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REVIEW OF THE STATUS OF SUPERCRITICAL WATER REACTOR TECHNOLOGY

by

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OBJECTIVE AND SCOPE OF REVIEW

At the request of the AEC, an evaluation of the supercritical water reactor was made. The evaluation was to include (1) a review and summary of information on supercritical water reactors, (2) an analysis of supercritical water reactors for production of economic nuclear energy, and (3) recommendation of the necessary research and development program to carry the concept to the stage where an economic energy producer can be constructed. This report encompasses only the first part of the proposed evaluation, namely, a review and summary of the technology that has been developed to date for the use of supercritical water as the coolant-moderator and the working fluid in a supercritical water reactor system.

The objective of this survey was to determine whether sufficient technology exists to perform a realistic analysis of the supercritical water reactor as a possible economic power producer. This report is not intended as an all-inclusive review of supercritical water systems. Instead its purpose is to review those aspects which were thought to be most important or crucial in a nuclear reactor. Both the classified and unclassified literature was studied, and in particular the AEC-supported work in this field was reviewed. The information necessary for such an evaluation is contained in the unclassified literature.

An attempt was made to make the summary as self-sufficient as possible. Figures and parts of text have been duplicated from other reports where necessary so that the possession of the complete bibliography is not needed to follow the context of the report. In addition, comments on various aspects of the work reviewed are interjected where deemed pertinent.

INTRODUCTION

Interest in supercritical water as a reactor coolant has mounted as the desire to increase the overall thermal efficiency of reactor plants has increased. As an example, a supercritical reactor cycle could increase the thermal efficiency of the conventional pressurized water reactor cycle by more than 50%. The extension of the pressurized water and boiling water reactor concepts to a supercritical water reactor appears to be a logical step in the development of water-cooled power plants, a step similar to the one occurring in the conventional commercial central station plants. The potential gains of such a move, of course, must be weighed on an economic balance sheet.

Supercritical pressure reactor systems will undoubtedly have some stringent technological problems. However, of significant importance is the fact that the large technical effort that has been devoted to the development of non-nuclear supercritical central station power plants will supply data and information that is directly applicable to nuclear systems. At present one supercritical prototype boiler (the 125-Mw Philo unit) is in operation, and additional larger size units are either under construction or in the design stages. Consequently, components such as valves, piping, turbines, feedwater pumps and heaters for operation at turbine throttle pressures up to 5000 psi and temperatures up to 1200°F have been developed to the point where they are considered suitable for commercial application.

Work under AEC sponsorship on supercritical water reactors seems to have been limited and sporadic in nature. The AEC-sponsored studies reviewed were (1) the Pratt and Whitney study of a ducted blower propulsion system using a supercritical reactor as a heat source, (2) the WCAP evaluation of supercritical water reactor plants for the Maritime Reactors Branch, and (3) a conceptual design of a supercritical pressure power reactor prepared by Hanford.

Each of the AEC-sponsored studies, as well as the commercial boiler experiences, is reviewed and then a general discussion of some of the major technological problems is presented.

CONCLUSIONS

The conclusions that have been drawn as a result of this survey are as follows:

1. Sufficient technology and data exist at present to carry out a comprehensive design and economic study of the supercritical water reactor concept.
2. While, on the basis of this study, it is impossible to state conclusively that the supercritical water reactor could achieve economic power, its potential appears to justify further investigation.
3. Operation of the supercritical water reactor on the direct cycle offers the highest probability for achieving economic power.

4. The major gap in supercritical water technology pertaining to a reactor system is the lack of information on the magnitude of the problems of deposition of radioactivity in the external system and of the buildup of internal crud under irradiation.

5. The type of reactor complex chosen strongly influences the plant economics. Any design study should cover a variety of reactor systems.

REVIEW OF AEC SUPERCRITICAL WATER REACTOR DESIGN STUDIES

Numerous supercritical water reactor concepts are possible. As far as can be determined, only three AEC-sponsored studies have been made of a supercritical water reactor system. Of these, none can really be classified as a complete design study of a central station plant. A brief review of each of these studies is presented for illustrating the approaches that are possible and the widely varying conclusions that were reached.

The Supercritical Water Reactor for the Pratt and Whitney Aircraft Ducted Blower Propulsion System

A summary of the work done by Pratt and Whitney Aircraft up to the time of the stoppage of work on the supercritical water reactor propulsion system is given in references (1) to (10). The reactor for the ducted blower propulsion system as proposed by Pratt and Whitney was a solid fuel element reactor which was cooled, moderated and reflected by light water. The fluid leaving the reactor at approximately 1000°F and 5000 psi provides energy for a high-power steam turbine which exhausts to an air-cooled condenser at approximately 450°F. The condensed water is returned through a high-pressure centrifugal pump to the reactor inlet. Thrust is obtained both from the ducted blower and from the heat added to the air in condensing the turbine discharge steam. The system is shown schematically in Figure 1. The pertinent reactor parameters are shown in Table I.

Four types of fuel elements for the reactor were considered: a perforated wafer fuel element, a strut-type fuel element, a parallel plate fuel element, and a flat and corrugated plate fuel element.

Of these, the most promising was thought to be the wafer type of element, shown in Figure 2. The other type of element that was given serious consideration was the strut type of element, shown in Figure 3. The principal advantage of the latter is a higher heat transfer coefficient and reduced sensitivity of wall temperatures to nonuniformity of dimensions and heating. However, there were serious mechanical design problems and the unit had a higher overall pressure drop.

