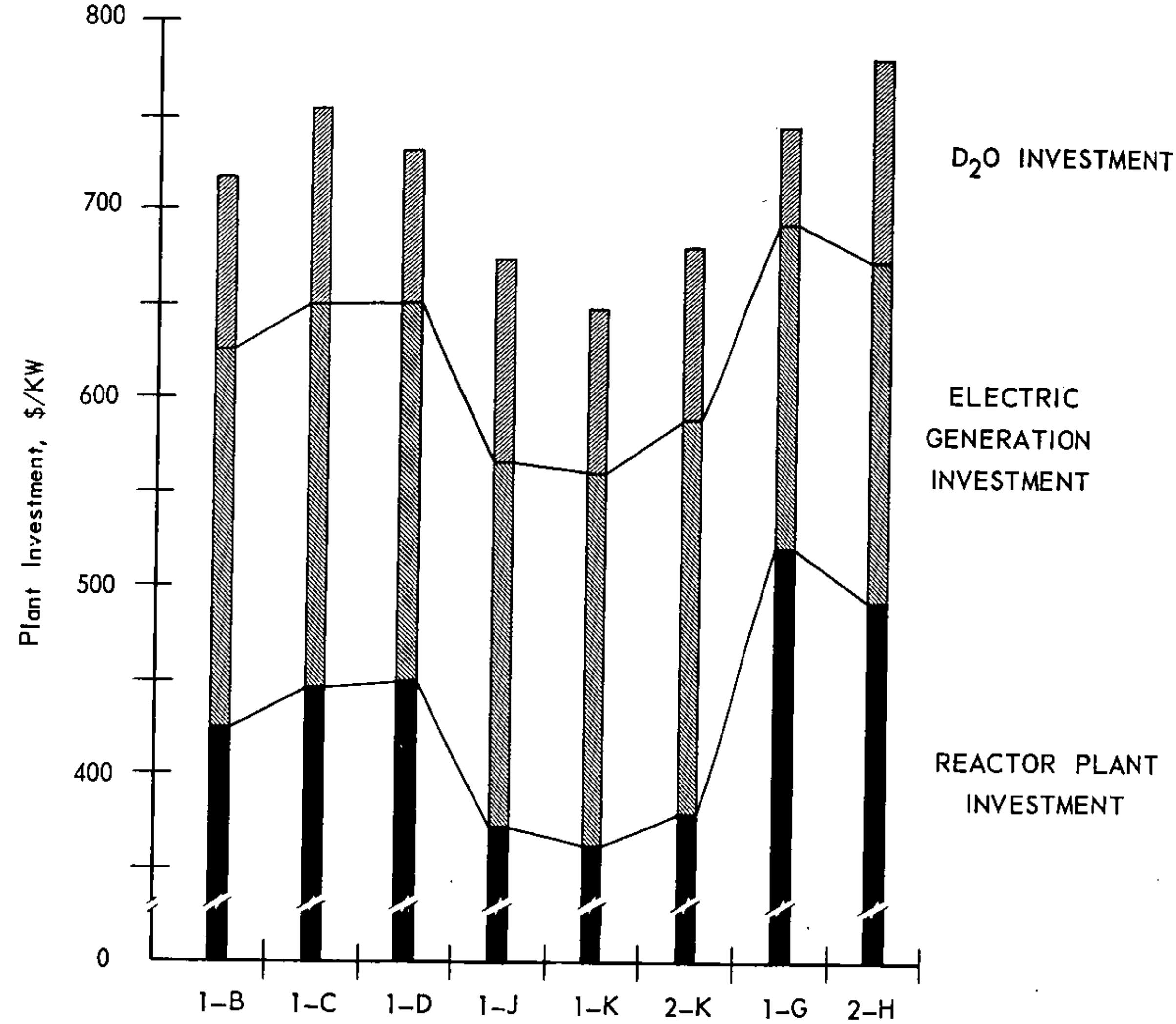
| CASE 1C | CASE 1J | CASE 1K | CASE 1G | CASE 2H |
|---|---|---|---|---|
| 100 | 100 | 100 | 100 | 100 |
| Liquid $D_2O$ | Boiling $D_2O$ | Boiling $D_2O$ | Helium Gas | $D_2O$ Steam |
| Pressure Vessel Cold Moderator | Pressure Vessel Hot Moderator | Pressure Tube Cold Moderator | Pressure Vessel Cold Moderator | Pressure Vessel Cold Moderator |
| 1.1 | 1.0 | 1.0 | 1.1 | 1.1 |
| 3.0 | 3.0 | 3.0 | 3.0 | 3.0 |
| 12.1 | 10.8 | 10.8 | 15.7 | 15.7 |
| 5.8 | 4.5 | 3.1 | 8.1 | 9.0 |
| 7.0 | 3.2 | 3.3 | 8.7 | 3.8 |
| 0.7 | - | 0.8 | 0.8 | 0.9 |
| 6.2 | 5.8 | 5.4 | 6.4 | 6.5 |
| 2.6 | 2.6 | 2.6 | 1.8 | 2.6 |
| 2.7 | 2.7 | 2.7 | 2.7 | 2.8 |
| 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| 1.2 | 1.1 | 1.1 | 1.3 | 1.3 |
| 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| 44.8 | 37.1 | 36.2 | 52.0 | 49.1 |
| 0.5 | 0.5 | 0.5 | 0.4 | 0.4 |
| 3.3 | 3.2 | 3.5 | 2.5 | 2.7 |
| 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 13.4 | 12.7 | 12.7 | 11.3 | 11.9 |
| 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| 0.5 | 0.6 | 0.6 | 0.4 | 0.5 |
| 20.2 | 19.5 | 19.8 | 17.1 | 18.0 |
| 65.0 | 56.6 | 56.0 | 69.1 | 67.1 |
| 10.3 | 10.9 | 8.9 | 5.2 | 10.9 |
| 13.0 | 11.3 | 11.2 | 13.8 | 13.4 |
| 1.8 | 2.0 | 1.6 | 0.9 | 2.0 |
| 1.8 | 2.8 | 4.2 | 3.2 | 2.6 |
| 0.6 | 0.6 | 0.5 | 0.3 | 0.6 |
| 1.8 | 1.8 | 1.8 | 1.8 | 1.8 |
| 19.0 | 18.5 | 19.3 | 20.0 | 20.4 |

TABLE III
ECONOMIC SURVEY OF 100 TO 460 eMW $D_2O$-MODERATED
POWER REACTORS FUELED WITH NATURAL URANIUM

| | CASE 1B | CASE 1B-200 | CASE 1B-300 | CASE 1B-400 | CASE 1D |
|---|---|---|---|---|---|
| GENERAL | | | | | |
| 1. Net Electrical Output, MW | 100 | 200 | 300 | 400 | 100 |
| 2. Coolant | Liquid $D_2O$ | Liquid $D_2O$ | Liquid $D_2O$ | Liquid $D_2O$ | Liquid $D_2O$ |
| 3. Reactor Type | Pressure Vessel Hot Moderator | Pressure Vessel Hot Moderator | Pressure Vessel Hot Moderator | Pressure Vessel Hot Moderator | Pressure Tube Cold Moderator |
| PLANT COST ESTIMATE, MILLIONS OF DOLLARS | | | | | |
| REACTOR PLANT | | | | | |
| 1. Site Development | 1.1 | 1.0 | 1.0 | 1.1 | 1.1 |
| 2. Fuel Handling | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 |
| 3. Reactor Bldg. & Containment | 12.2 | 16.0 | 17.0 | 20.7 | 12.1 |
| 4. Reactor | 4.6 | 6.7 | 7.8 | 8.9 | 6.1 |
| 5. Coolant System | 6.6 | 10.2 | 14.0 | 19.5 | 7.4 |
| 6. Moderator System | - | - | - | - | 0.5 |
| 7. Control & Protective System | 6.1 | 6.9 | 7.7 | 7.6 | 5.9 |
| 8. Purification & Waste Systems | 2.6 | 2.9 | 3.0 | 3.2 | 2.6 |
| 9. Fuel Charging & Discharging | 2.7 | 2.7 | 2.7 | 2.7 | 2.7 |
| 10. Control & Service Building | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| 11. Building Services | 1.2 | 1.2 | 1.1 | 1.2 | 1.2 |
| 12. General Facilities | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| REACTOR PLANT TOTAL | 42.5 | 53.0 | 59.7 | 70.3 | 45.0 |
| ELECTRICAL GENERATION PLANT | | | | | |
| 13. Site Development | 0.5 | 0.5 | 0.7 | 0.9 | 0.5 |
| 14. Pump House | 3.2 | 4.6 | 6.2 | 7.3 | 3.2 |
| 15. Turbine Building | 1.0 | 1.2 | 1.8 | 1.8 | 1.0 |
| 16. Generating Equipment | 13.4 | 20.3 | 33.3 | 40.1 | 13.3 |
| 17. Electrical Facilities | 1.5 | 2.0 | 3.3 | 3.9 | 1.5 |
| 18. Building Services | 0.5 | 0.7 | 0.9 | 0.9 | 0.5 |
| ELECTRICAL GENERATION TOTAL | 20.1 | 29.3 | 46.2 | 54.9 | 20.0 |
| TOTAL PLANT | 62.6 | 82.3 | 105.9 | 125.2 | 65.0 |
| $D_2O$ INVENTORY, MILLIONS OF DOLLARS | 9.3 | 13.8 | 20.3 | 26.1 | 8.1 |
| POWER COST, MILLS/kwh | | | | | |
| 1. Fixed Charges, Plant (14%) | 12.5 | 8.2 | 7.1 | 6.3 | 13.0 |
| 2. Fixed Charges, $D_2O$ (12.5%) | 1.7 | 1.2 | 1.2 | 1.2 | 1.4 |
| 3. Fuel Costs | 2.5 | 2.5 | 2.5 | 2.6 | 2.4 |
| 4. $D_2O$ Losses (4% per year) | 0.5 | 0.4 | 0.4 | 0.4 | 0.5 |
| 5. Operating, Maintenance Labor, Supplies | 1.8 | 1.2 | 0.9 | 0.8 | 1.8 |
| TOTAL POWER COST | 19.0 | 13.5 | 12.1 | 11.3 | 19.1 |

Notes:
1. Turbine Plant containment and shielding are assumed not required.
2. Credit is taken for recovery of Pu and U-235 from spent fuel.
3. Cost estimates include escalation to plant completion in 1962.
4. A plant load factor of 80% is assumed.
5. Research and development costs are not included.
6. For additional assumptions, see Discussion, Section C.

| CASE 1D-200 | CASE 1D-300 | CASE 1D-460 | CASE 2K | CASE 1K-200 | CASE 1K-300 | CASE 1K-430 |
|---|---|---|---|---|---|---|
| 200 | 300 | 460 | 100 | 200 | 300 | 430 |
| Liquid $D_2O$ | Liquid $D_2O$ | Liquid $D_2O$ | Boiling $D_2O$ | Boiling $D_2O$ | Boiling $D_2O$ | Boiling $D_2O$ |
| Pressure Tube Cold Moderator | Pressure Tube Cold Moderator | Pressure Tube Cold Moderator | Pressure Tube Cold Moderator | Pressure Tube Cold Moderator | Pressure Tube Cold Moderator | Pressure Tube Cold Moderator |
| 1.0 | 1.0 | 1.1 | 1.0 | 0.9 | 0.8 | 0.8 |
| 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 | 3.0 |
| 16.5 | 16.6 | 19.3 | 10.8 | 10.8 | 11.0 | 11.0 |
| 6.5 | 8.7 | 10.5 | 4.8 | 6.7 | 9.2 | 12.8 |
| 11.8 | 14.3 | 20.5 | 2.9 | 3.5 | 4.4 | 5.1 |
| 2.1 | 2.6 | 4.1 | 1.0 | 1.5 | 2.0 | 2.9 |
| 6.6 | 6.8 | 8.0 | 5.4 | 6.7 | 7.6 | 8.6 |
| 2.9 | 3.0 | 3.2 | 2.7 | 3.3 | 3.6 | 3.9 |
| 2.7 | 2.7 | 2.7 | 2.8 | 2.7 | 2.7 | 2.7 |
| 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| 1.2 | 1.2 | 1.1 | 1.1 | 1.1 | 1.0 | 0.9 |
| 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| 56.7 | 62.3 | 75.9 | 37.9 | 42.6 | 47.7 | 54.1 |
| 0.5 | 0.7 | 1.0 | 0.5 | 0.6 | 0.8 | 0.9 |
| 4.8 | 6.3 | 8.4 | 2.8 | 4.5 | 5.7 | 6.7 |
| 1.2 | 1.8 | 2.1 | 1.0 | 1.2 | 1.8 | 1.8 |
| 20.3 | 33.3 | 51.1 | 14.5 | 21.5 | 35.5 | 45.4 |
| 2.0 | 3.3 | 4.9 | 1.5 | 2.0 | 3.2 | 4.1 |
| 0.6 | 0.9 | 1.0 | 0.6 | 0.8 | 1.0 | 1.0 |
| 29.4 | 46.3 | 68.5 | 20.9 | 30.6 | 48.0 | 59.9 |
| 86.1 | 108.6 | 144.4 | 58.8 | 73.2 | 95.7 | 114.0 |
| 13.5 | 19.8 | 25.6 | 9.2 | 13.4 | 19.0 | 25.7 |
| 8.6 | 7.2 | 6.3 | 11.8 | 7.3 | 6.4 | 5.3 |
| 1.2 | 1.2 | 1.0 | 1.6 | 1.2 | 1.1 | 1.1 |
| 3.5 | 3.2 | 2.8 | 2.3 | 2.7 | 2.5 | 2.0 |
| 0.4 | 0.4 | 0.3 | 0.5 | 0.4 | 0.4 | 0.3 |
| 1.2 | 0.9 | 0.7 | 1.8 | 1.2 | 0.9 | 0.7 |
| 14.9 | 12.9 | 11.1 | 18.0 | 12.8 | 11.3 | 9.4 |




LIQUID - COOLED REACTORS

- 1-B: Hot moderator, pressure vessel
- 1-C: Cold moderator, pressure vessel
- 1-D: Cold moderator, pressure tube

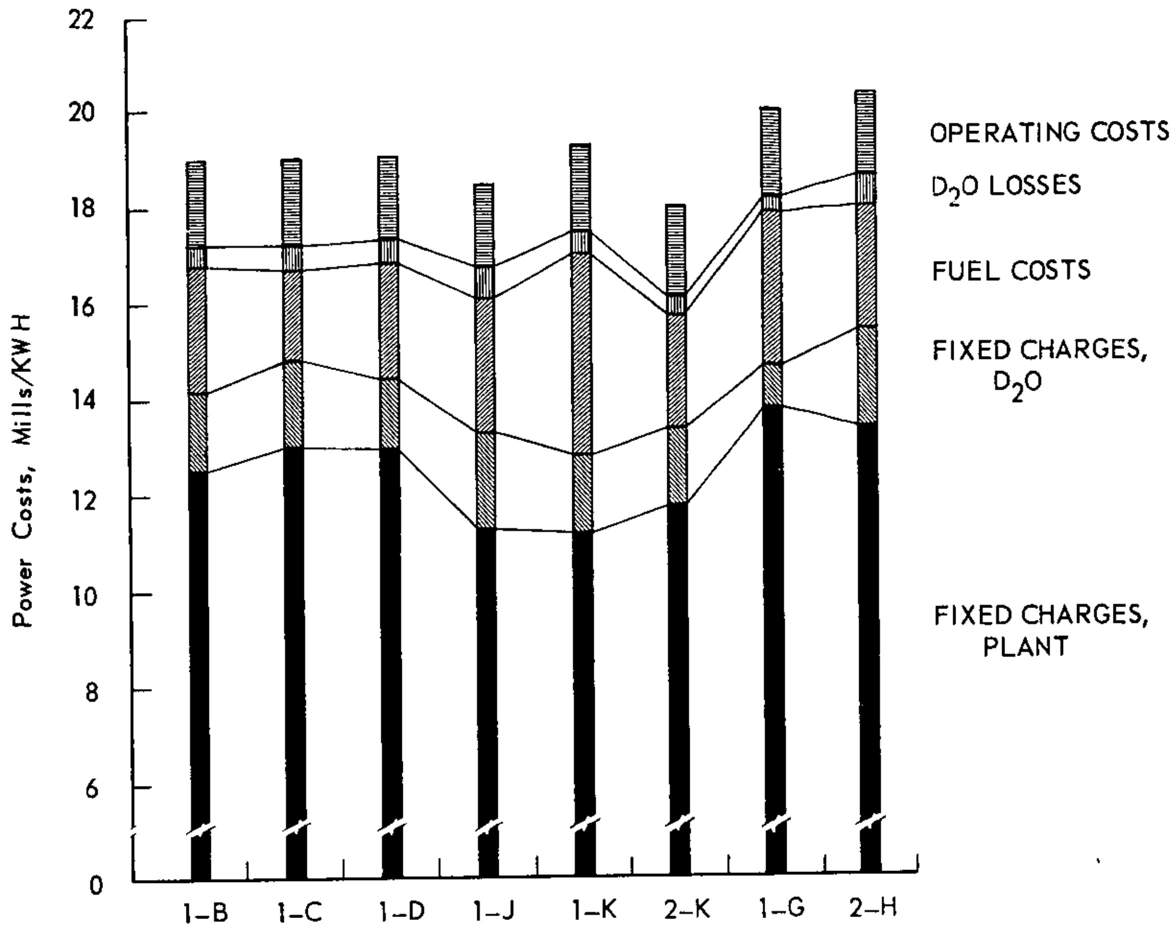
BOILING - $D_2O$ REACTORS

- 1-J: Hot moderator, pressure vessel
- 1-K: Cold moderator, pressure tube
- 2-K: Cold moderator, pressure tube

GAS - COOLED REACTORS

- 1-G: Helium - cooled
- 2-H: $D_2O$ steam - cooled

FIGURE 1 – PLANT INVESTMENT FOR 100 eMW $D_2O$ - MODERATED POWER PLANTS




LIQUID - COOLED REACTORS

1–B: Hot moderator, pressure vessel
1–C: Cold moderator, pressure vessel
1–D: Cold moderator, pressure tube