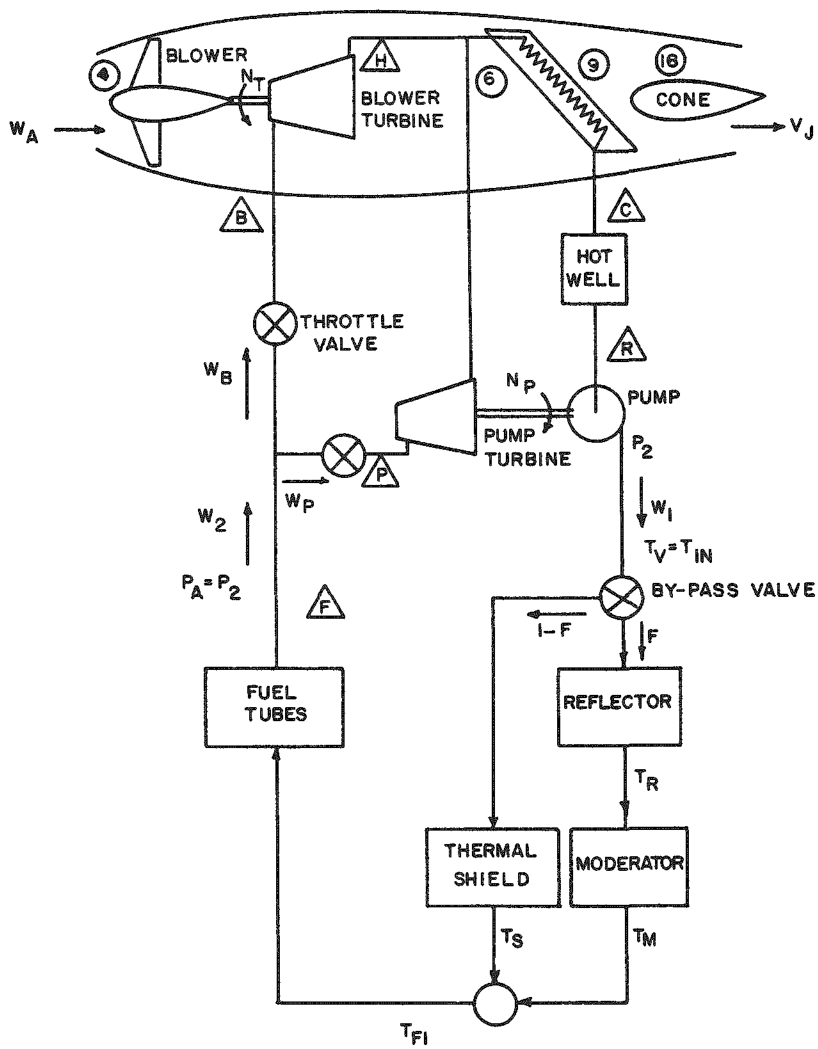

Figure 1

Schematic of Supercritical Water-Ducted Blower Propulsion System

Table I

Reactor inlet temperature	450°F
Reactor exit temperature	1000°F
Pressure	5000 psi
Flow rate	430 lb/sec
Average water density	0.4 gm/cc
Reactor power	410 Mw

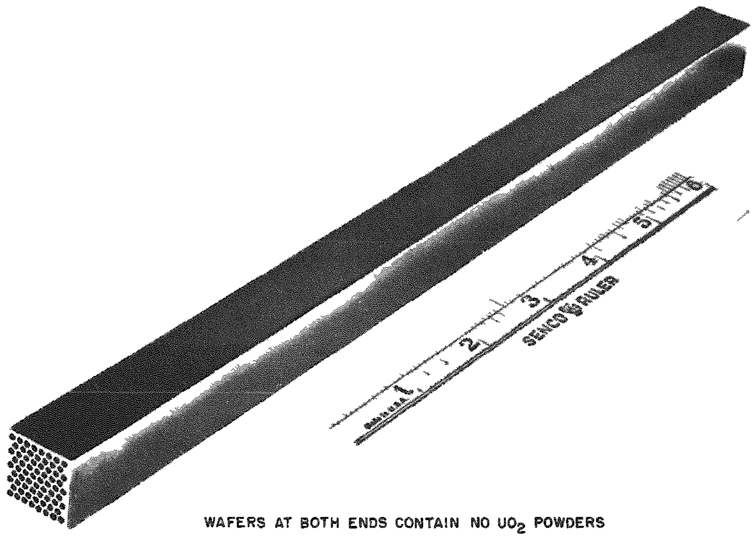

Figure 2

Completely Clad Prototype Perforated Wafer Fuel Element Assembly

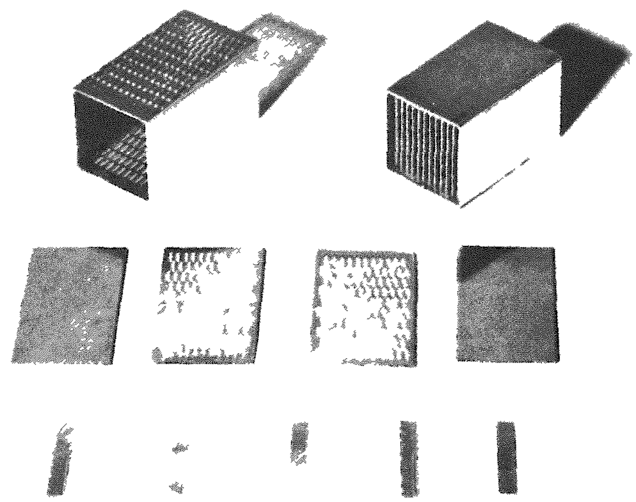

Figure 3

Strut Type Fuel Element Sub-Assembly

The wafer type of element, a clad stainless steel-UO_2 cermet, seemed to be the best overall element from a standpoint of design, fabrication, and flow and heat transfer characteristics.

Considerable component development, materials investigation, corrosion work, and heat transfer studies were done for the reactor. This is the basic value of the Pratt and Whitney work. As can be seen from the fuel element designs, the reactor was designed to be a compact, high-power density unit. Since the compactness necessary to an aircraft reactor is not necessary for a central station power plant, much of the development necessary for the aircraft reactor (such as compact condensers and cores) is not directly applicable to the design of central station power reactors.

The development associated with this project that is of interest will be treated under the specific general headings.

Supercritical Water Reactor Reference Design by Westinghouse Atomic Power Department (Ref. 11, 12)

Westinghouse Atomic Power Department prepared a reference design of a supercritical water reactor as part of work done under contract to the Maritime Reactors Branch, Division of Reactor Development, U.S. Atomic Energy Commission. The study was to encompass the following phases:

Phase I - Review of the available technical information applicable to supercritical water systems.

Phase II - Study and development of a supercritical water reactor system conceptual design.

Phase III - Evaluation of the supercritical water reactor system as a merchant ship propulsion plant.

The work under Phase I of this project was reported in WCAP-543.[12]

Three cycles (shown in Figures 4, 5, and 6) were considered in the study for the reference design reported in WCAP-500.[11] The cycles are the direct cycle, the throttled direct cycle and the indirect cycle. Because of the rapid change of physical properties with temperature, the designers decided to avoid having the water pass through the critical point in the reactor. The fear was expressed that this would promote instabilities in flow, heat transfer and reactivity. This decision led to undue complications in all the cycles. It is surprising that such concern was expressed as late as December of 1957, since the boiling reactors had already demonstrated stable operation under conditions considerably worse than property changes of supercritical water. As a result, the decision made not to let the fluid pass through the critical point in the reactor appears to be unwarranted.

Because of the fear of radioactive deposits in the secondary system of a direct cycle plant, an indirect cycle was chosen for the plant. The schematic flow diagram of this cycle is shown in Figure 4. In this system, 1.547×10^6 pounds per hour of supercritical steam are circulated through the reactor core and heat exchanger. The coolant, at a pressure of 4000 psia, is increased 140°F in temperature while passing through the reactor. This is based on an inlet temperature of 860°F and an average bulk outlet temperature of 1000°F. The coolant is then passed through two heat exchangers,

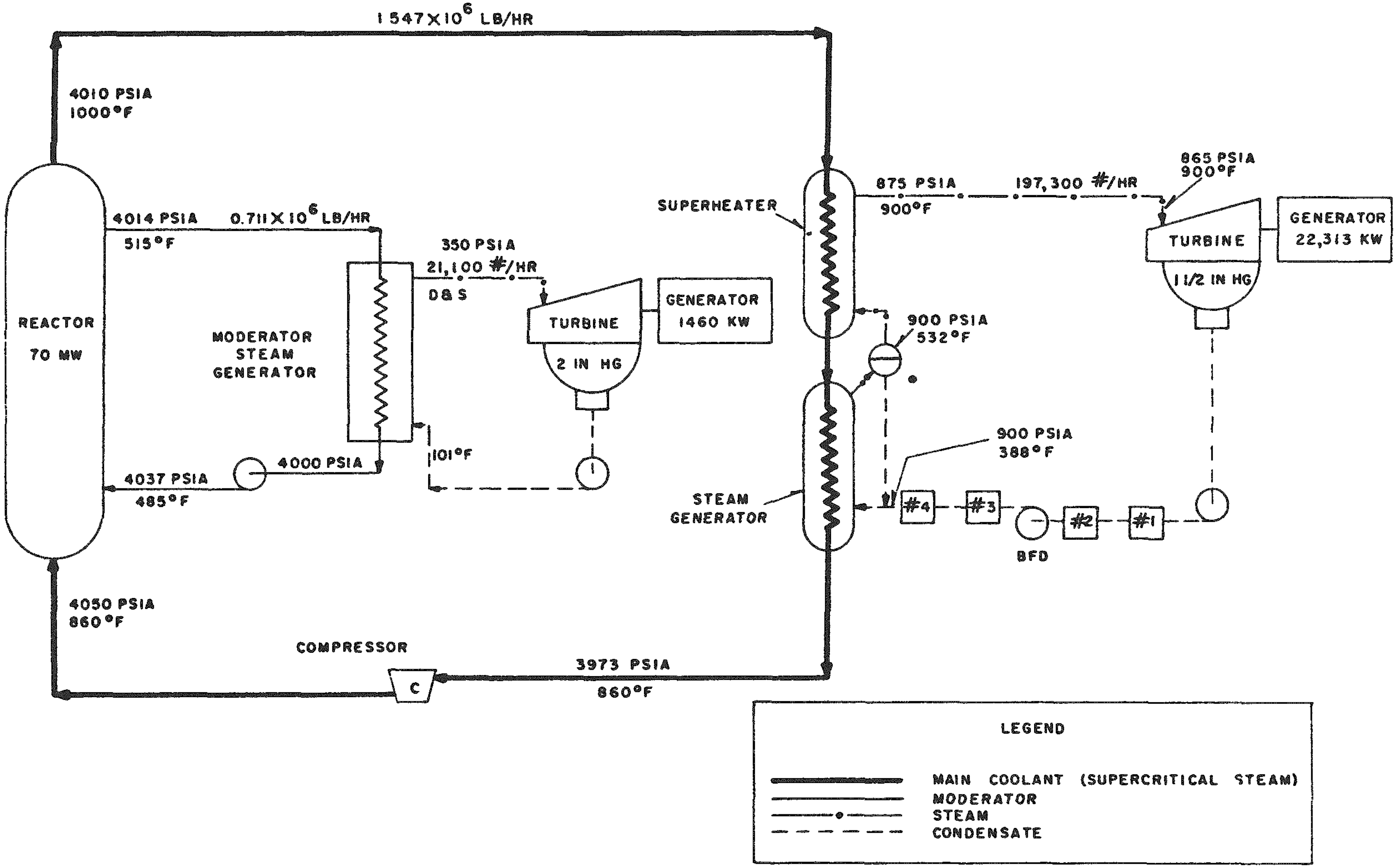

Figure 4

Schematic Flow Diagram - Indirect Cycle

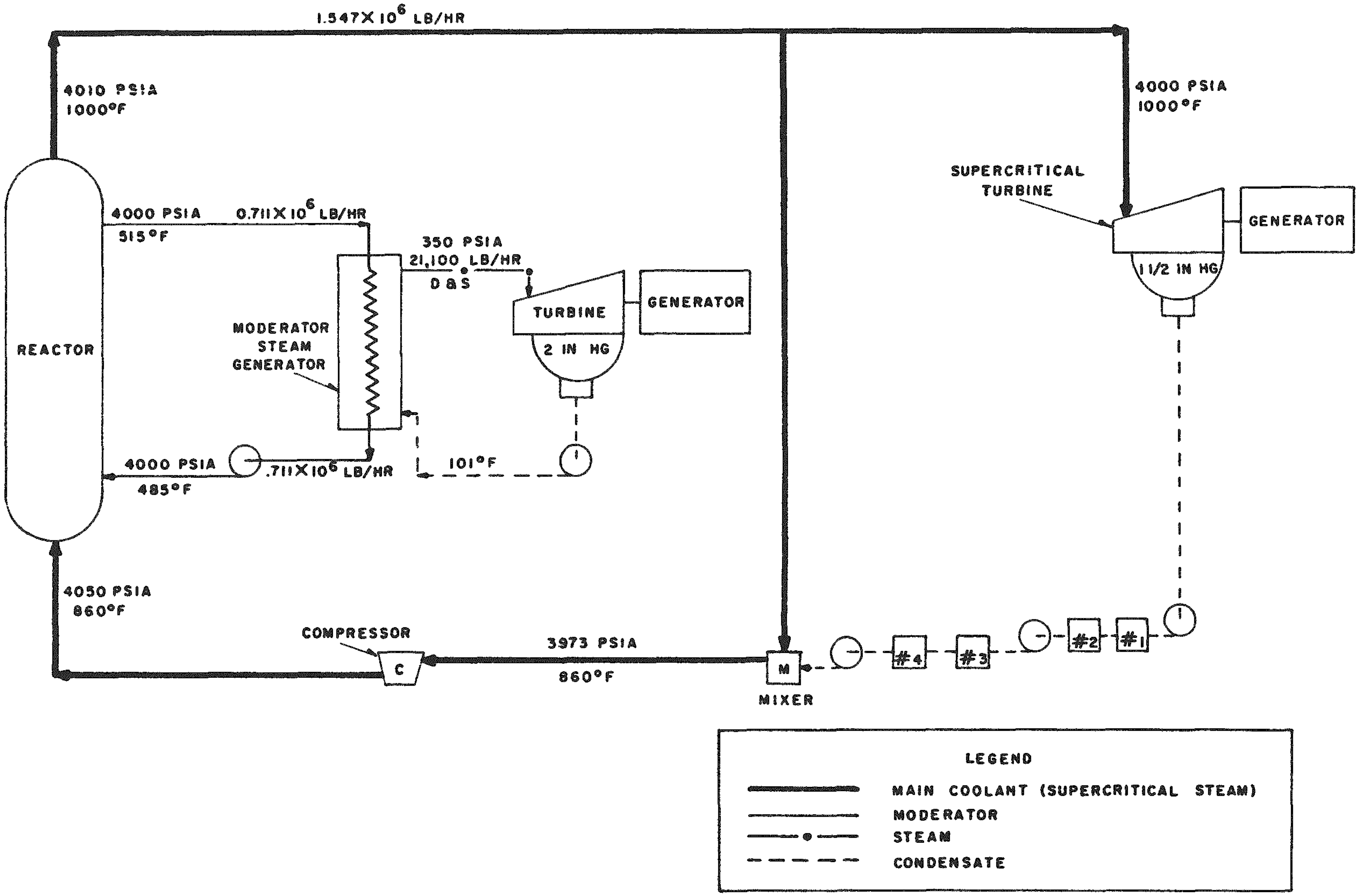

Figure 5

Schematic Flow Diagram - Direct Cycle

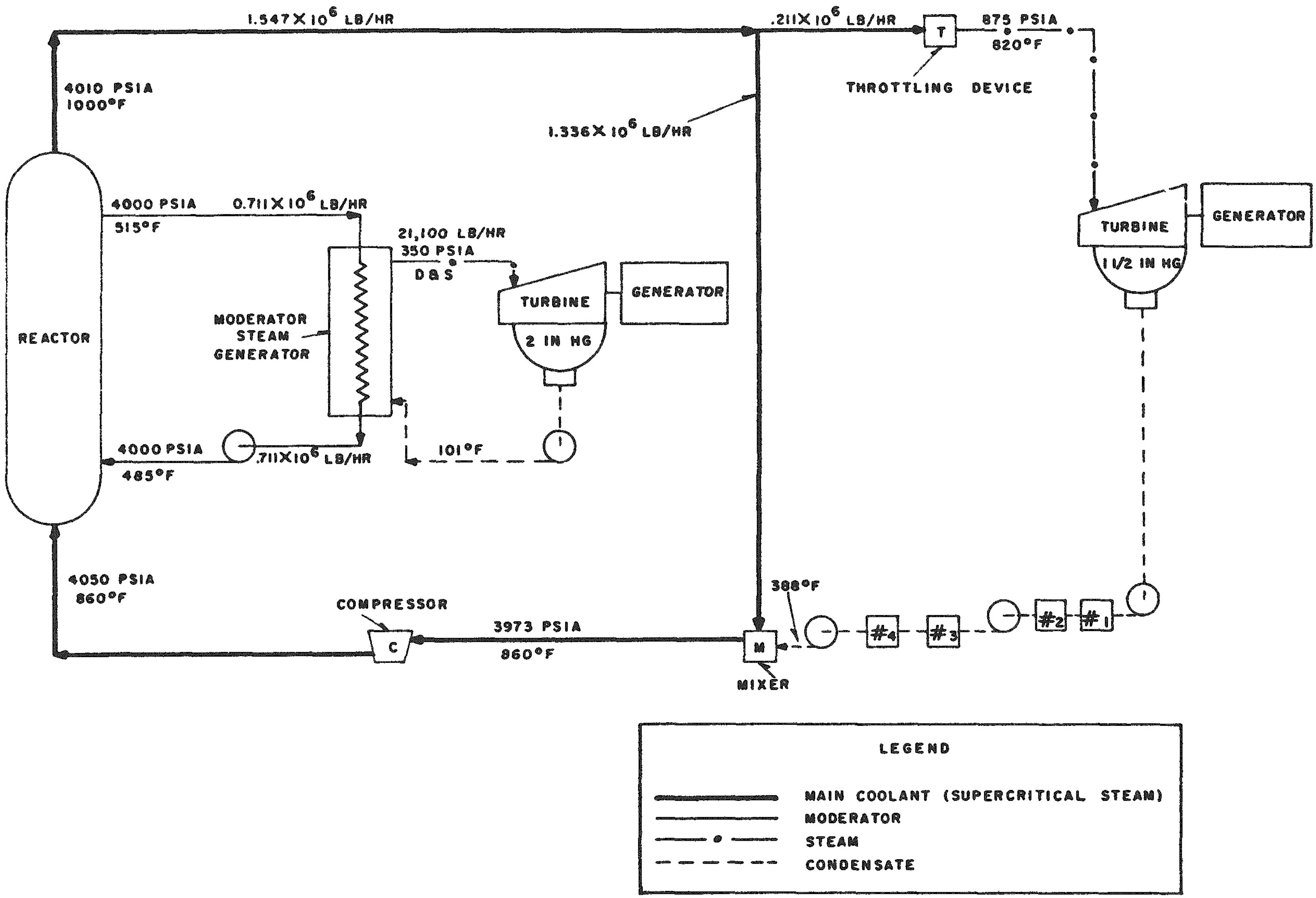

Figure 6

Schematic Flow Diagram - Throttled Direct Cycle in series, which serve as the heat sink for the reactor. They are, functionally, a superheater and evaporator. Feedwater for the steam power plant, at a temperature of 388°F, is fed into the evaporator-superheater, resulting in the production of 197,300 pounds per hour of secondary steam at a pressure of 875 psia and a temperature of 900°F, which are common steam conditions for power plants. This steam is used to drive the generation machinery of the plant. A separate heat exchanger cools the moderator and provides steam for a separate low pressure turbine.

The reactor core and vessel arrangement envisioned are shown in Figure 7. The reactor vessel has an ID of 64 inches and an overall length of 24 feet. The vessel material is carbon steel, type SA-302B, and has a design pressure of 5000 psi. The inside surface is clad with stainless steel. There are two flows within the reactor vessel. Water at 4000 psia and average temperature of 500°F is used for a moderator. Supercritical steam being heated from 860°F to 1000°F cools the fuel assemblies. To reduce leakage between the two fluids, a unitized core of welded construction was proposed.