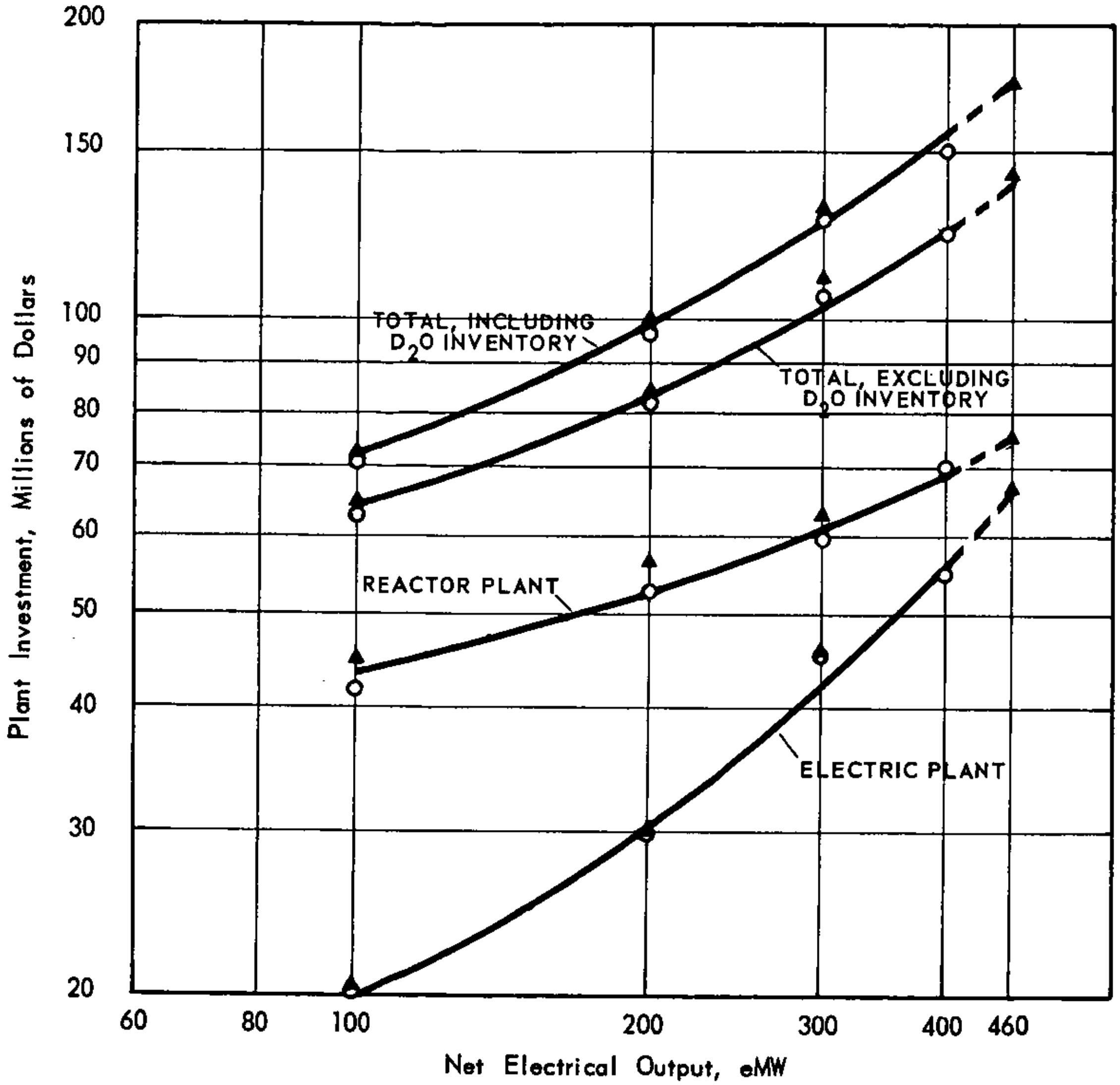
BOILING - $D_2O$ REACTORS

1–J: Hot moderator, pressure vessel
1–K: Cold moderator, pressure tube
2–K: Cold moderator, pressure tube

GAS - COOLED REACTORS

1–G: Helium - cooled
2–H: $D_2O$ steam - cooled

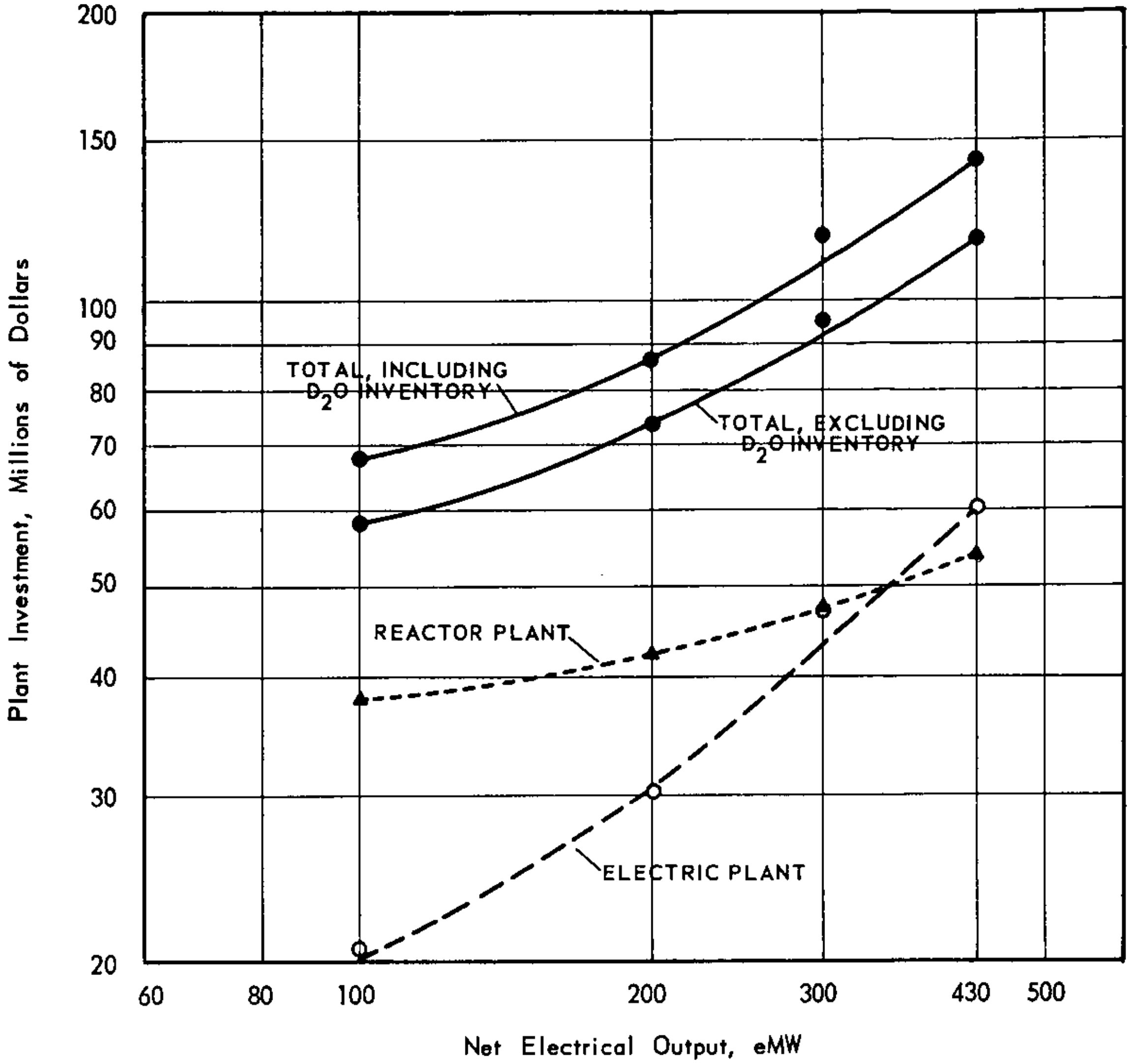
FIGURE 2 – POWER COSTS FOR 100 eMW $D_2O$ - MODERATED POWER PLANTS




KEY:

▲ = Pressure tube reactor
○ = Pressure vessel reactor

FIGURE 3 – PLANT INVESTMENT vs. CAPACITY: LIQUID-$D_2O$-COOLED REACTORS




KEY:

● ——— = Total cost

▲ - - - - = Cost of reactor plant

○ — — = Cost of electric-generating plant

FIGURE 4 – PLANT INVESTMENT vs. CAPACITY: BOILING-$D_2O$-COOLED REACTORS

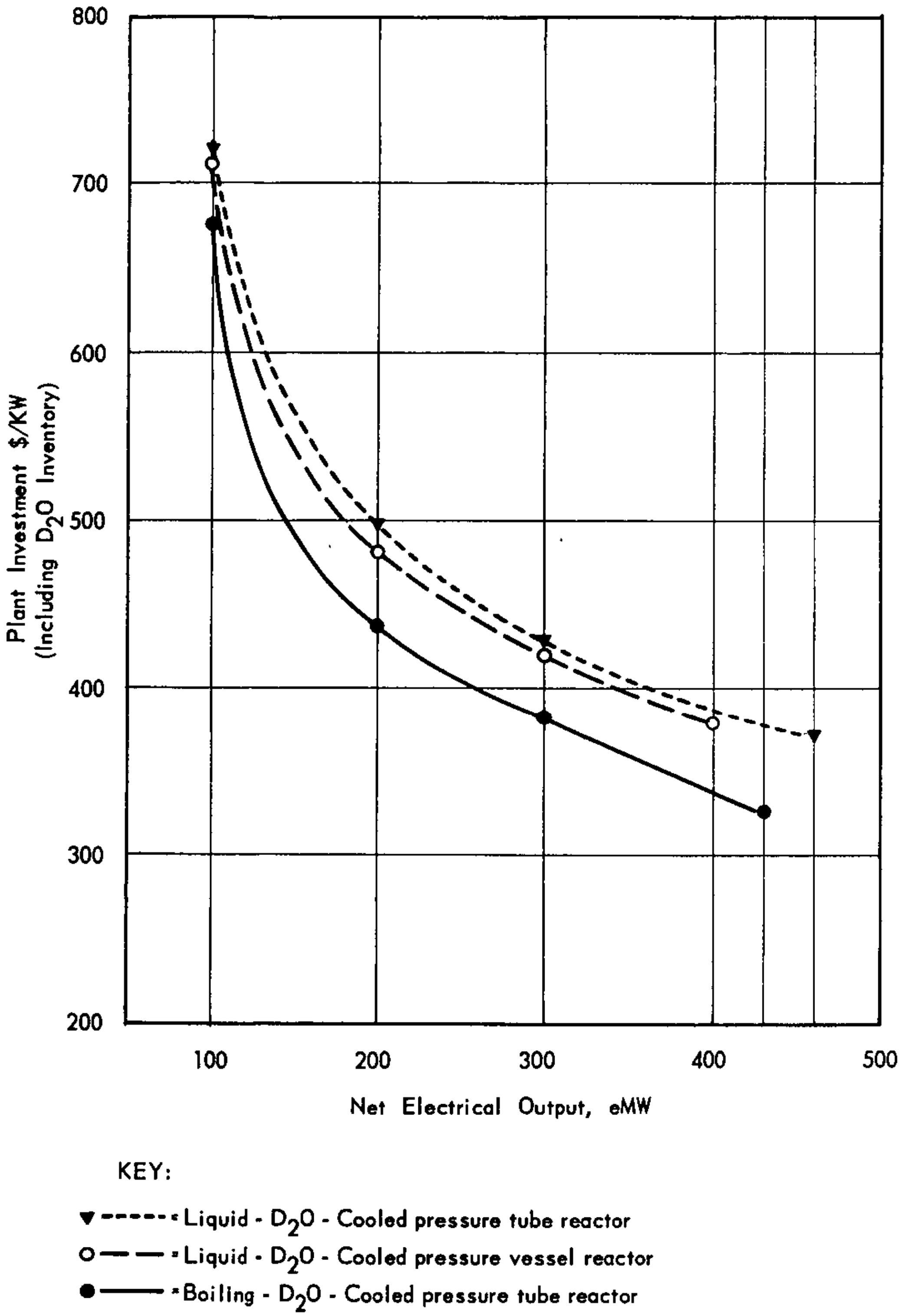
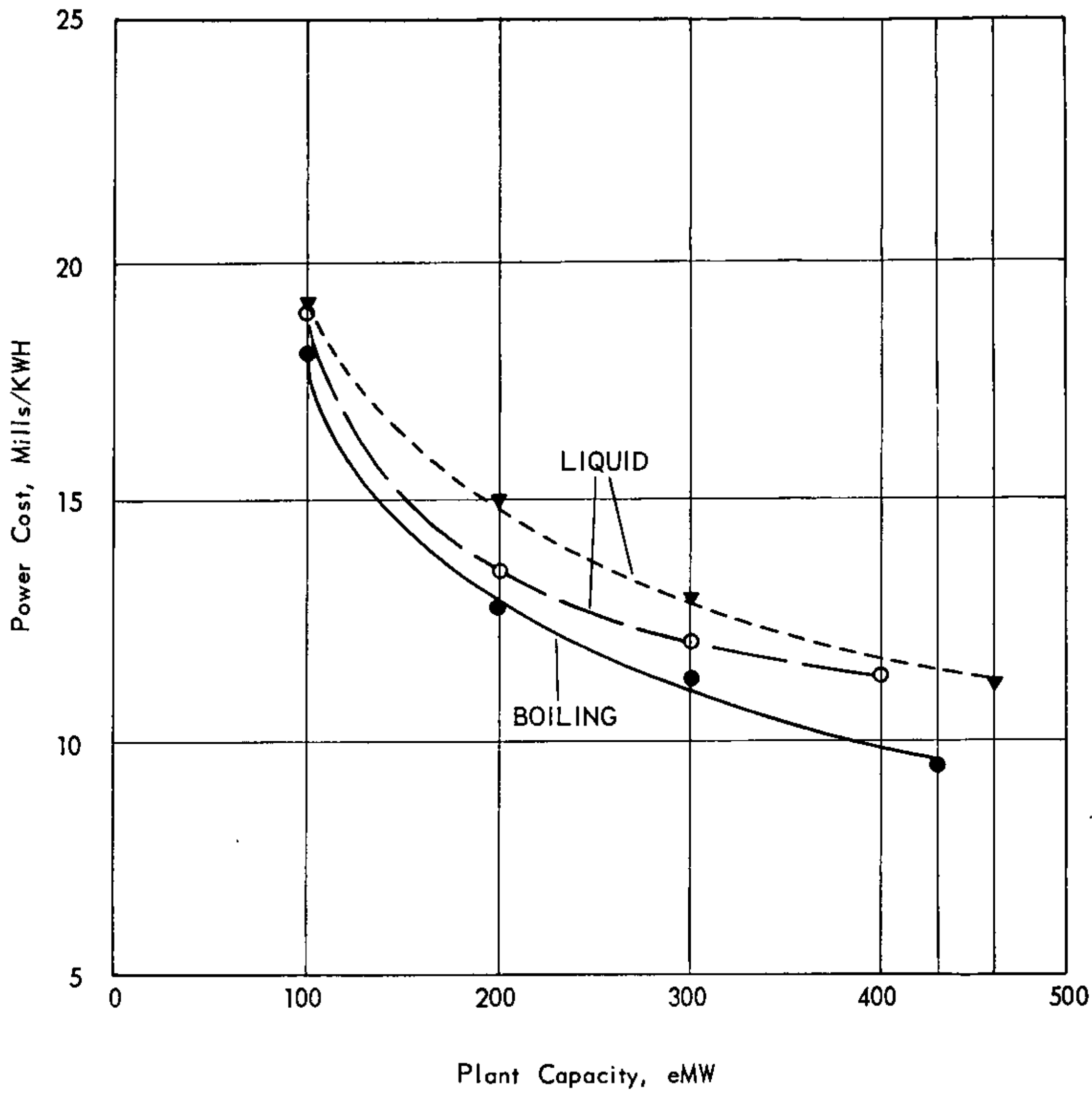


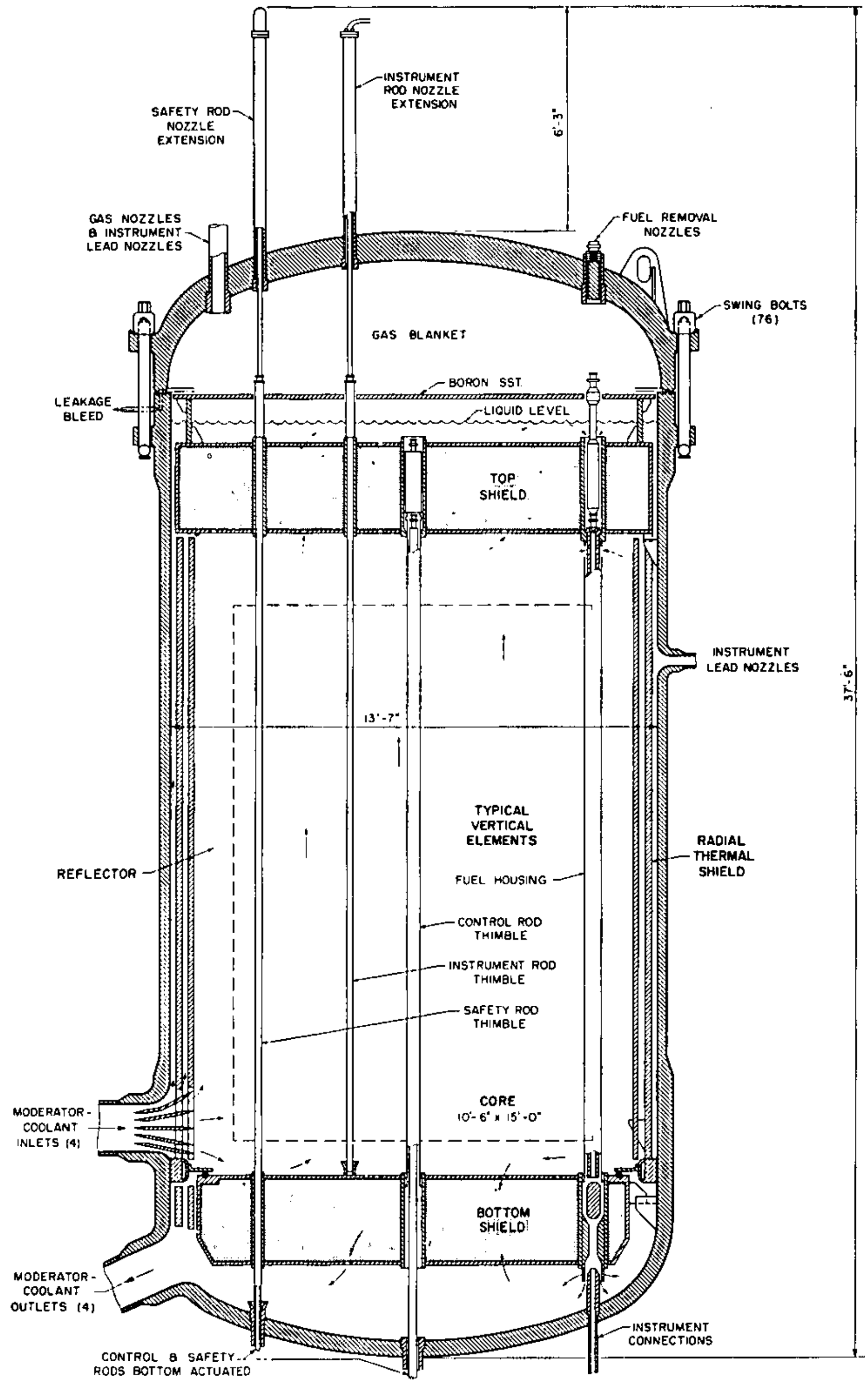

FIGURE 5 – PLANT INVESTMENT vs. CAPACITY
FOR $D_2O$ MODERATED POWER REACTORS




KEY:

▼- - - - - - - = pressure tube reactor
○——— ——— = pressure vessel reactor
●————— = boiling $D_2O$ reactor

FIGURE 6 – POWER COST vs. PLANT CAPACITY
FOR $D_2O$ MODERATED POWER REACTORS




GENERAL NOTES

1. $D_2O$ VOLUME OF VESSEL - 24,000 GAL
2. DESIGN PRESSURE = 711 PSIG

FIGURE 7 – PRESSURE VESSEL REACTOR - LIQUID $D_2O$ COOLED - HOT MODERATOR
(Case 1B – 100 eMW)

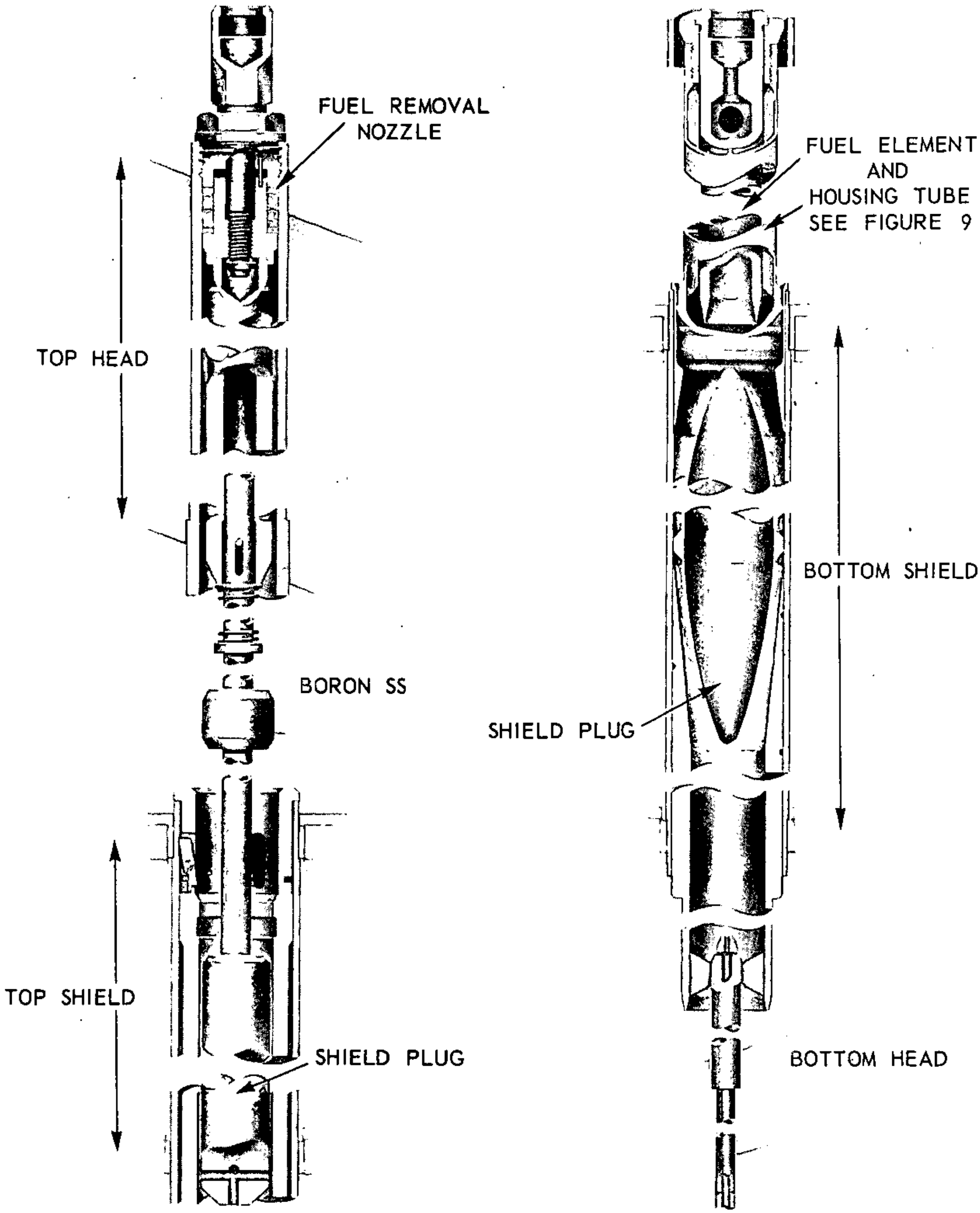



FIGURE 8 - TYPICAL FUEL ELEMENT AND HOUSING TUBE ASSEMBLY

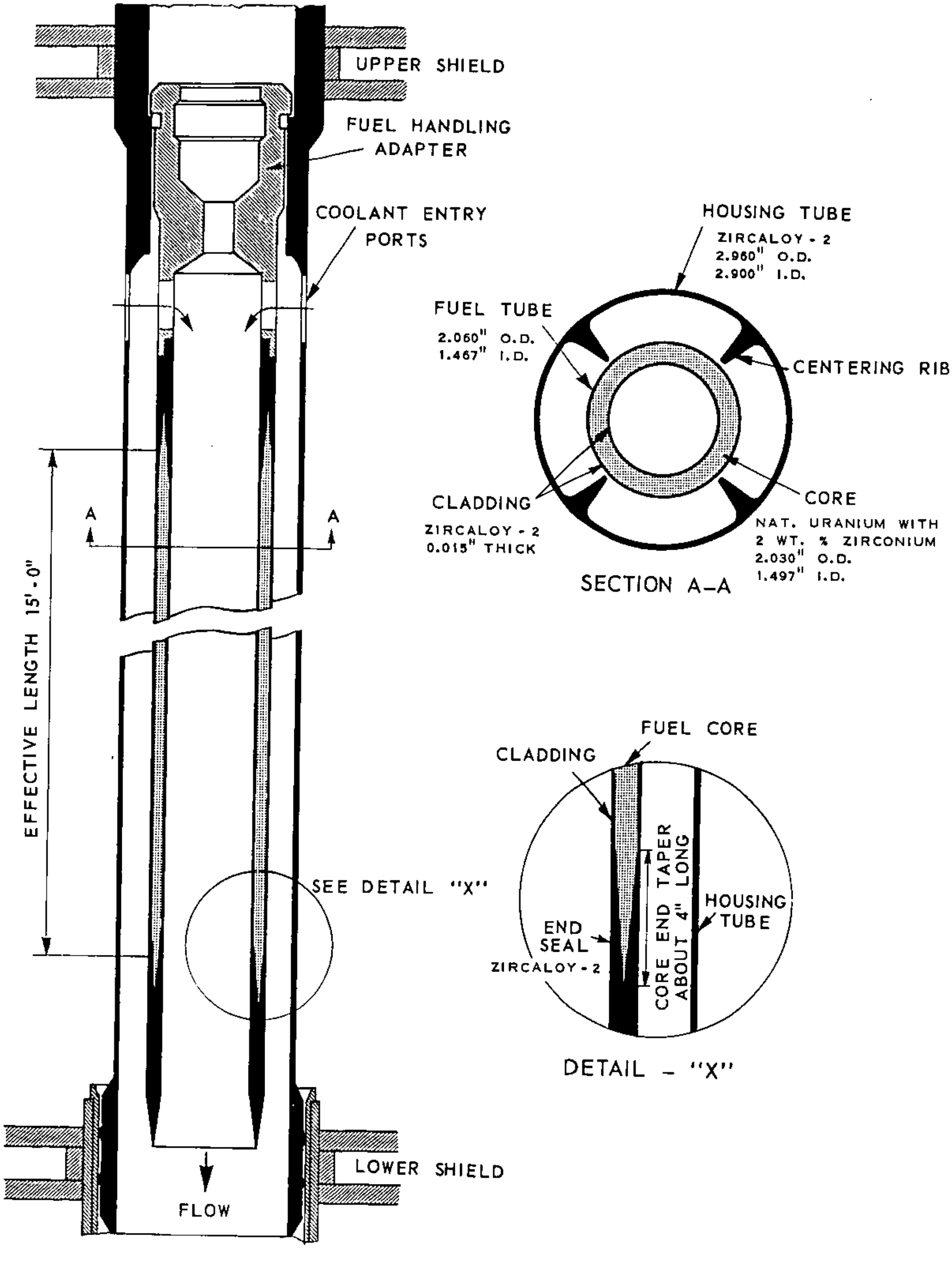
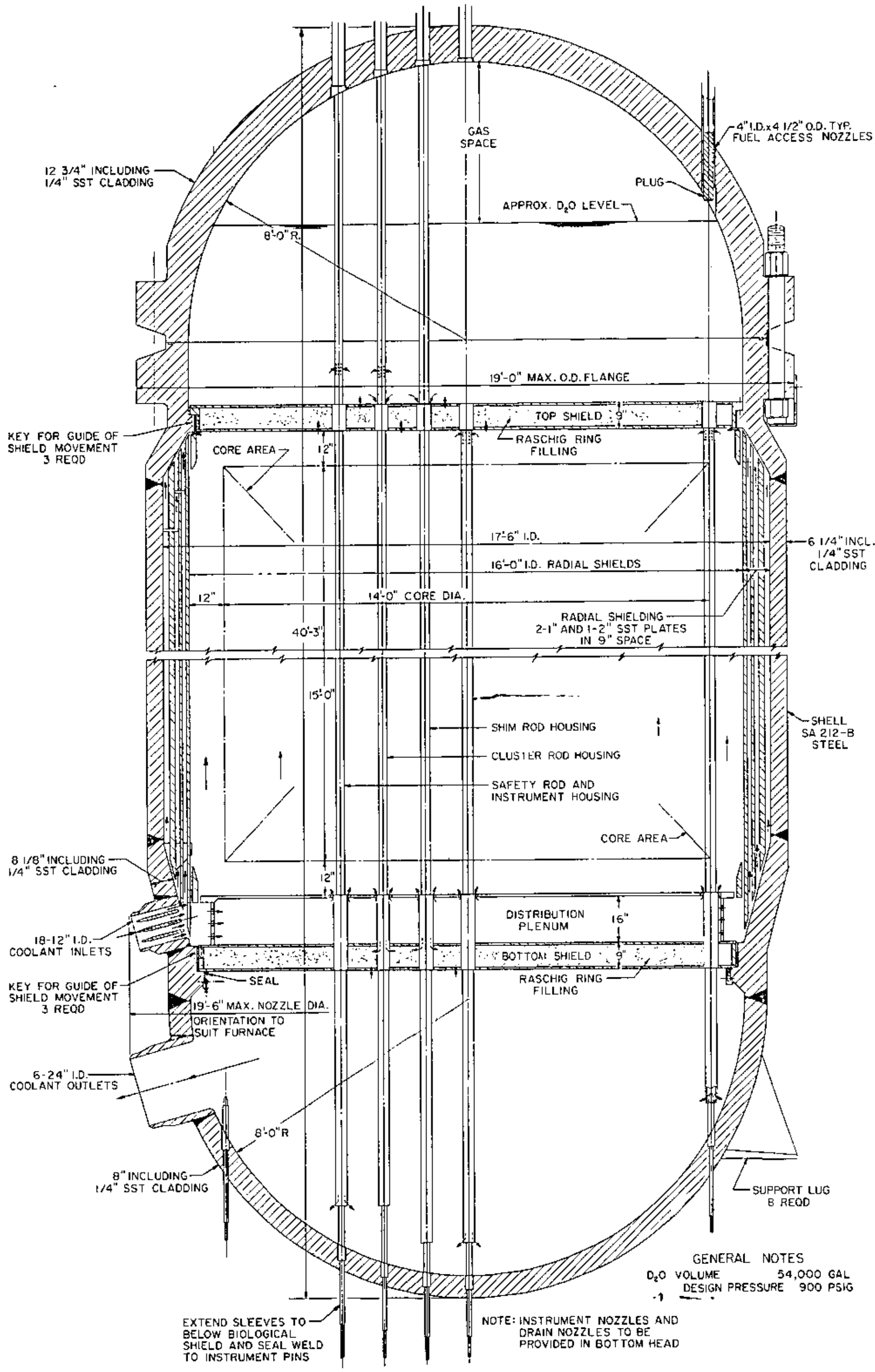



FIGURE 9 – TYPICAL FUEL ELEMENT AND HOUSING TUBE SECTION




✓ Fuel Pressure Tube deleted

Tube deleted

FIGURE 10 – PRESSURE VESSEL REACTOR: LIQUID-$D_2O$-COOLED, HOT MODERATOR (B SERIES, 400 eMW)

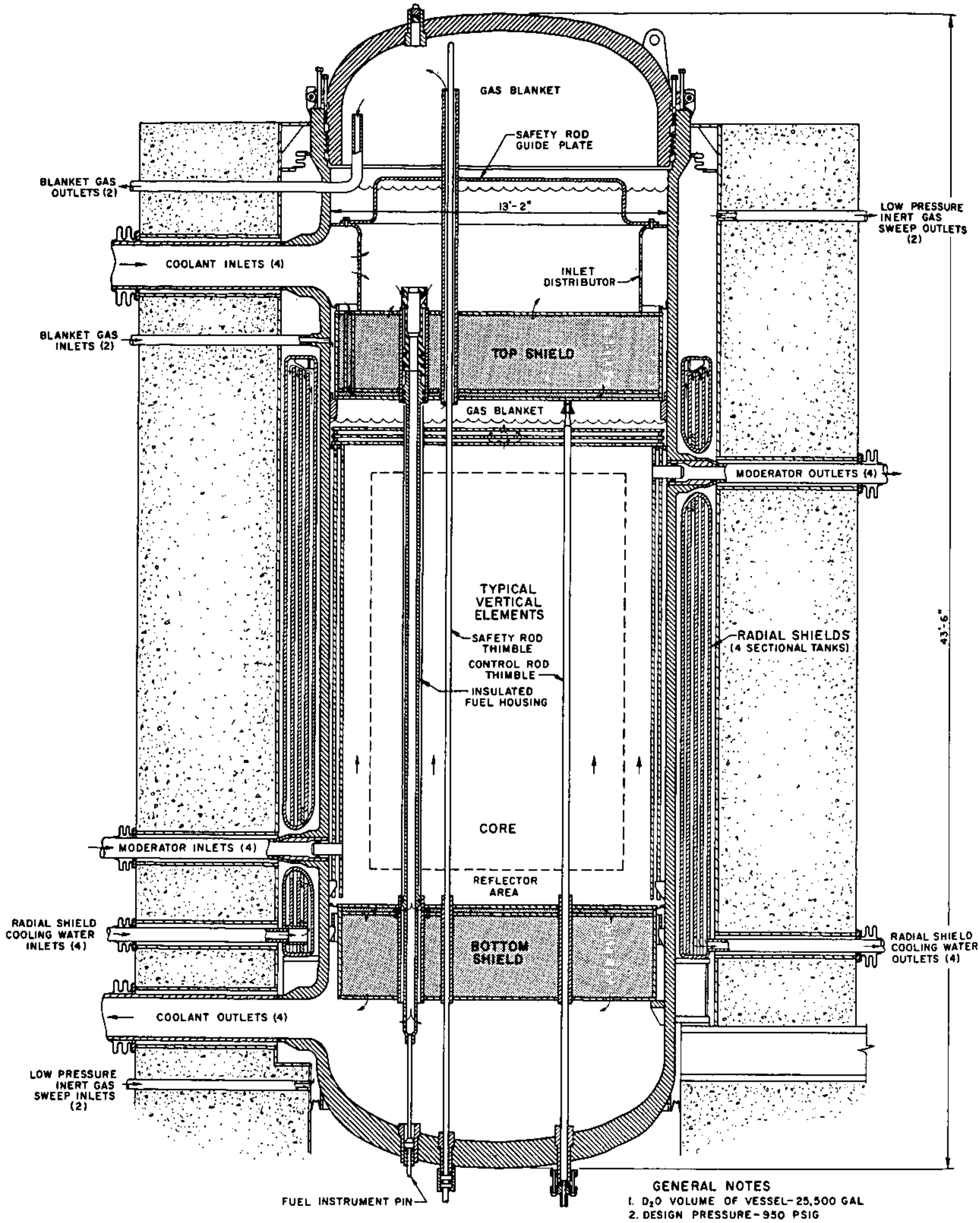



FIGURE 11 – PRESSURE VESSEL REACTOR: LIQUID-$D_2O$-COOLED, COLD MODERATOR (CASE 1C, 100 eMW)