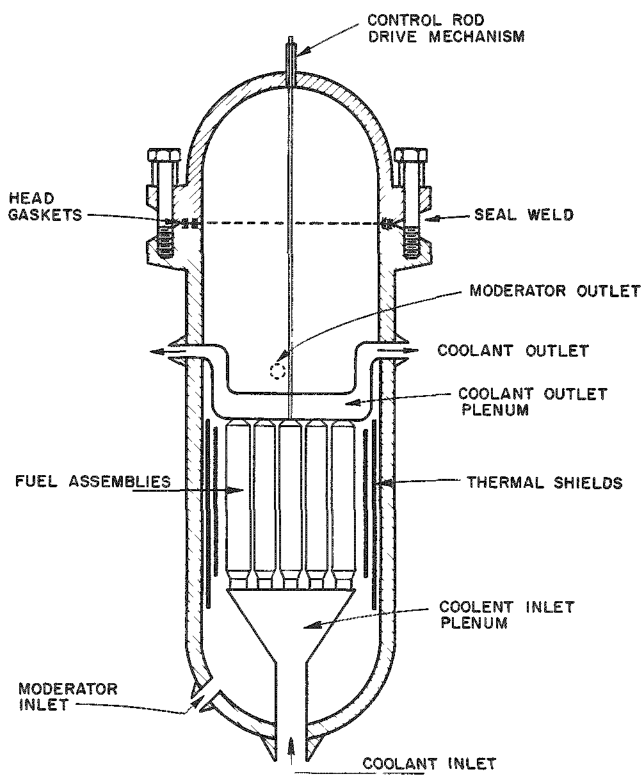

Figure 7

Schematic-Core and Pressure Vessel Schematic-
Westinghouse Reference Design

The basic fuel assembly is shown in Figure 8. It consists of seven close-packed rods surrounded by a double tube shroud. The fuel rods consist of uranium oxide pellets clad in stainless steel. The pertinent reactor parameters are listed in Table II.

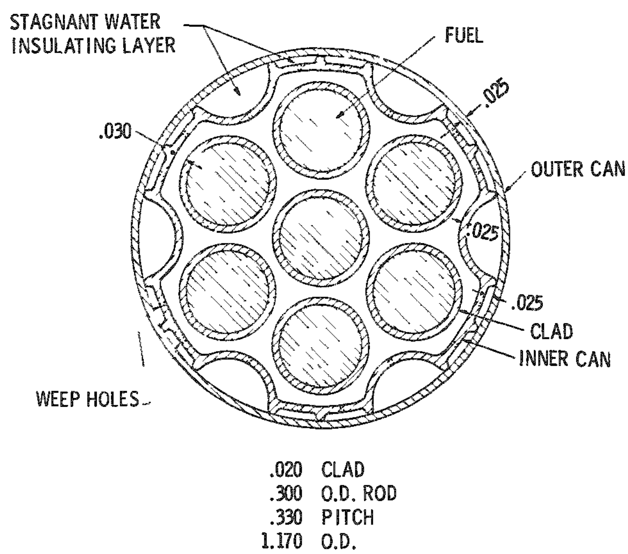

Figure 8

Fuel Element Sub-Assembly

Table II

Reactor power (th)	70 Mw
Electrical output	21,237 kw
Steam pressure (at turbine)	865 psia
Steam temperature (at turbine)	900°F
Coolant pressure	4000 psia
Core diameter	41.6 in.
Core height	60 in.
Coolant flow rate	1.55×10^6 lb/hr

The costs of the reference design proposed were compared with a pressurized water reactor of the same electrical output. The comparative costs for the supercritical water reactor and pressurized water reactor were 18.99 mills/kwh and 13.55 mills/kwh, respectively.

Hanford Supercritical Pressure Power Reactor Conceptual Design (Ref. 13)

As an extension of previous HAPO studies of high-efficiency nuclear electric power systems, a conceptual design of a supercritical plant was prepared by HAPO. The basic purposes of the study were to explore the economic and technical feasibility of such a plant, and to discover problem areas in which development work would be required. The example plant was designed by combining features of the Plutonium Recycle Test Reactor,[14] the multiple hole internally cooled fuel element concept developed by HAPO,[15] and the Philo supercritical pressure steam plant.[16] No attempt was made to optimize the plant operating conditions of the reactor design.

The proposed reactor is a 300-Mw thermal unit, with heavy water moderation and light water coolant. It contains 300 vertical fuel channels arranged in an eight-inch-square lattice. The reactor is controlled by adjusting the moderator level. The reactor would serve as the heat source for a power-generating system similar to the Philo Number 6 generator, which uses a tandem-compound, double-flow steam turbine operating on 4500 psi and 1150°F steam.

The flow circuit for the reactor and steam-electric generating plant is shown in Figure 9. Feedwater is pumped to the reactor at 5800 psi and 525°F. In two passes through the reactor the fluid is heated to 1150°F at 5500 psi, and is then fed into a steam-reheat heat exchanger. The coolant enters a second steam reheat exchanger at 1150°F and 5000 psi following a third reactor pass. After a fourth pass through the reactor, water enters the supercritical turbine at 1150°F and 4500 psi. The two heat exchangers reheat the steam to 1050°F at 1150 psi and 1000°F at 180 psi, respectively. Full-load steam flow is 675,000 lb/hr.

The fuel element assemblies proposed for this reactor are internally cooled UO_2 elements, three inches in diameter and ten feet long. The fuel element arrangement is shown in Figure 10. Each element contains 12 axial coolant channels, arranged in two circular patterns of four tubes and eight tubes. The coolant flows downward in six of the tubes and returns in the other six. To restrict the transfer of heat from the fuel assembly to the moderator, the exterior of the assembly is maintained at about 500°F by insulating the fuel from the 20-mil Zircaloy can which contains the assembly. The proposed insulating material is zirconia sintered in an argon atmosphere. For the purposes of the study, 20-mil thick Inconel-X tubing was specified for the internal jacket. In the return channels of fuel elements used for the second, third, and fourth reactor coolant passes, internal jacket wall temperatures of the order of 1300°F and pressures between 4500 and 5500 psi would be encountered for the design operating conditions used in this study. It was recognized that under such conditions a 20-mil Inconel-X wall would not have the strength required for high exposure irradiation.

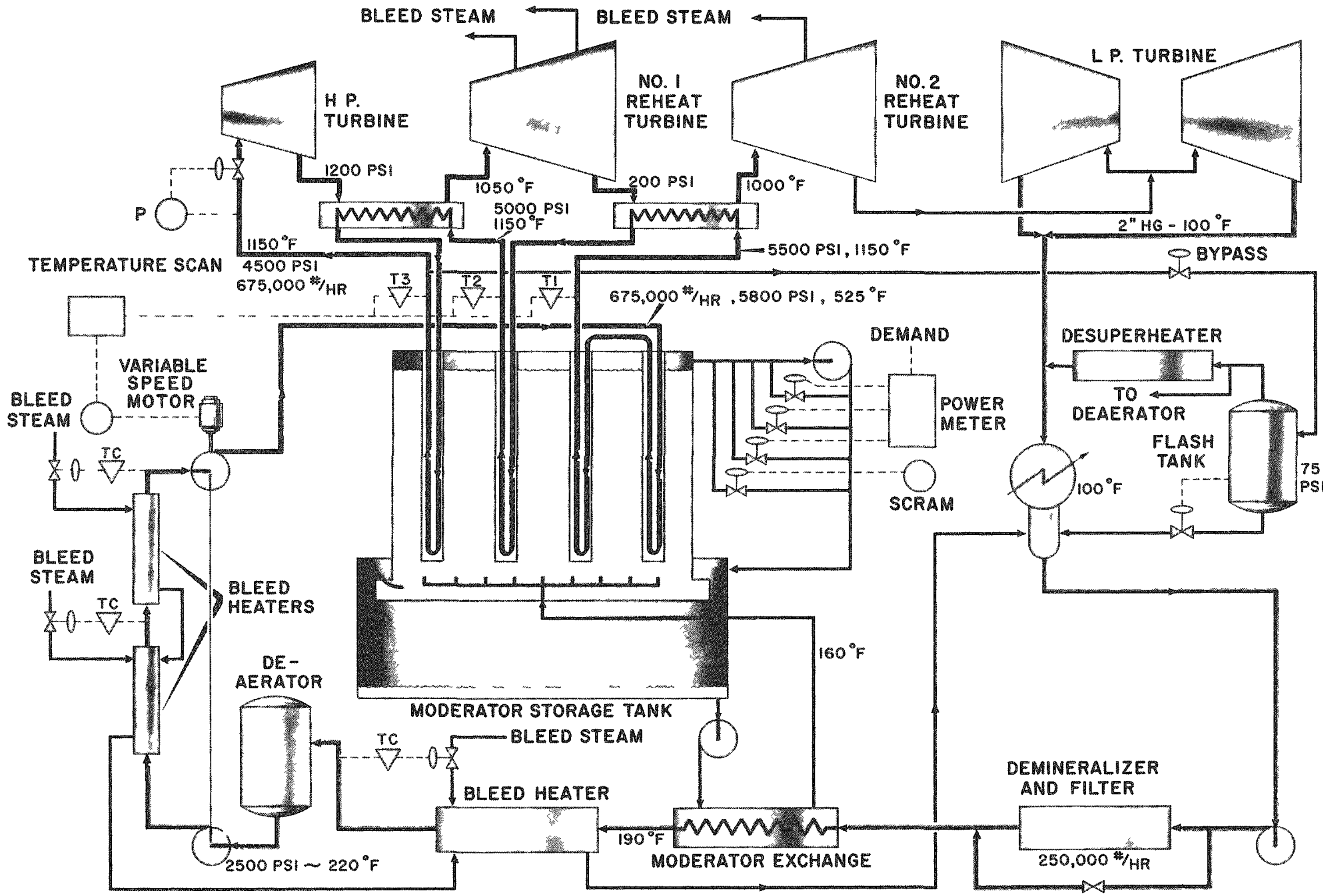

Figure 9

Steam-Electric Generating Plant

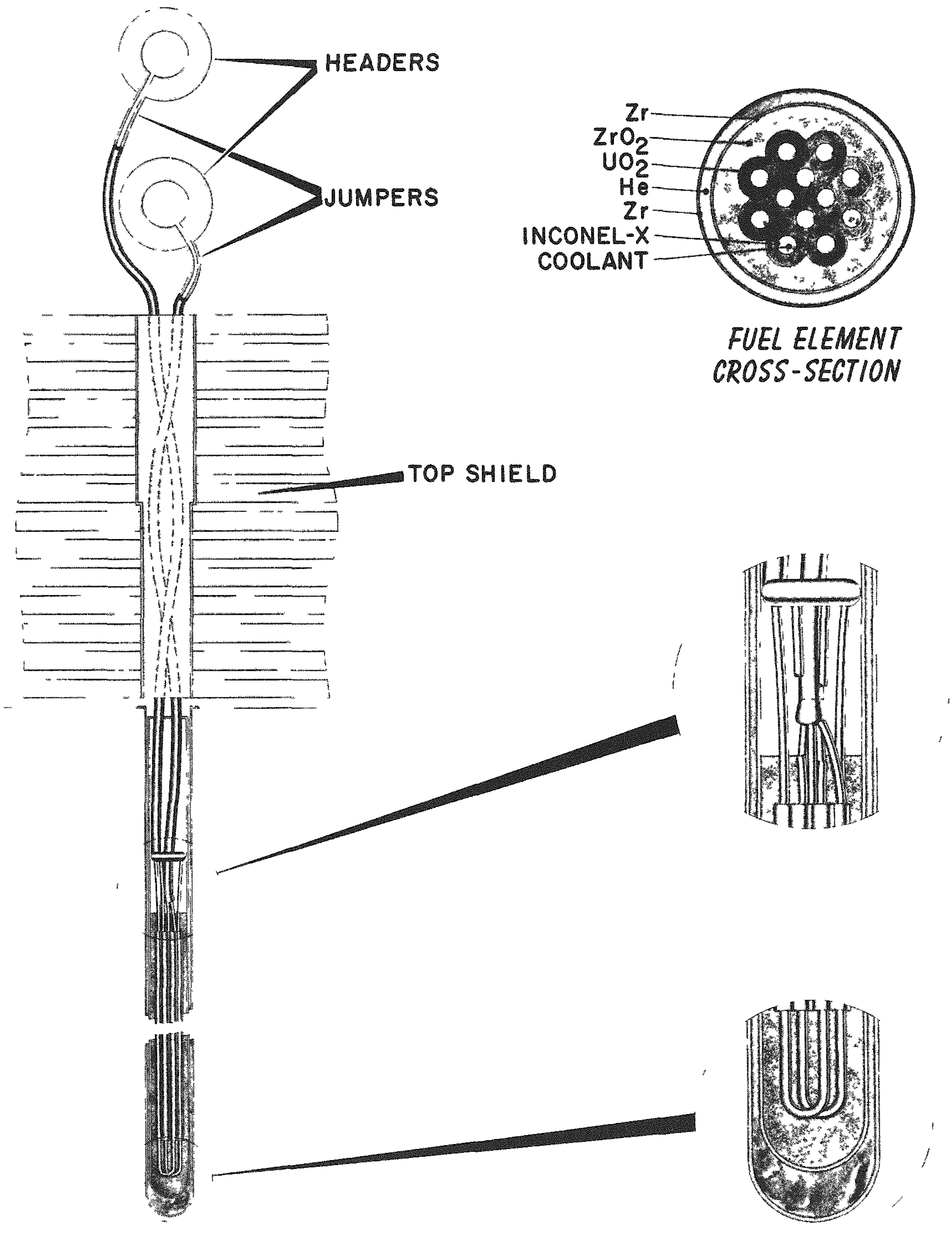

Figure 10

Fuel Element Arrangement

Figure 11 shows an artist's conception of the proposed reactor. The reactor proper consists of a cylindrical tank of half-inch carbon steel, 15 feet in diameter and 13 feet high. The tank contains 300 vertically suspended fuel element thimbles arranged in an eight-inch-square lattice array. From 30 to 50 vertical shim controls are interspersed throughout the active region. The reactor tank serves as a container for the heavy water moderator and reflector. Heavy water is introduced continuously at the bottom of the tank and flows out over a weir beneath the tank and through top overflow lines. The overflow is collected in the moderator storage tank, passed through a heat exchanger, and then returned to the reactor tank. Helium pressure (about 5 psi) in the storage tank and at the weir is controlled to maintain the height of the moderator in the reactor tank. A scram is effected by opening gas line valves between the top of the reactor tank and the weir. The gas pressures are thus equalized, allowing the moderator to drain over the weir. The fuel elements are suspended from the inlet and outlet headers by one-inch OD, 0.200-inch wall jumpers made of 316 stainless steel. All header and jumper connections