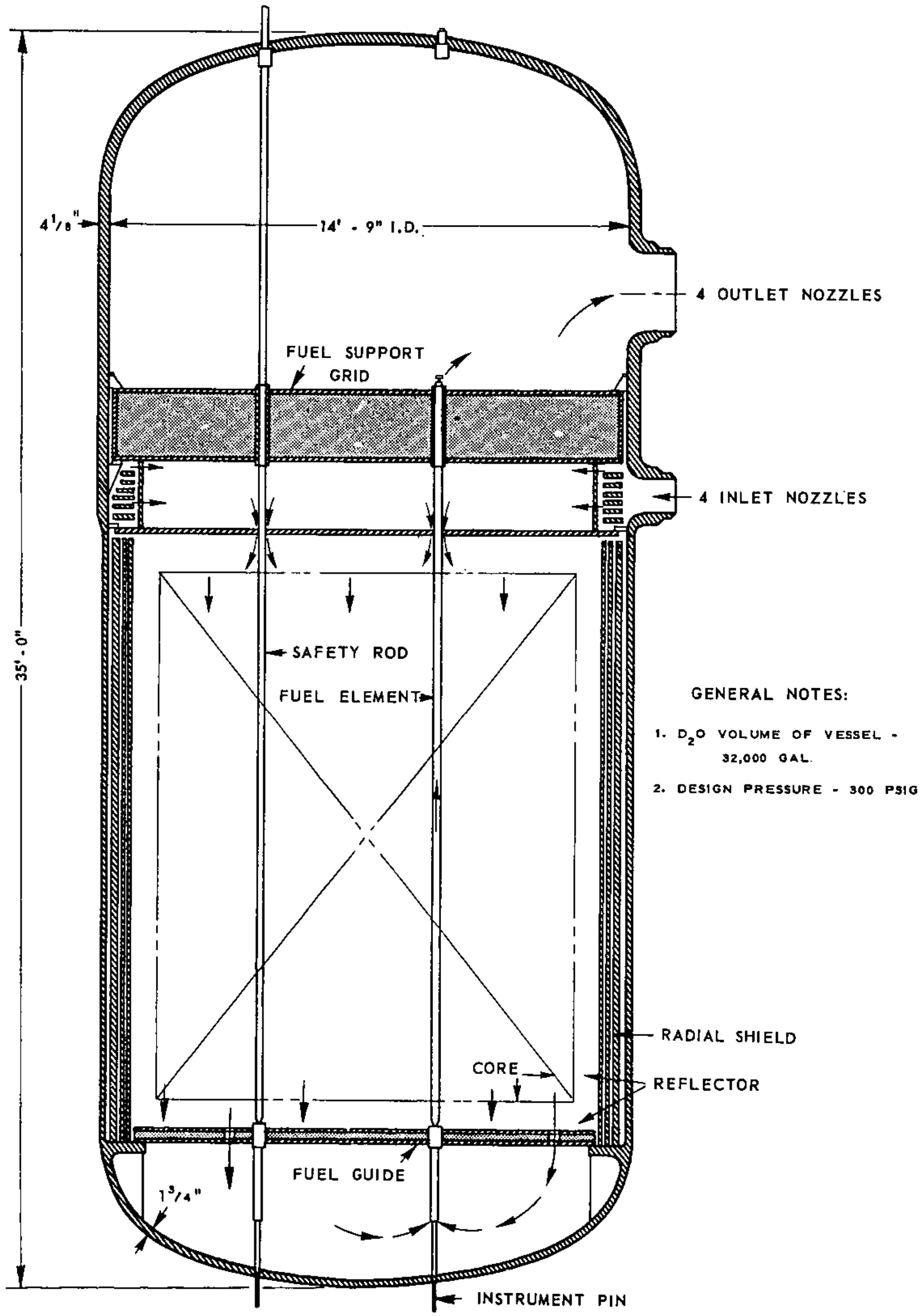
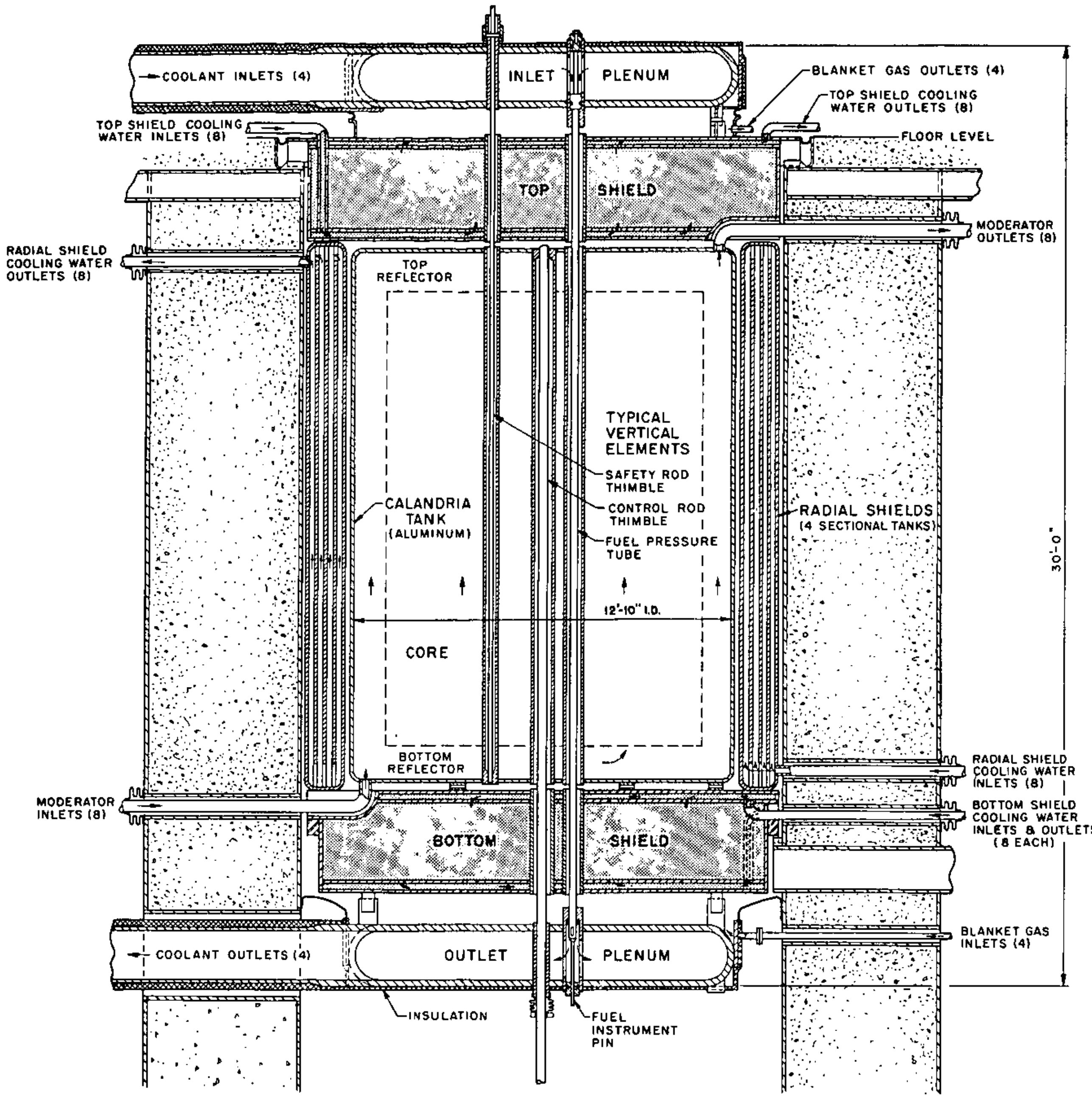


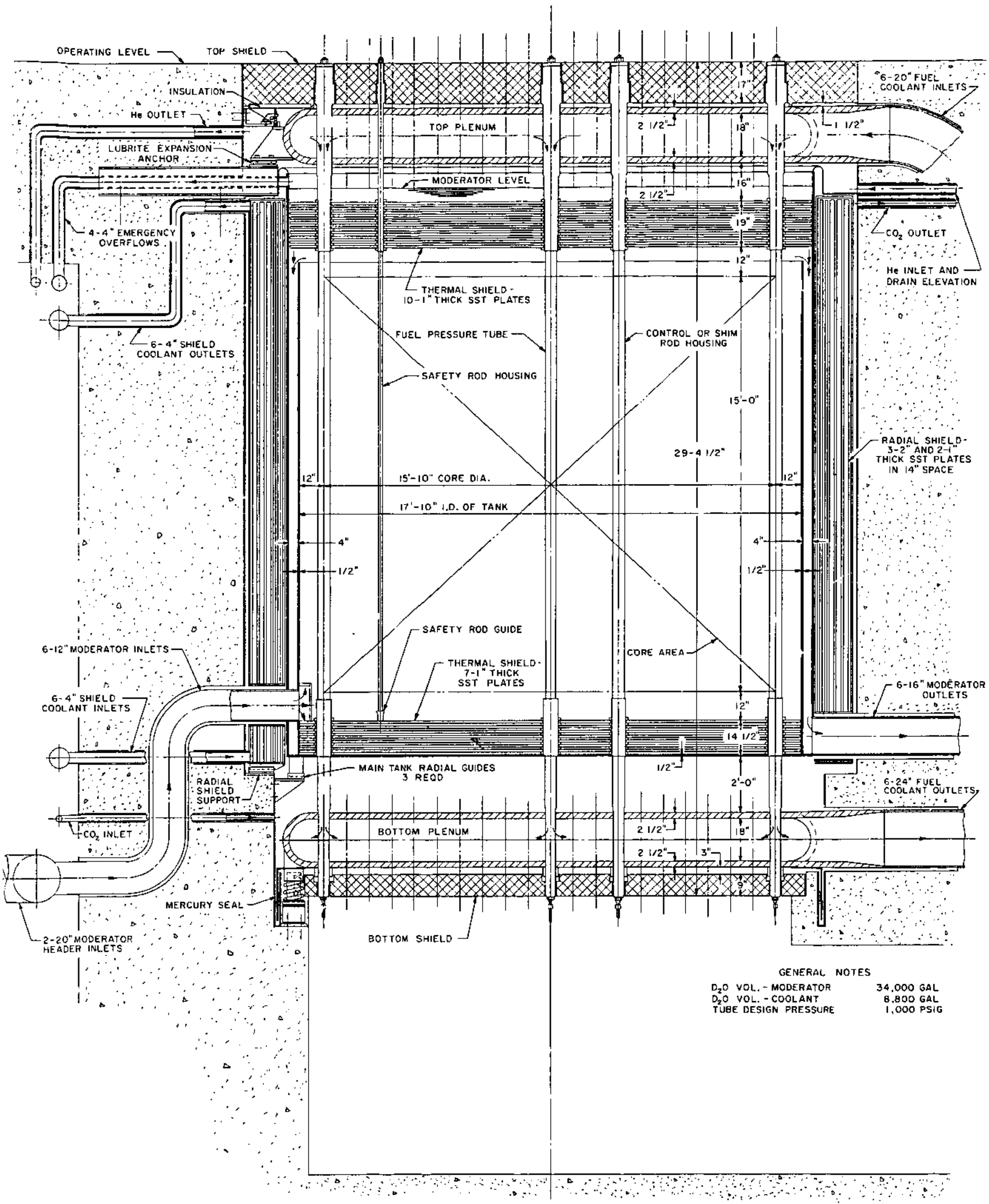

FIGURE 12 – PRESSURE VESSEL REACTOR: BOILING-$D_2O$-COOLED, HOT MODERATOR (CASE 1J, 100 eMW)




GENERAL NOTES

1. DESIGN PRESSURES- PLENUMS & TUBES- 1,000 PSIG
2. $D_2O$ MODERATOR VOLUME- 14,600 GAL
3. $D_2O$ COOLANT VOLUME- 4,400 GAL

FIGURE 13 – PRESSURE TUBE REACTOR: LIQUID-$D_2O$-COOLED, COLD MODERATOR (CASE 1D, 100 eMW)




GENERAL NOTES

| | |
|---|---|
| $D_2O$ VOL. - MODERATOR | 34,000 GAL |
| $D_2O$ VOL. - COOLANT | 8,800 GAL |
| TUBE DESIGN PRESSURE | 1,000 PSIG |

**FIGURE 14 – PRESSURE TUBE REACTOR: LIQUID-$D_2O$-COOLED, COLD MODERATOR (D SERIES, 460 eMW)**

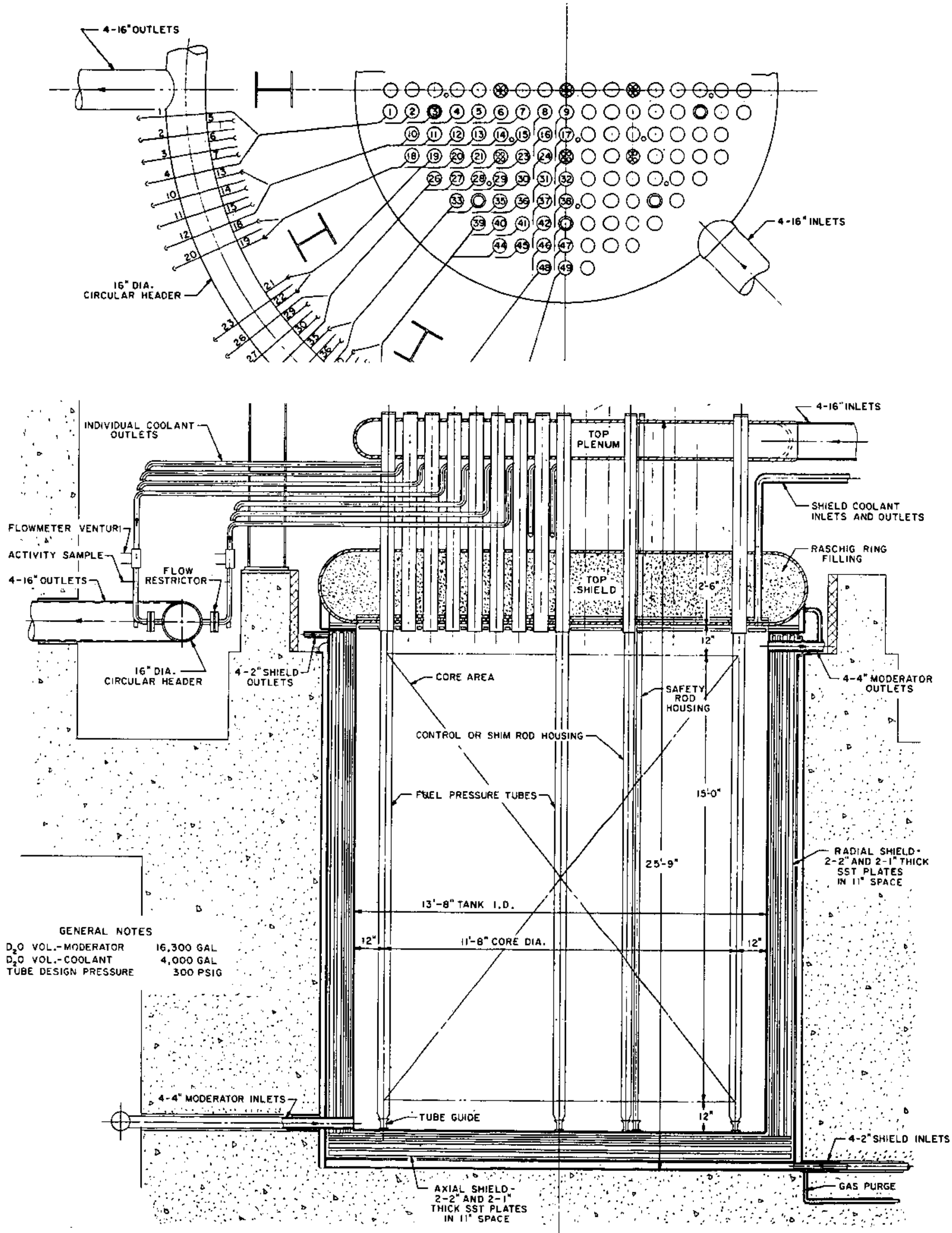



FIGURE 15 – PRESSURE TUBE REACTOR: BOILING-$D_2O$-COOLED, COLD MODERATOR (CASE 1K, 100 eMW)