are welded closures. Refueling is accomplished by lifting a circular header and attached fuel elements as a single assembly from the reactor and moving to a storage basin. Another header with fresh fuel elements is lowered into place and the headers connected by welding. The old fuel elements can then be removed and sent to the separations plant.

A detailed cost estimate for the reactor system was prepared by scaling costs up from PRTR costs. Three differently sized plants were studied and the costs cited ranged from a minimum of 4.9 to a maximum of 8.0 mills per kw hr.

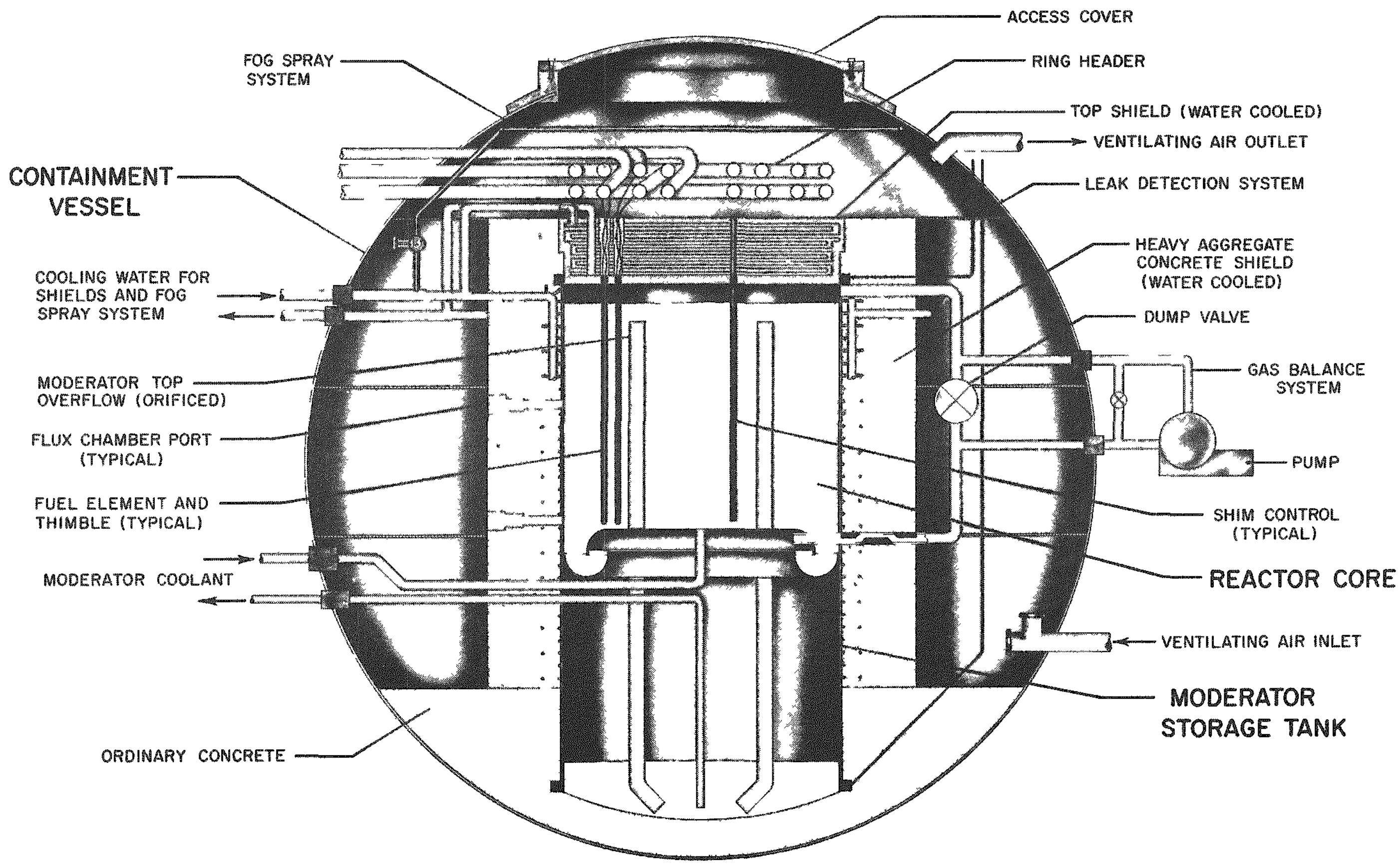

Figure 11

Super-Critical Pressure Power Reactor

STATUS OF SUPERCRITICAL WATER TECHNOLOGY

The following is a brief review of the technology that has been developed about several major problem areas which are felt to be highly pertinent to the development of a supercritical water reactor system. No attempt was made to review all available information on supercritical water systems. A very good start in this direction was an extensive survey made by Westinghouse under Phase I of its study in 1957. The results of this survey have been presented in WCAP 543.[12]

The technological areas that were surveyed in this review are Heat Transfer and Fluid Flow, Water Chemistry, Fluid Property Data, Component Development Power Cycles, and Materials of Construction.