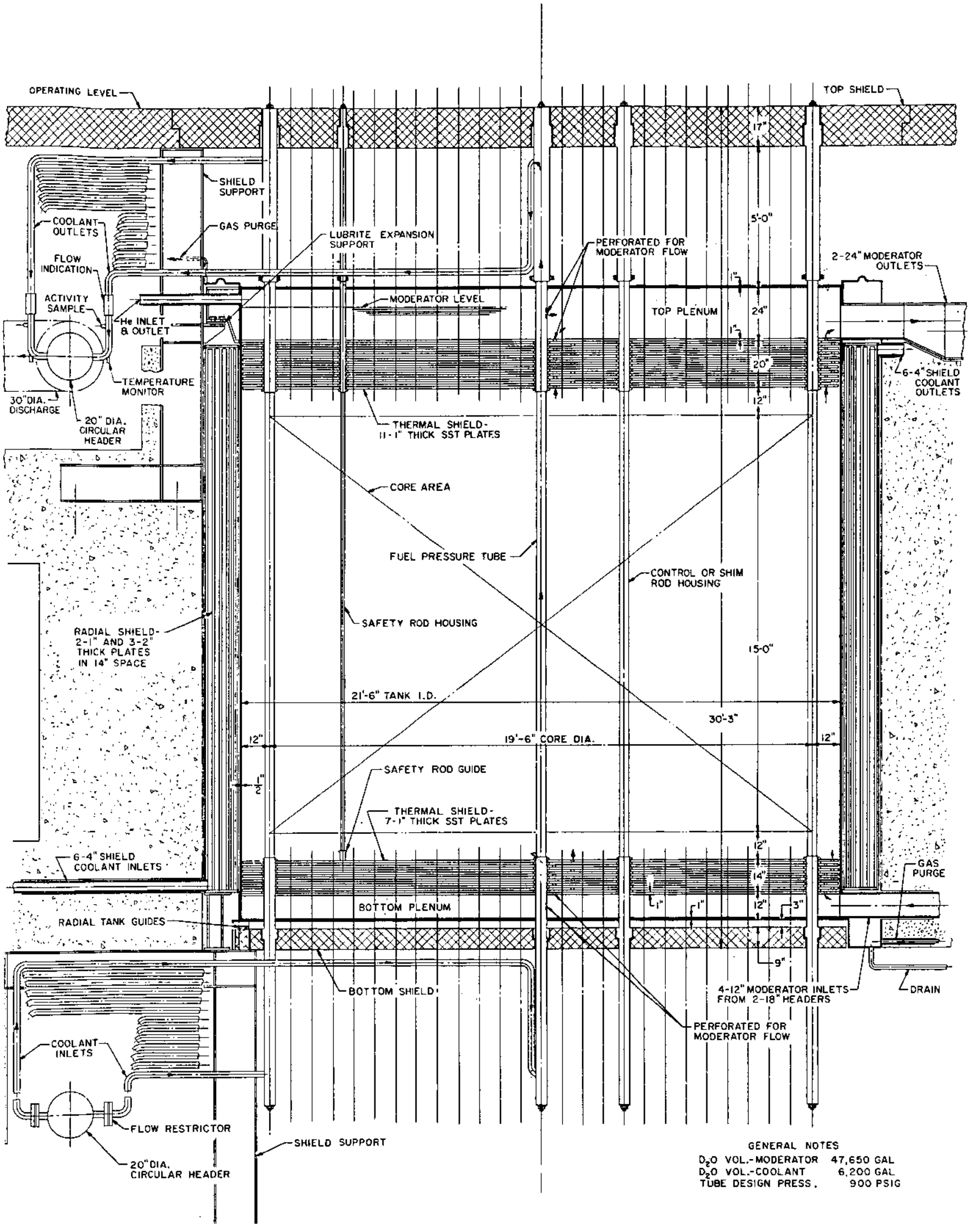



**FIGURE 16 – PRESSURE TUBE REACTOR: BOILING-$D_2O$-COOLED, COLD MODERATOR (K SERIES, 430 eMW)**

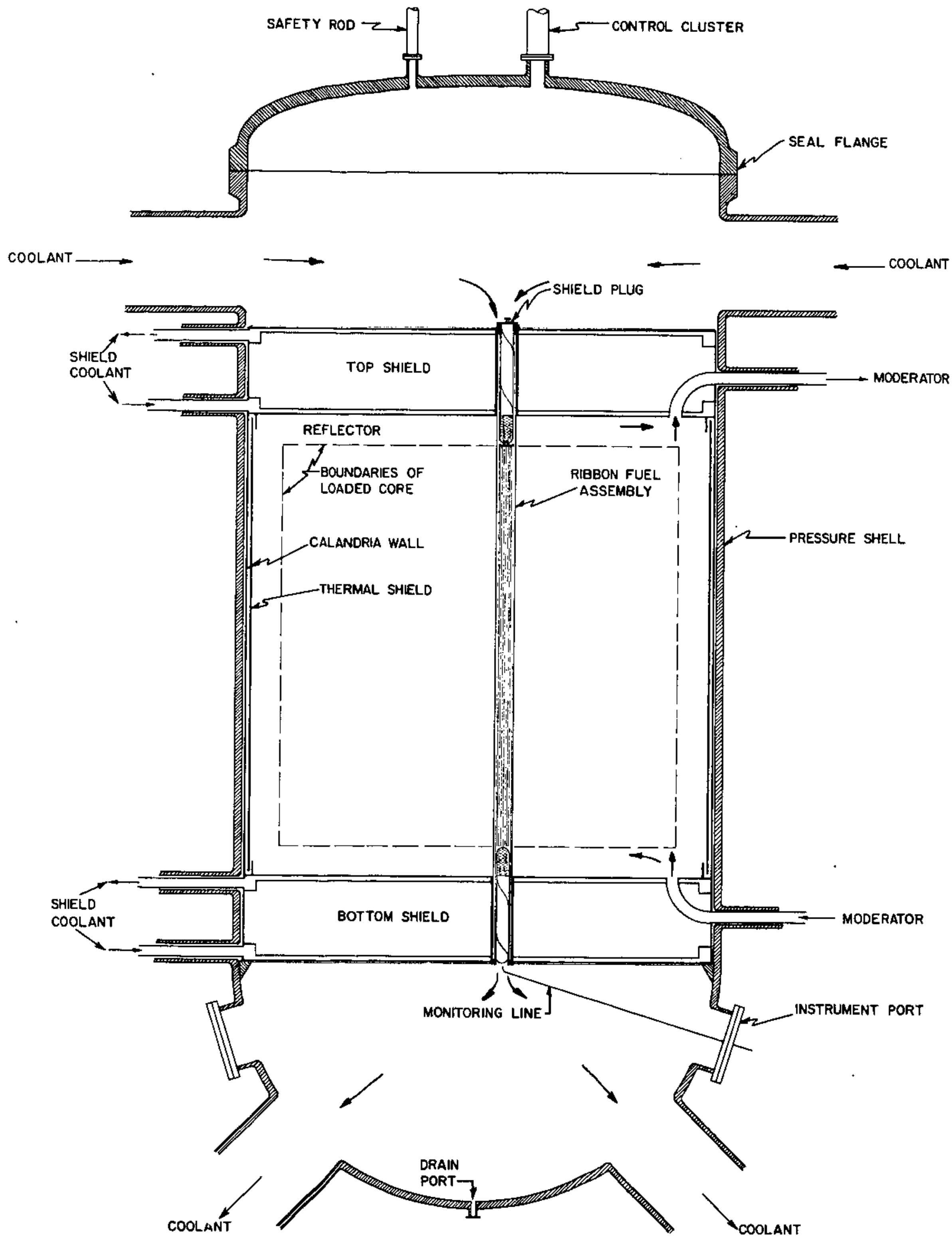



FIGURE 17 – PRESSURE VESSEL REACTOR: HELIUM-GAS-COOLED, COLD MODERATOR (CASE 1G, 100 eMW)

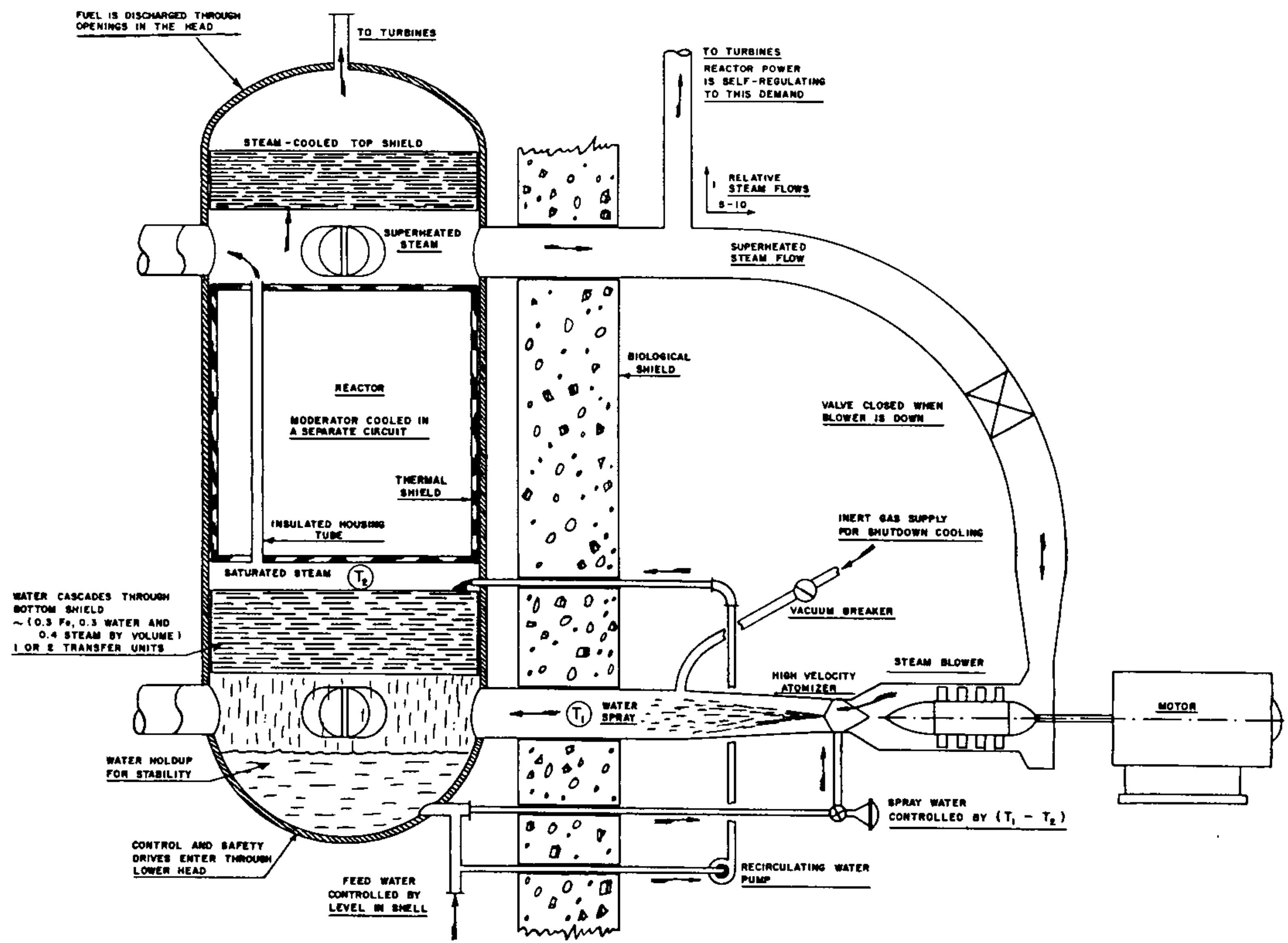



FIGURE 18 – PRESSURE VESSEL REACTOR: $D_2O$-STEAM-COOLED, COLD MODERATOR (CASE 2H, 100 eMW)

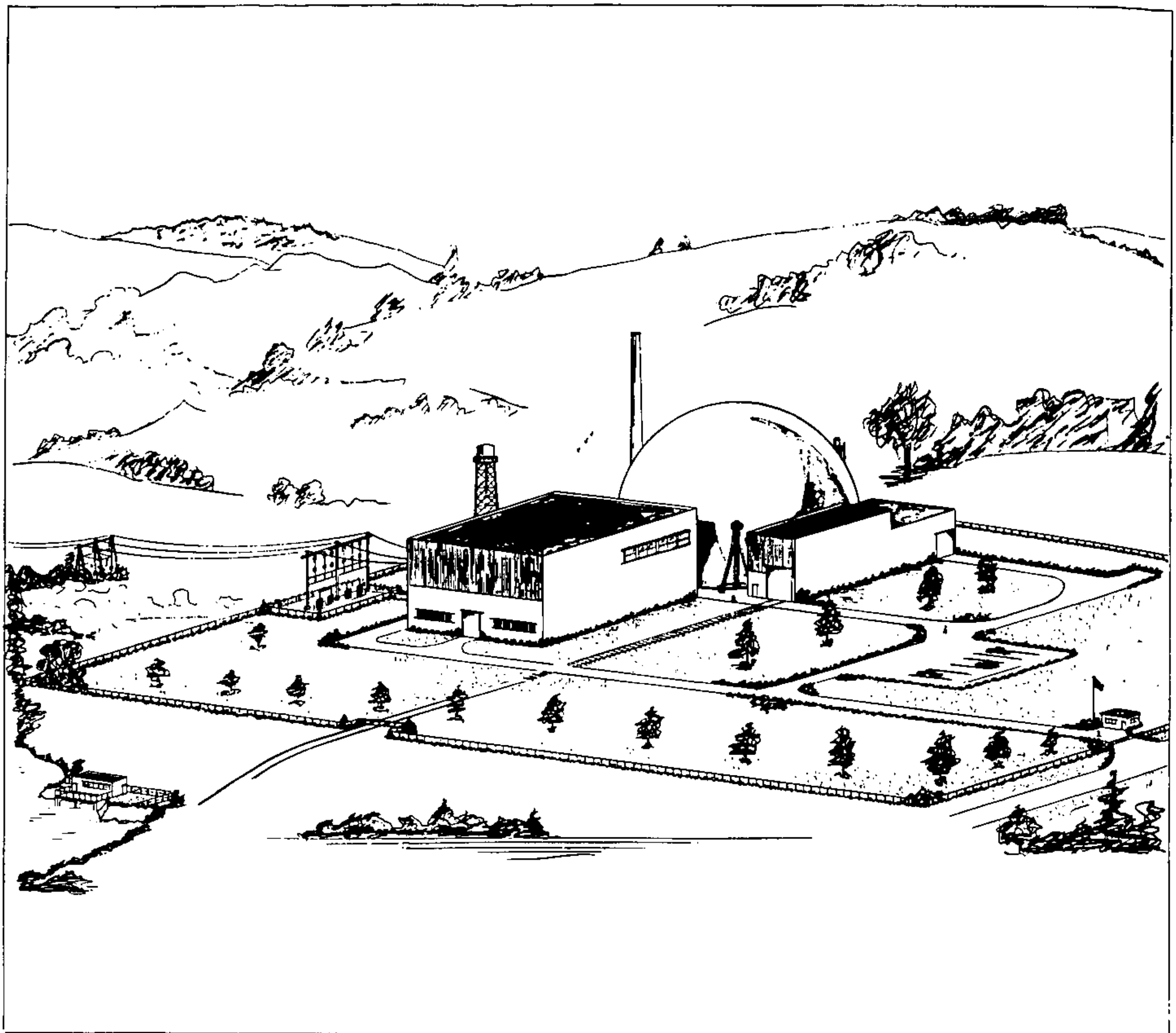
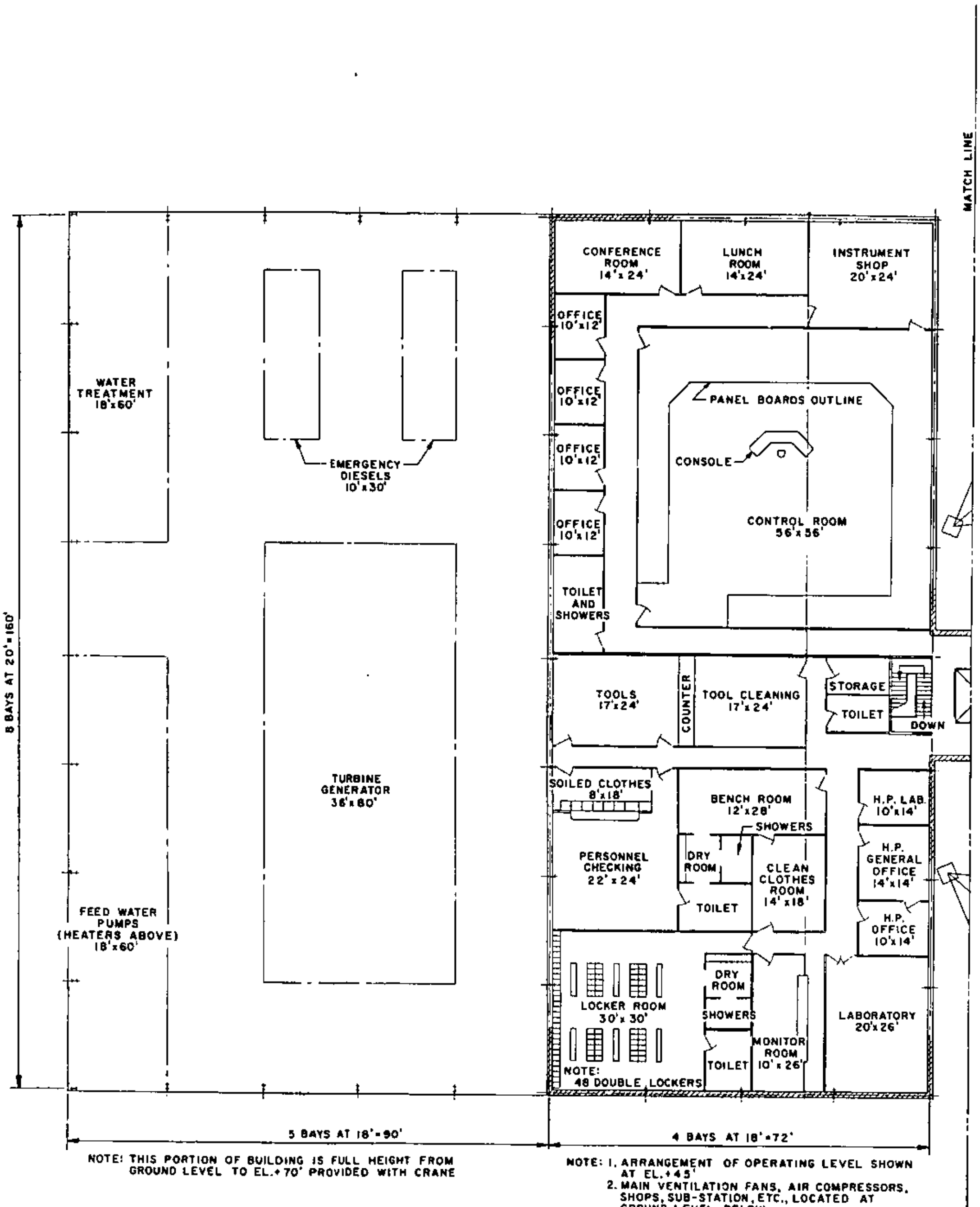


FIGURE 19 – PERSPECTIVE VIEW OF A $D_2O$ - COOLED - AND - MODERATED POWER REACTOR PLANT (CASE 1B, 100 eMW)

(Blank)




added

TURBINE BUILDING PLAN AT ELEV. + 45 FT.

FIGURE 20 – BUILDING ARRANGEMENT FOR A $D_2O$ - COOLED - AND - MODERATED POWER REACTOR (CASE 1B, 100 eMW)

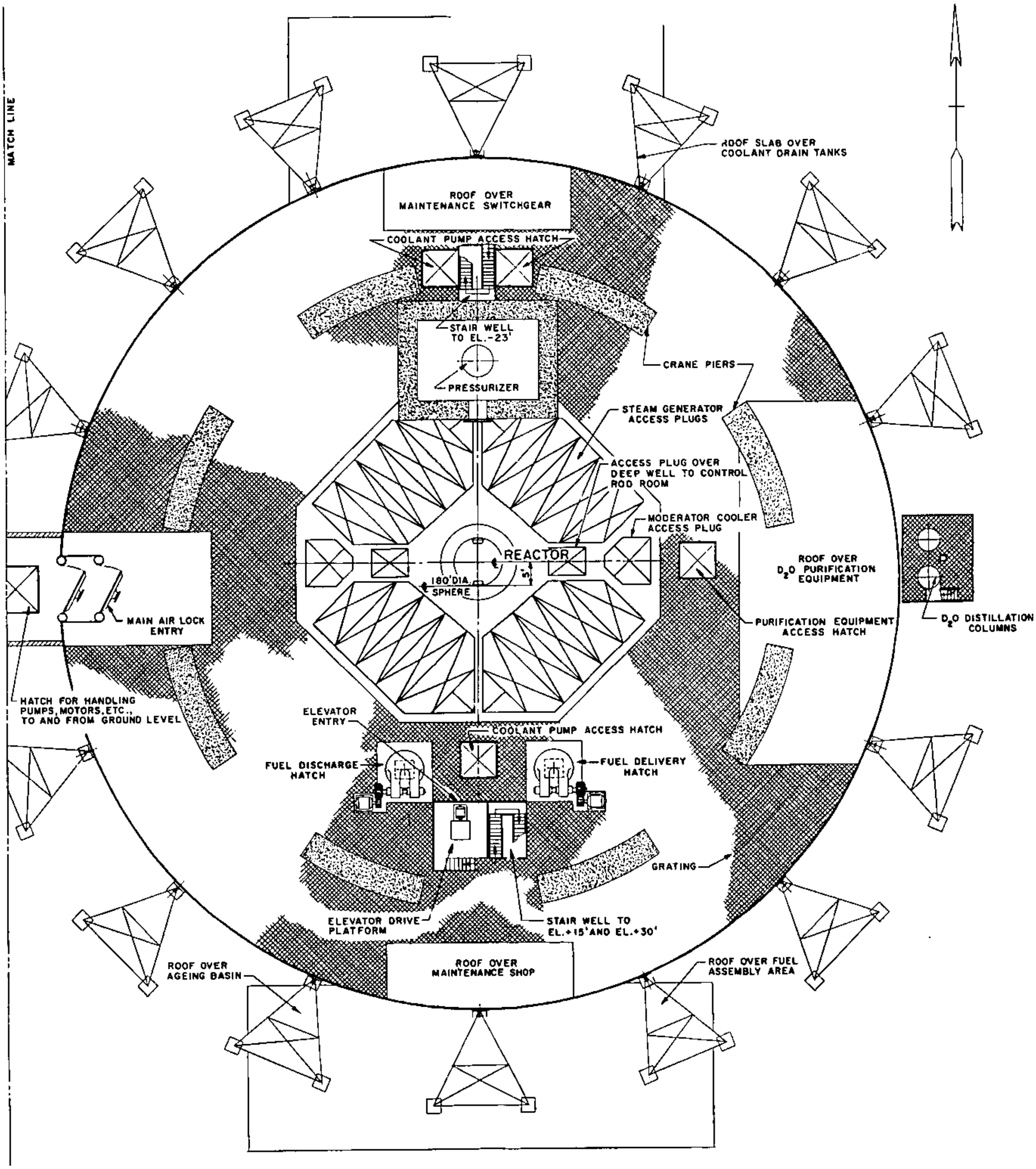
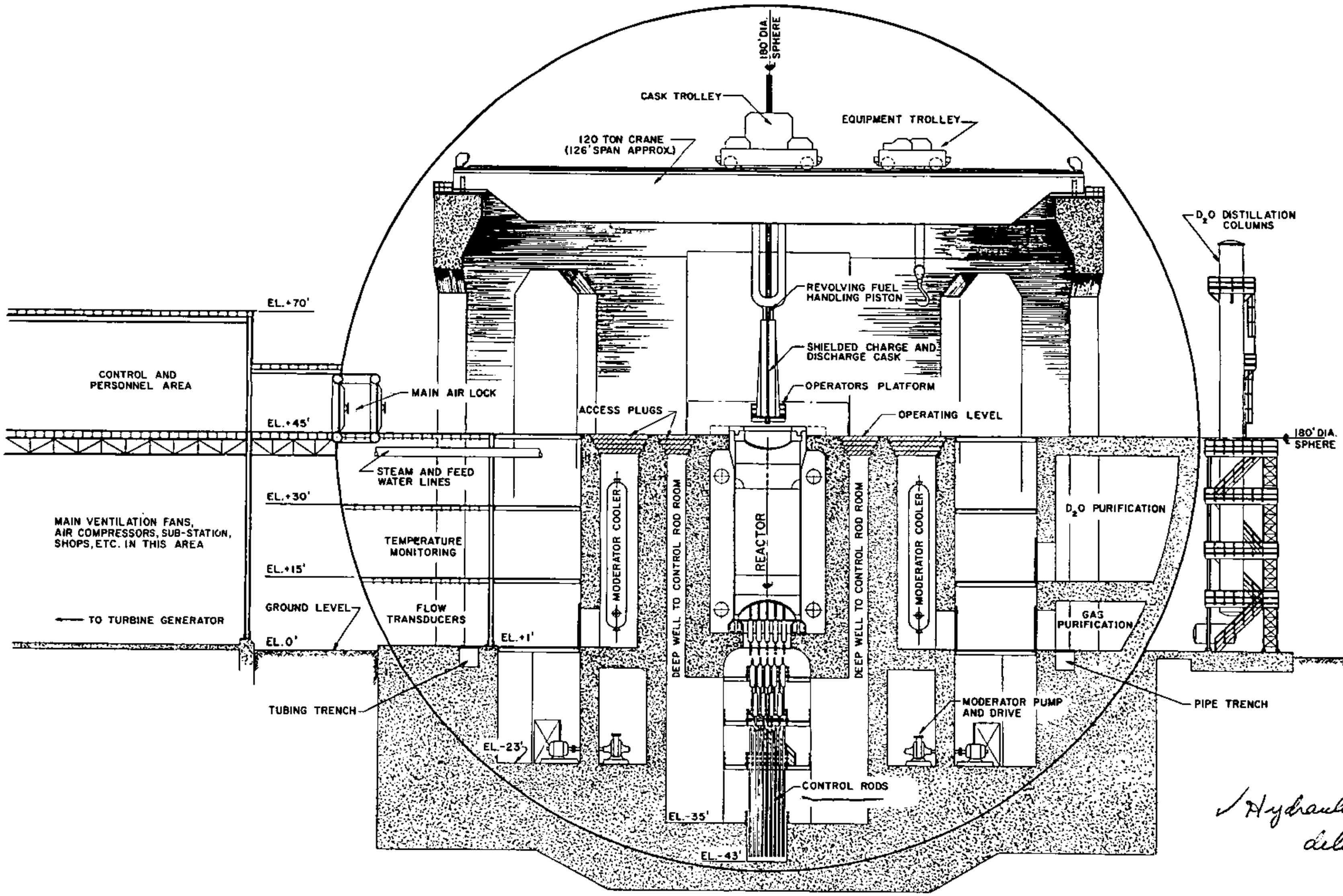



FIGURE 20 – (CONTINUED)

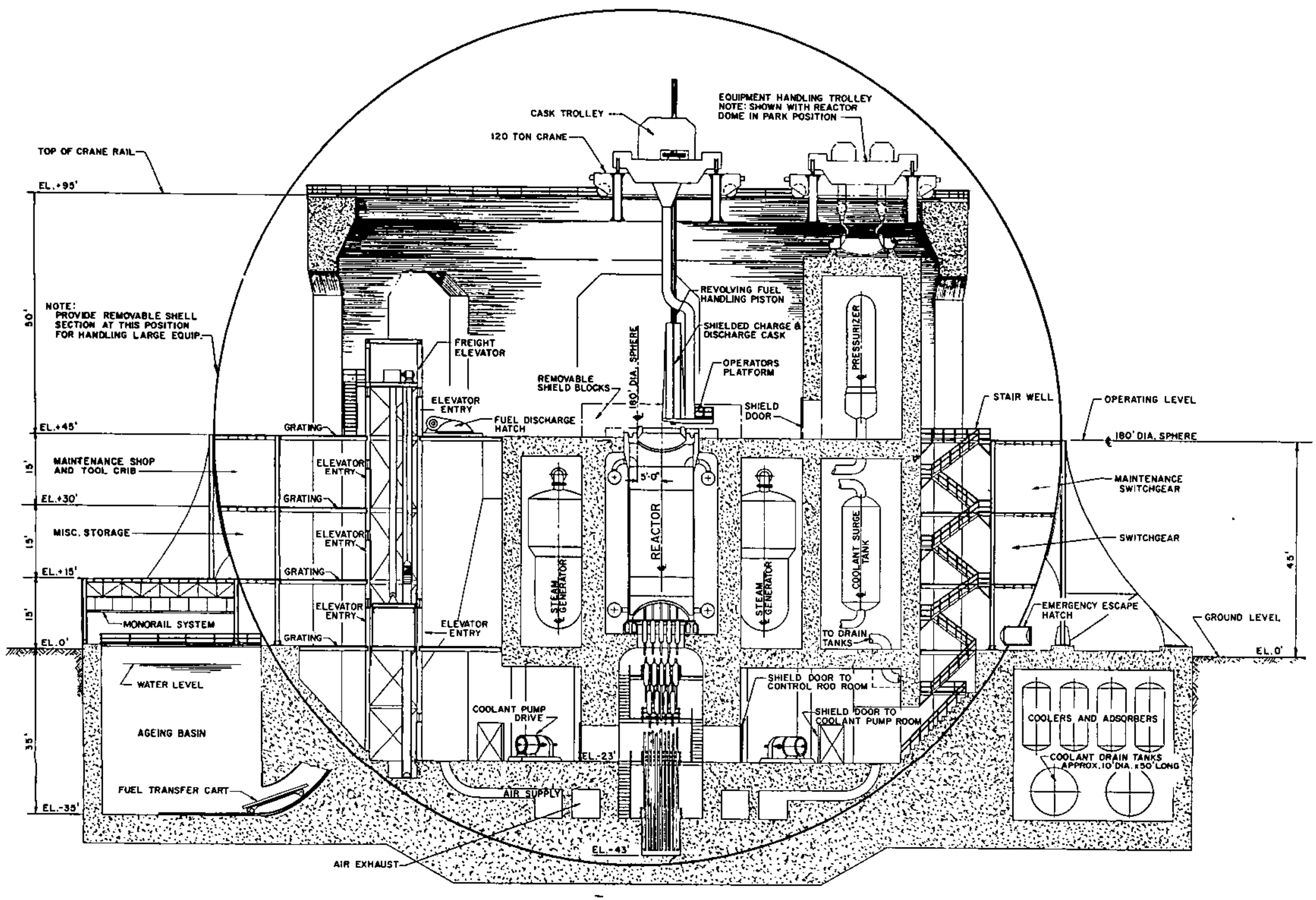
**REACTOR BUILDING PLAN AT ELEV. +45 FT** — added




✓ Hydraulic drives - deleted

CROSS SECTION LOOKING NORTH

FIGURE 21 – BUILDING ARRANGEMENT FOR A $D_2O$-COOLED-AND-MODERATED POWER REACTOR (CASE 1B, 100 eMW)




CROSS SECTION LOOKING WEST

FIGURE 22 – BUILDING ARRANGEMENT FOR A $D_2O$-COOLED-AND-MODERATED POWER REACTOR (CASE 1B, 100 eMW)

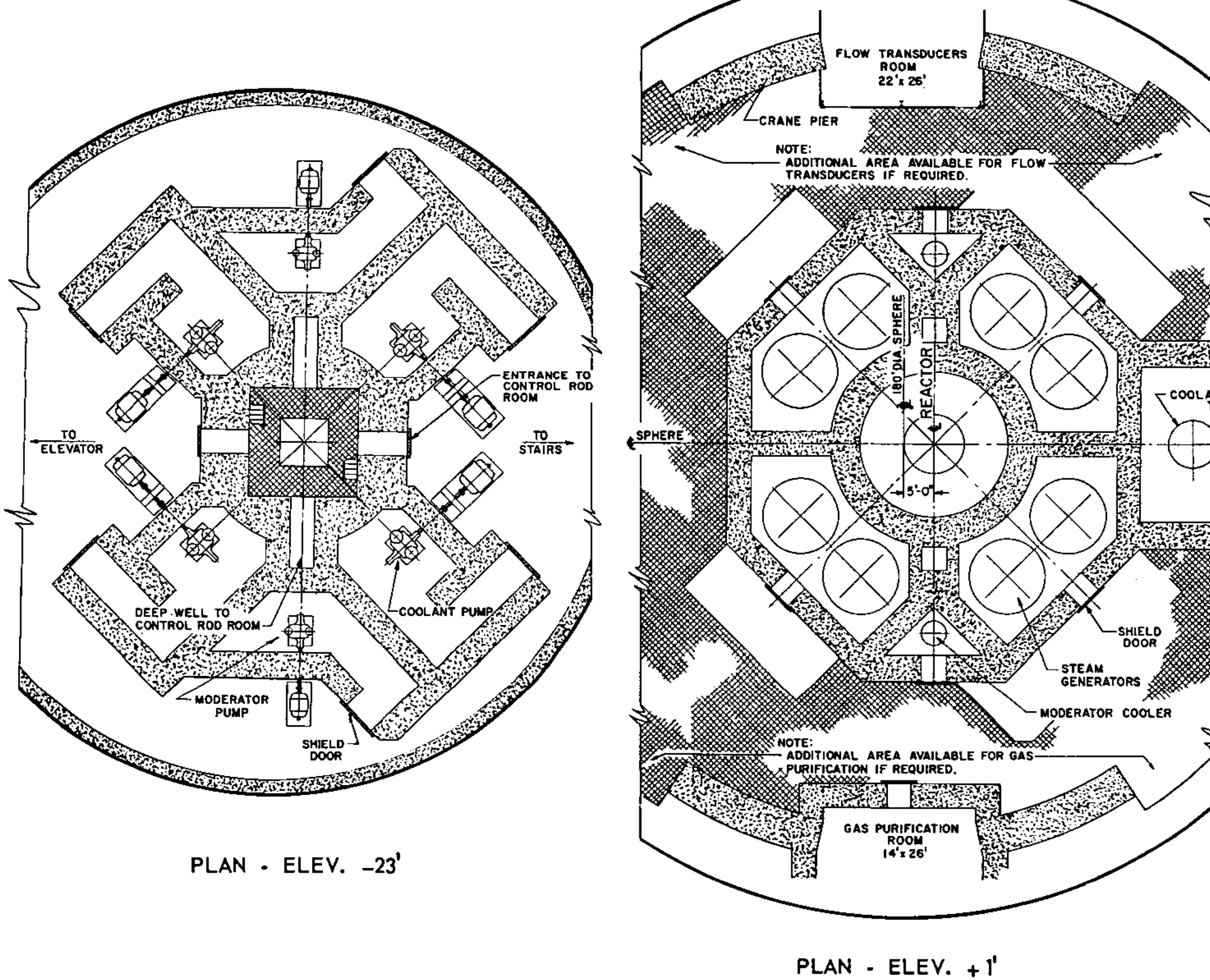
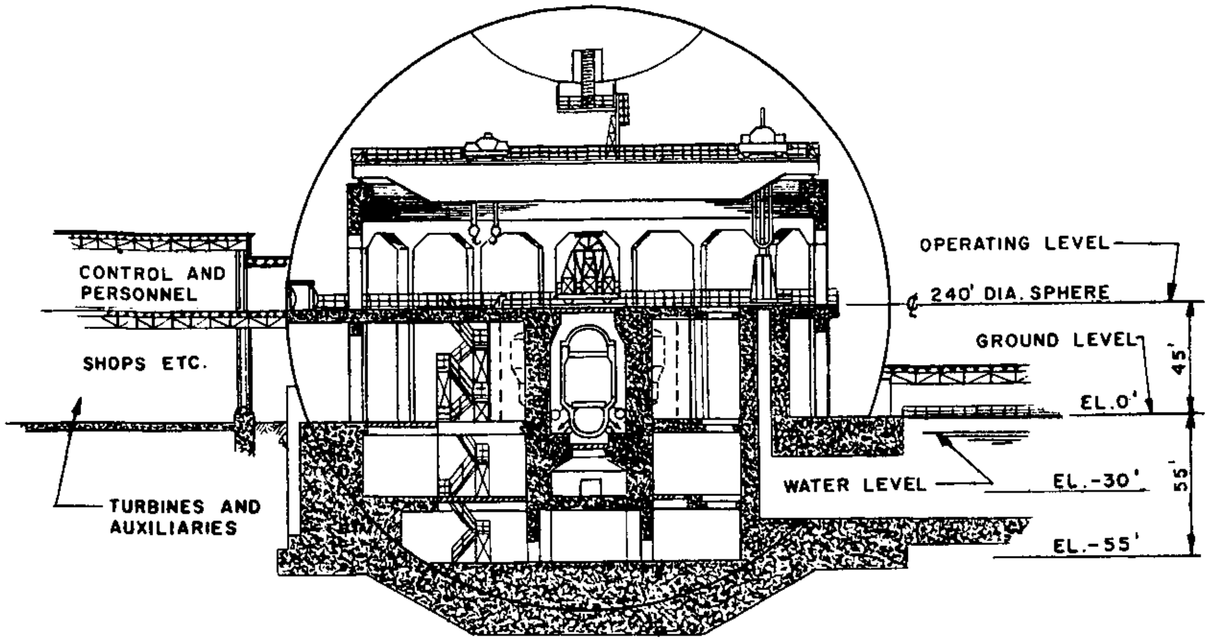
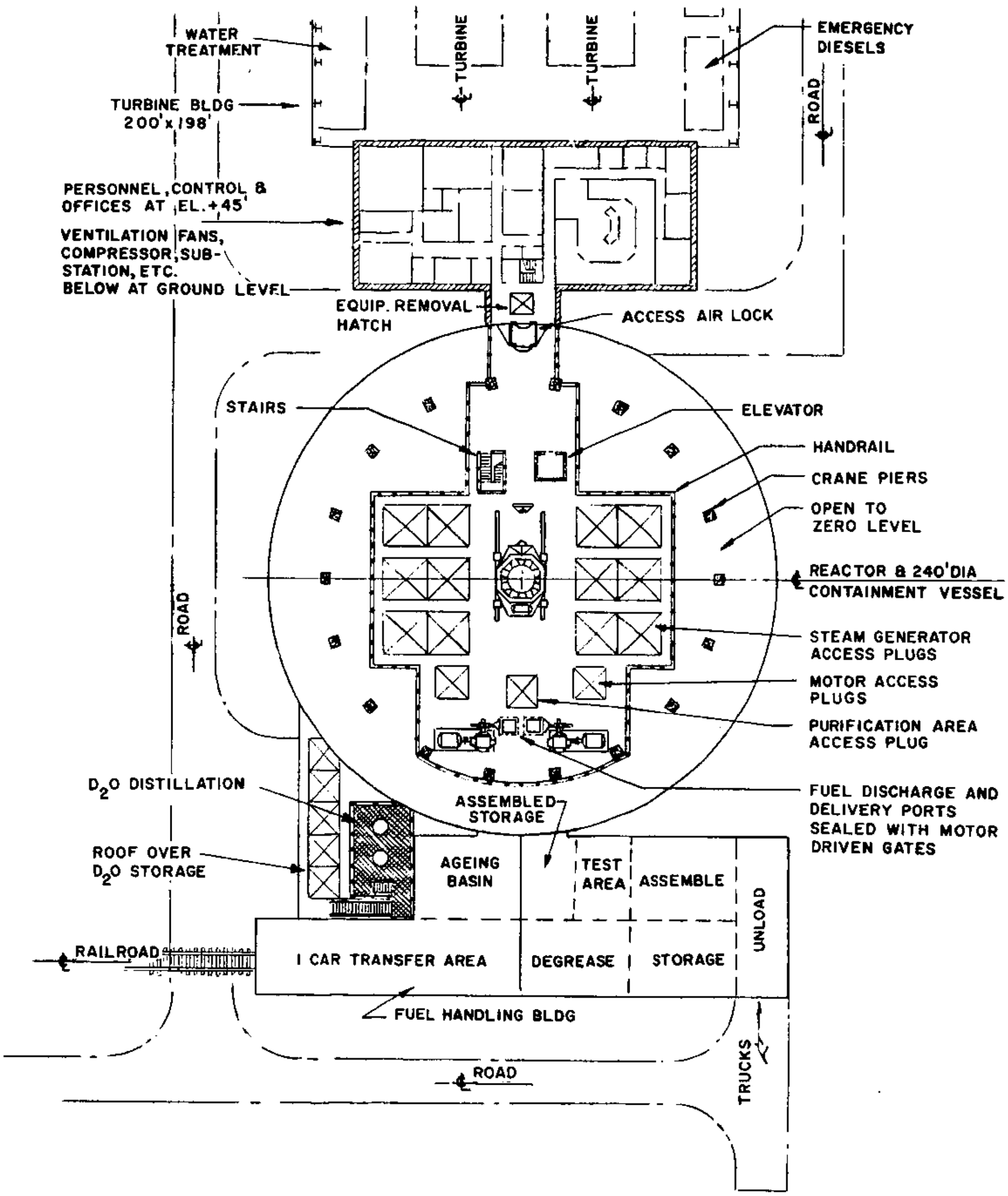



FIGURE 23 – BUILDING ARRANGEMENT FOR A $D_2O$-COOLED-AND-MODERATED POWER REACTOR (CASE 1B, 100 eMW)




CROSS SECTION

FIGURE 24 – BUILDING ARRANGEMENT FOR A 400 eMW HOT MODERATOR PRESSURE VESSEL POWER REACTOR
(Case IB-400)




PLAN AT OPERATING LEVEL
ELEV. +45 FT.

FIGURE 25 – BUILDING ARRANGEMENT FOR A 400 eMW HOT MODERATOR PRESSURE VESSEL POWER REACTOR (Case IB-400)

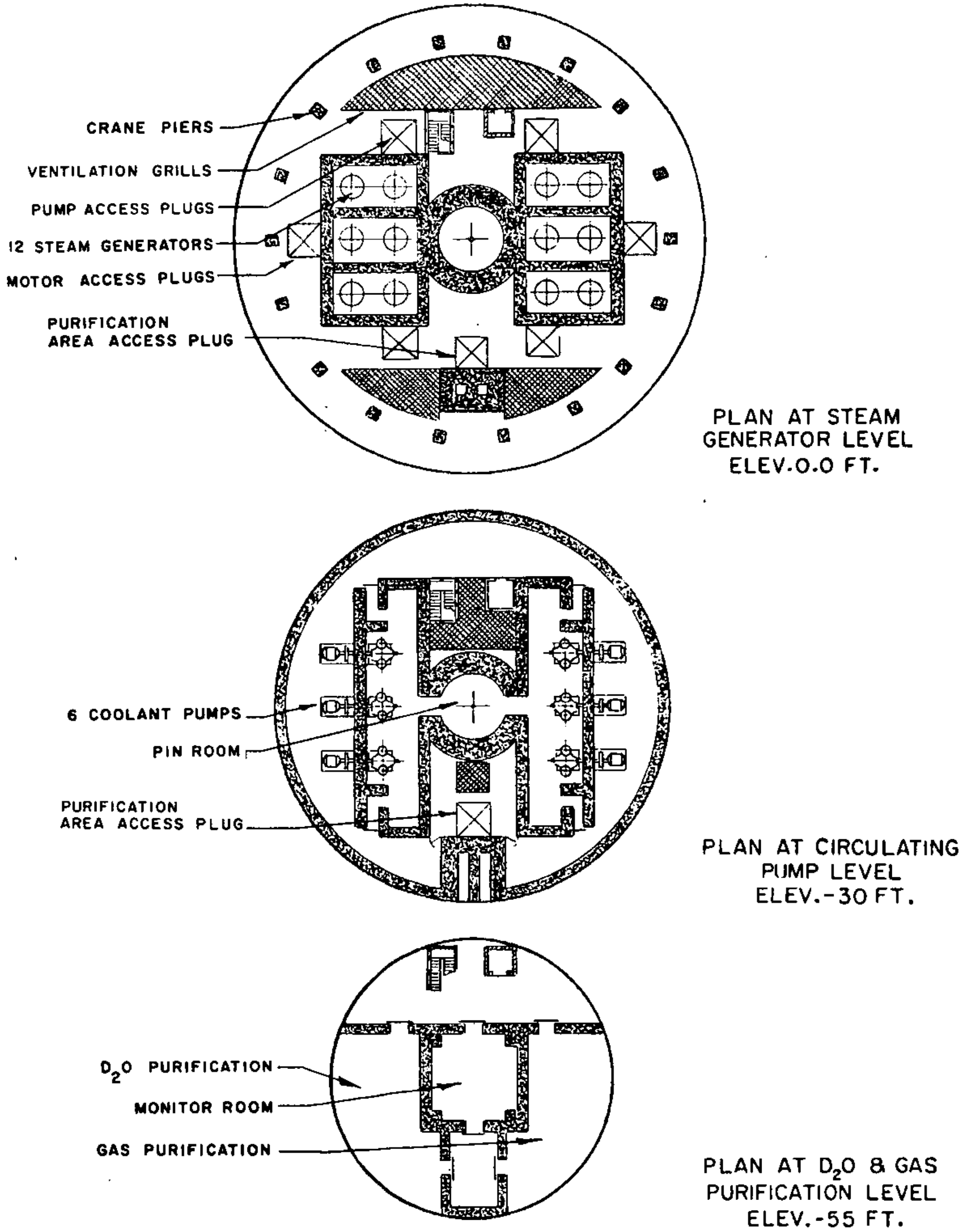
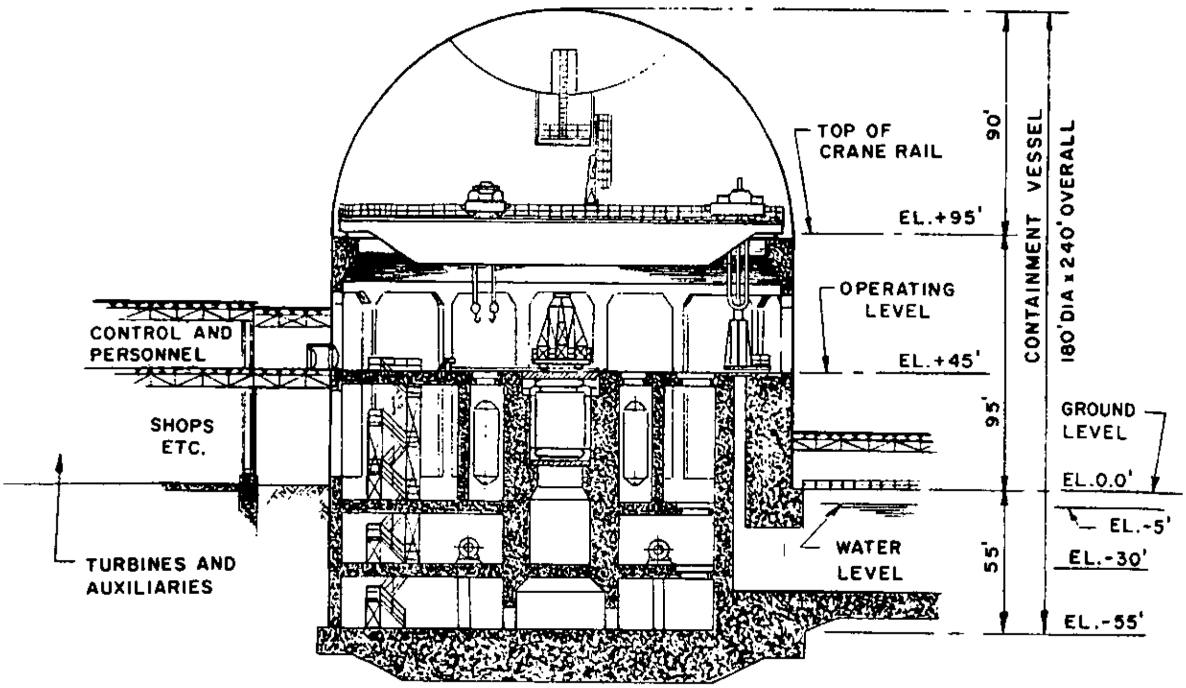
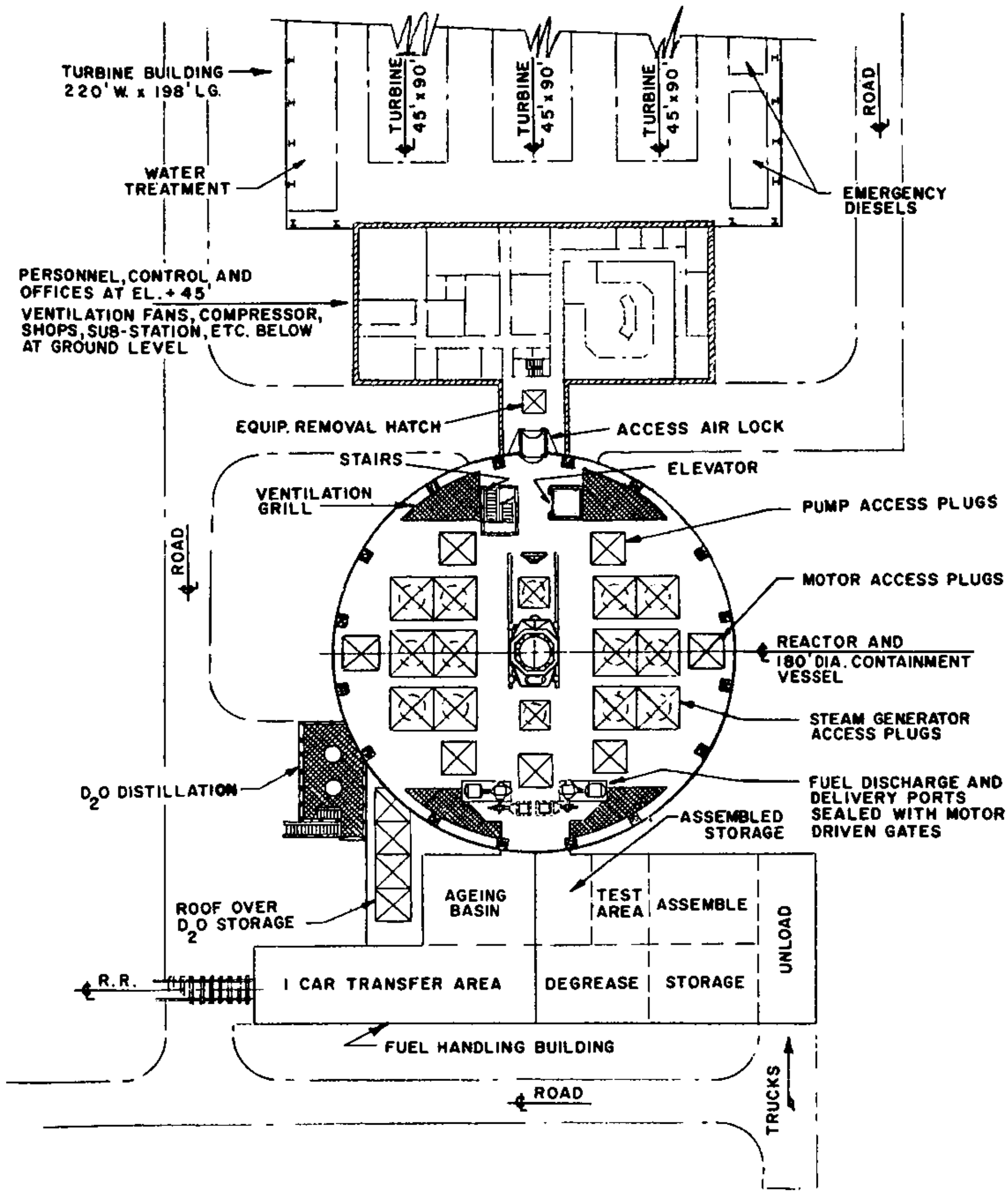



FIGURE 26 – BUILDING ARRANGEMENT FOR A 400 eMW HOT MODERATOR PRESSURE VESSEL POWER REACTOR
(Case IB-400)




CROSS SECTION

FIGURE 27 – BUILDING ARRANGEMENT FOR A 460-eMW LIQUID-$D_2O$-COOLED PRESSURE TUBE POWER REACTOR (CASE 1D, 460 eMW)




PLAN AT OPERATING LEVEL
ELEV. + 45 FT.

FIGURE 28 – BUILDING ARRANGEMENT FOR A 460-eMW LIQUID-$D_2O$-COOLED PRESSURE TUBE POWER REACTOR (CASE 1D-460)

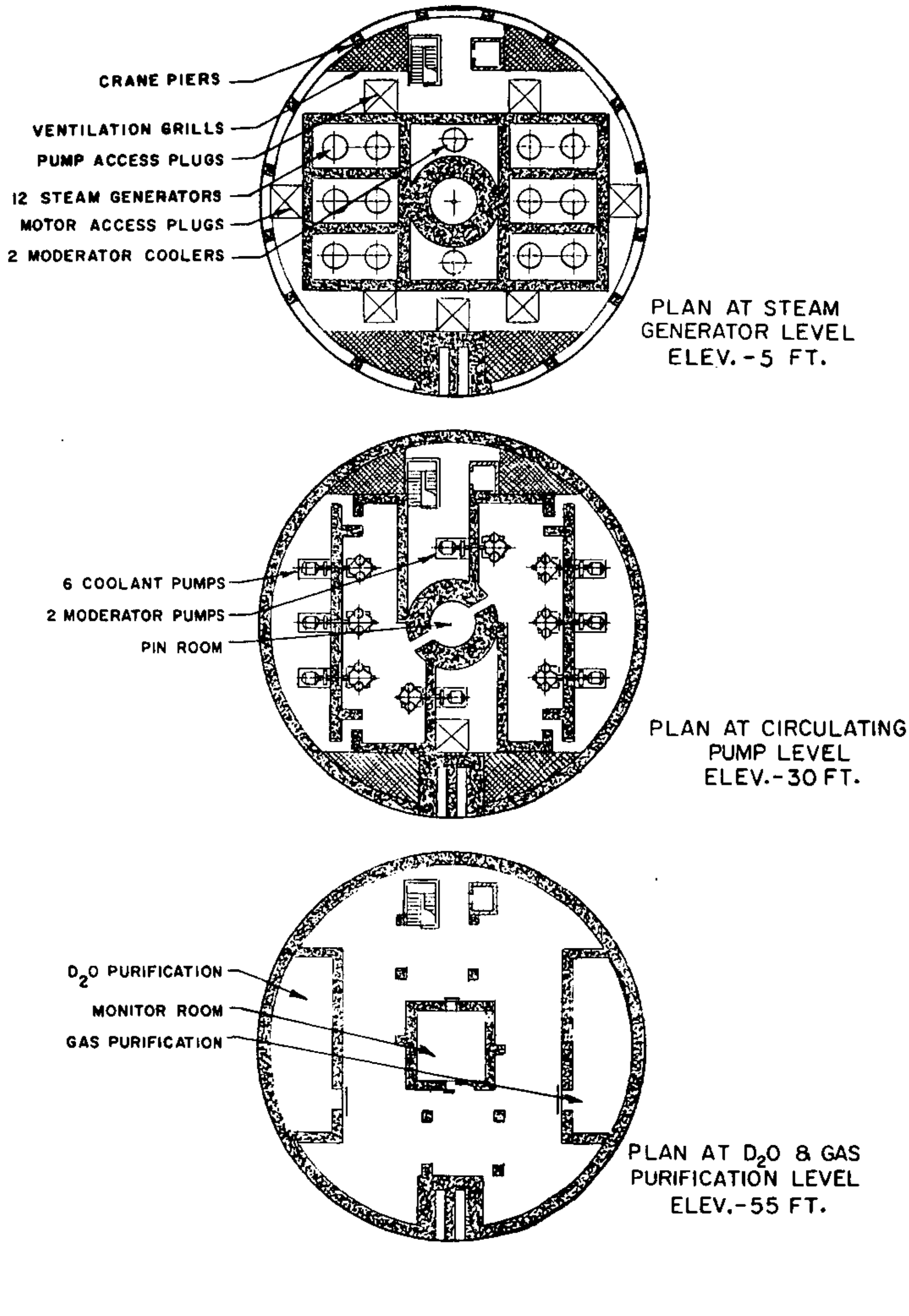



FIGURE 29 – BUILDING ARRANGEMENT FOR A 460-eMW LIQUID-$D_2O$-COOLED PRESSURE TUBE POWER REACTOR (CASE 1D-460)

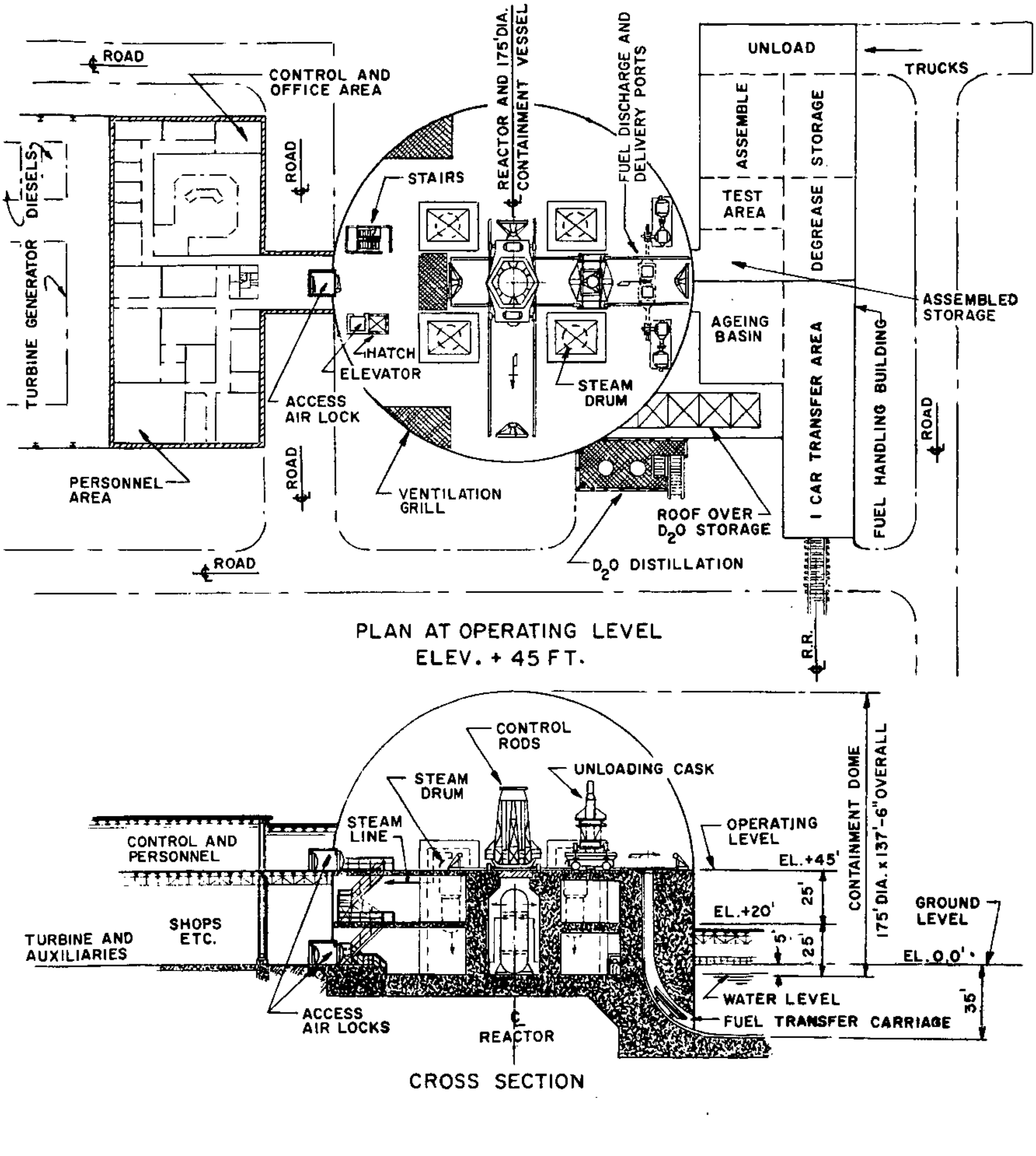
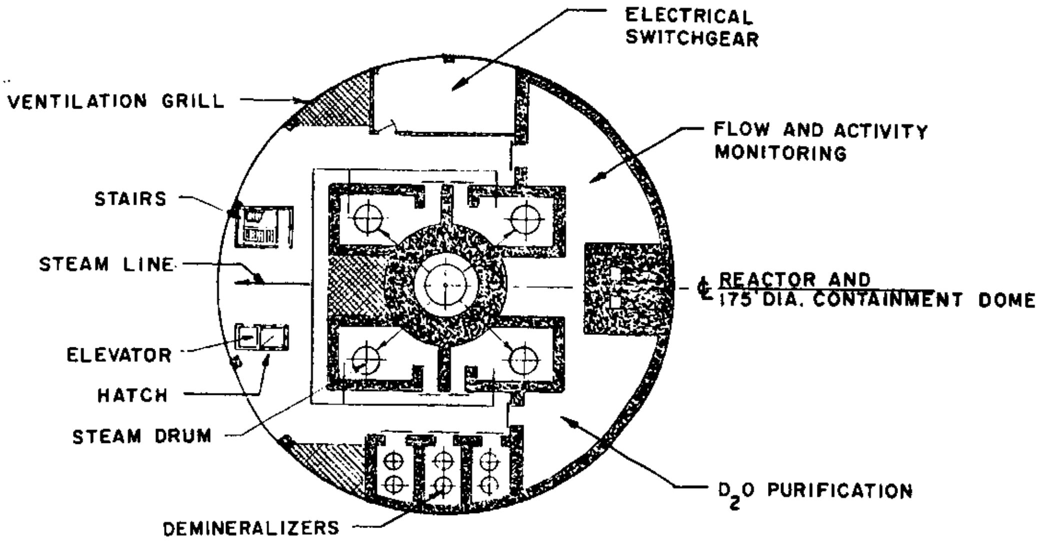
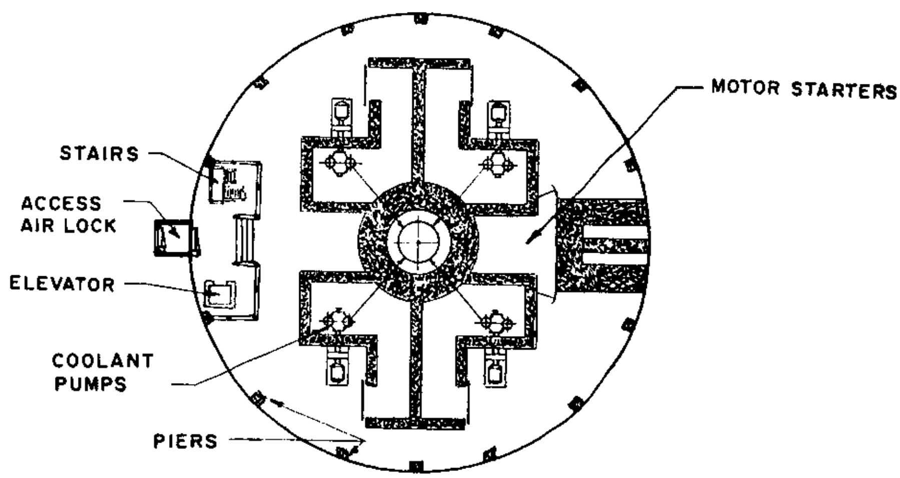



FIGURE 30 – BUILDING ARRANGEMENT FOR 100 eMW BOILING-$D_2O$-COOLED POWER REACTORS (CASES 1J, 1K, AND 2K)

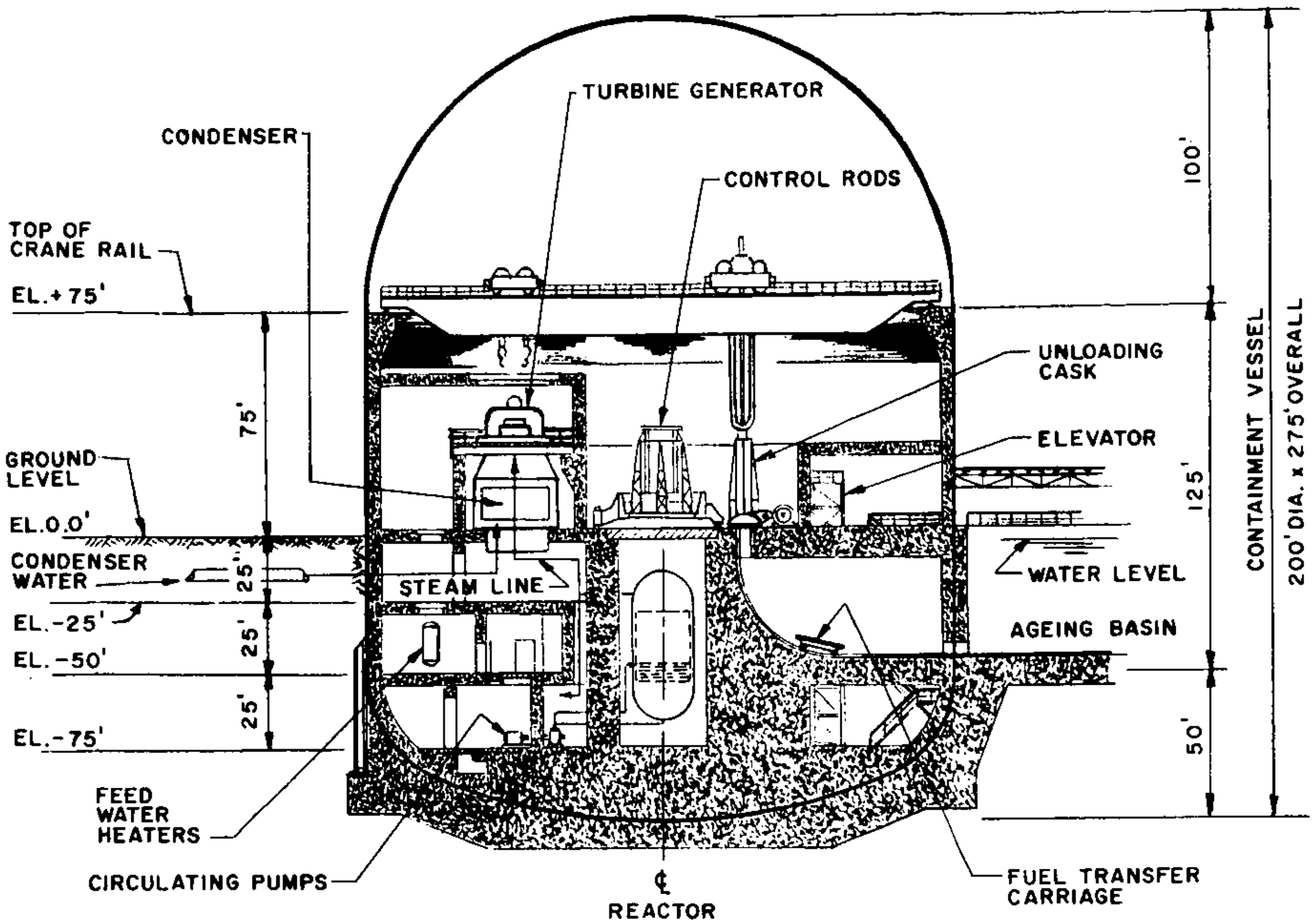



PLAN AT
ELEV. +20FT.



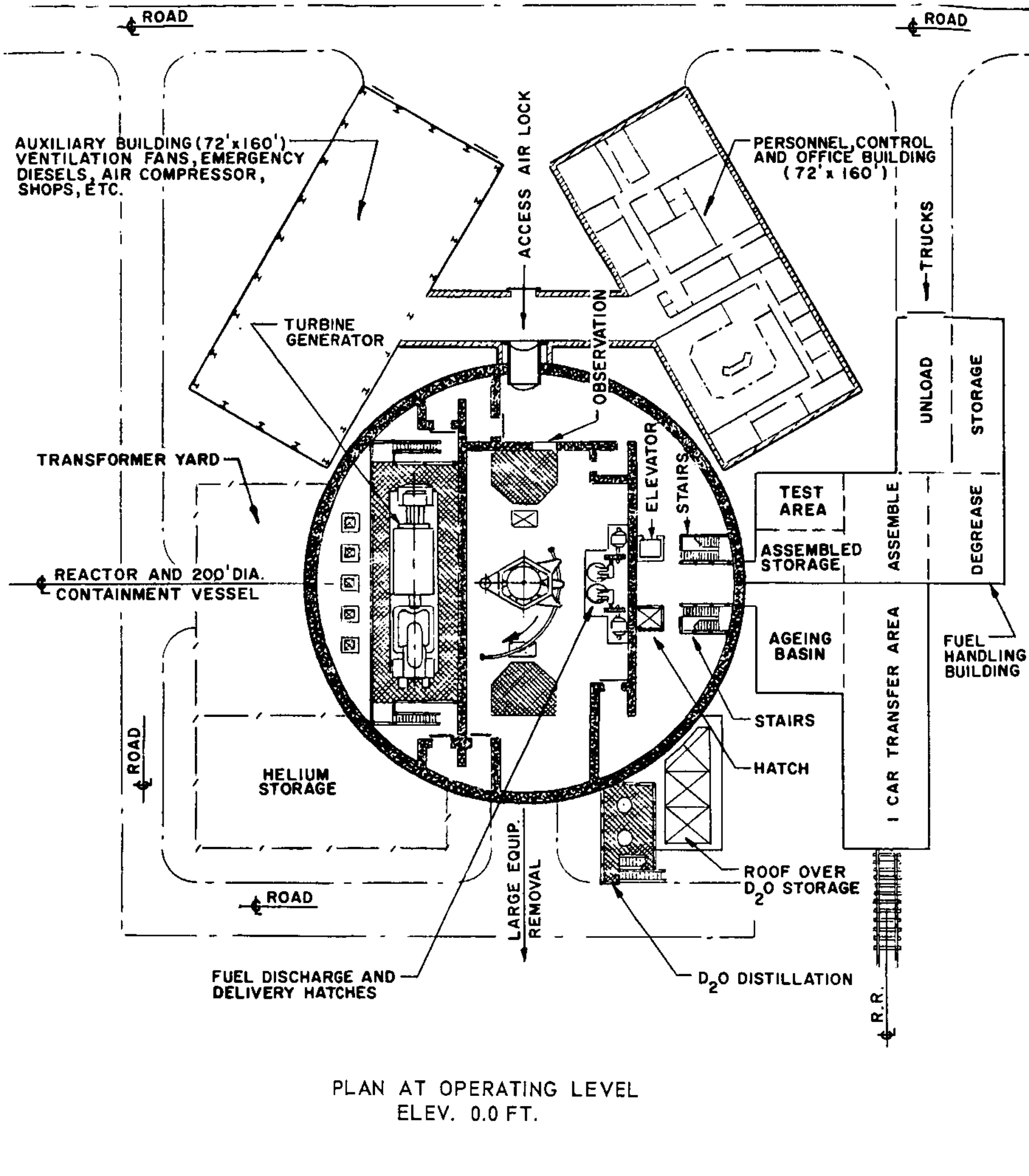

PLAN AT
ELEV.-5FT.

FIGURE 31 – BUILDING ARRANGEMENT FOR 100-eMW BOILING-$D_2O$-COOLED POWER REACTORS (CASES 1J, 1K, AND 2K)



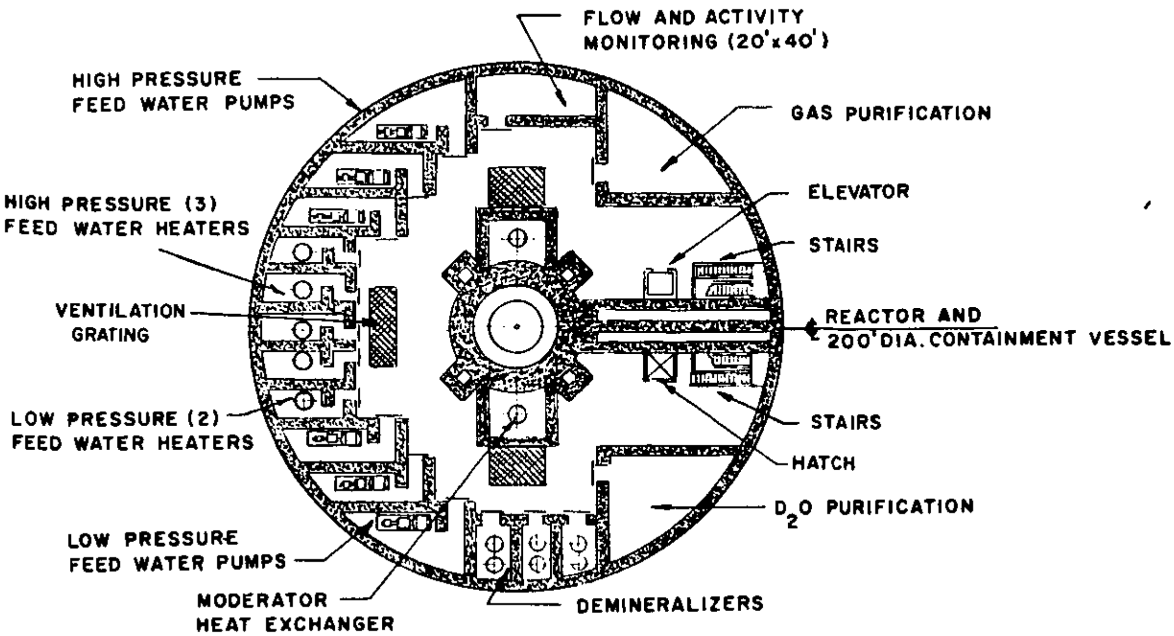

CROSS SECTION

FIGURE 32 – ALTERNATIVE BUILDING ARRANGEMENT FOR A 100-eMW $D_2O$-STEAM-COOLED POWER REACTOR
(Turbine Housed in Containment Vessel)

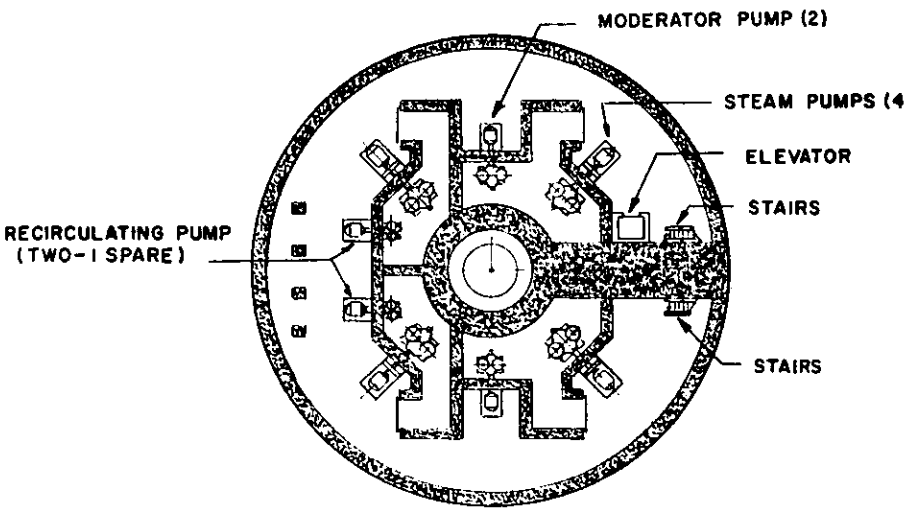



PLAN AT OPERATING LEVEL
ELEV. 0.0 FT.

**FIGURE 33 – ALTERNATIVE BUILDING ARRANGEMENT FOR A 100-eMW $D_2O$-STEAM-COOLED POWER REACTOR**
**(Turbine Housed in Containment Vessel)**




PLAN AT
ELEV.-50 FT.




PLAN AT
ELEV.-75 FT.

**FIGURE 34 – ALTERNATIVE BUILDING ARRANGEMENT FOR A 100-eMW $D_2O$-STEAM-COOLED POWER REACTOR**
**(Turbine Housed in Containment Vessel)**