Heat Transfer and Fluid Flow

In a supercritical water reactor the role of the steam film conductance becomes very important. The improvement of ceramic fuels would make values of the heat transfer coefficients more important, since designs would no longer be limited by fuel element centerline temperatures. There is very little experimental information available on heat transfer coefficients to supercritical water. McAdams[34] has presented limited results at 3500 psia. These results were incorporated into a general equation for heat transfer to superheated steam, and therefore are more applicable to heat transfer to subcritical steam. The range of variables covered at high pressures was very small, and beyond the range of temperatures where properties change rapidly. These results have, however, been generally used for heat transfer at higher pressures up to and through the critical temperatures where the equation is not applicable (as in WCAP 500).[11]

Pratt and Whitney presented the results of an extensive investigation of heat transfer to supercritical water flowing through small tubes in PWAC-109.[8] The investigation covered the range from 4000-8000 psi and bulk temperatures from 400-1000°F. The data appear to have been taken carefully and cover a wide range of variables.

One statement made in the introduction to PWAC-109 citing reasons for undertaking the investigations is of particular interest, and therefore is quoted in full. "One reason for anxiety was the behavior of the heat transfer coefficient for isothermal conditions over a range of wall temperatures when it was computed from the published properties. It appeared that above certain temperatures the heat transfer coefficient declined rapidly and this appeared to open up the possibility that the coefficient could decline more rapidly than the temperature differential could increase, thus allowing the wall temperature to rise indefinitely." This statement appears to have aroused concern in several core designs and resulted in the decision of Westinghouse not to let the fluid pass through the critical point in the reactor. The statement appears to be illogical. A decline in the heat transfer coefficient would be followed by a rise in wall temperature that exactly follows it; this behavior is expected by definition of heat transfer coefficients. It is interesting to note that the area in which the heat transfer is declining is the one in which the most confidence can be placed in conventional methods of computing heat transfer coefficients.

The majority of the data were taken at 5000 psi in tubes 0.050 in. and 0.075 in. ID and 8 in. long. Enough data points were obtained at 4000, 6500, and 8000 psi to obtain a correlation based on the idea of grouping all of the properties which are functions of the wall and bulk temperatures in a manner suggested by the normal heat transfer equation for forced convection heating. The normal type of dimensionless group correlation was not used because of uncertainties in the property values for supercritical water, particularly the transport properties. Thus the heat transfer equation can be written as

$$\frac{hD}{k_B} = \frac{q''}{T_W - T_B} \frac{D}{k_B} = \text{constant } Pr_B^{1/3} \, Re_B^{0.8} \quad ,$$

provided the properties do not vary greatly between those at bulk temperatures and those at wall temperature. It appeared reasonable that the same equation would be applicable at some temperature which was a function of T_W and T_B. Then the equation can be rewritten:

$$q'' \frac{D^{0.2}}{g^{0.8}} = \text{constant } (T_W - T_B) \, k^{.667} \, \mu^{.467} \, C_p^{.333} = F(T_W, T_B) \quad .$$

Thus, if the 0.8 power relationship on the mass velocity and the 0.2 relationship on the diameter hold, a correlation of the type shown in Figure 12 can be used. The mass velocity relation was checked and found to be true. The diameter effect was also apparently true, so that Figure 12 represents a reasonable correlation of the experimental data that is not dependent upon property values.

Several anomalous effects were observed in the course of the experiments. A change in the nature of the heat transfer mechanism was observed at high heat flux rates under certain conditions. The heat transfer rate increased in a manner resembling boiling and was accompanied by a loud whistling noise and other evidences of vibration. Goldmann[19] postulated that a heat transfer mechanism could exist that is strongly affected by the "explosion" of liquid-like aggregates, which then collapse into liquid-like aggregates again in the manner similar to the growth of bubbles observed in boiling liquids.

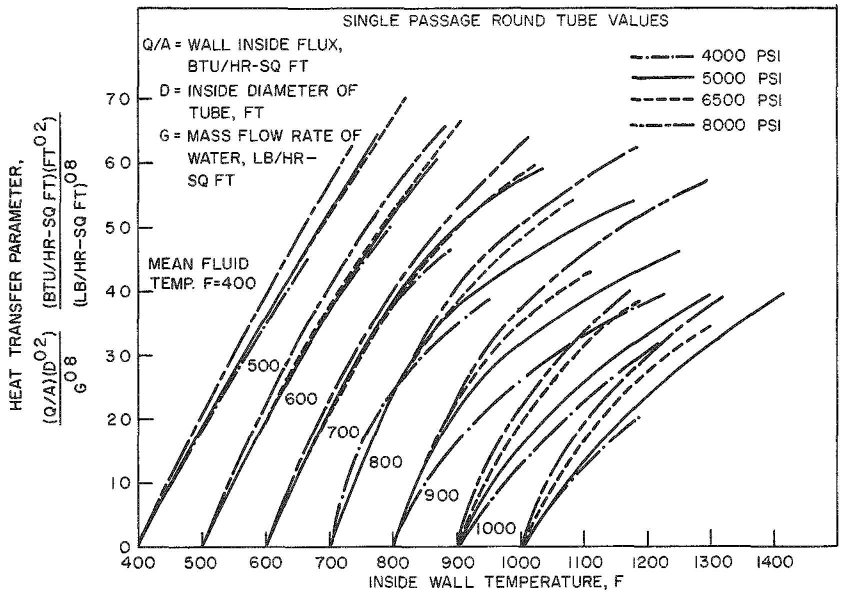

Figure 12

Correlation of Heat Transfer Data for Supercritical Water At Various Pressures

Dickinson and Welch[20] have presented the results of an investigation at 3500 and 4500 psi. The tests were run on 9.540-in. and 9.300-in. ID tubes 63 in. long. The data covered a wide range of bulk water temperatures, flow rates and heat fluxes. Because of uncertainties in the physical properties, the data were presented as a function of surface temperature, as in Figure 13. Their conclusions were:

1. For design purposes, it is satisfactory to use the conventional formula for pipe flow: $Nu = 0.023\ Re^{0.8}\ Pr^{0.4}$, at surface temperatures below 600°F. Properties would be evaluated at the bulk temperature.

2. In the range from 800 to 1100°F, a constant Stanton number of 0.00189 can be used. The specific heat should be evaluated at the surface temperature.

3. In the range from 660 to 800°F, coefficients are high, owing to an apparent boiling-like phenomenon, and it is probably safest to assign some constant value to the coefficient in this temperature range depending on the mass velocity and the pressure.

The data of Dickinson and Welch at 4500 psi are compared with the Pratt and Whitney correlation in Figure 14. As can be seen, agreement is excellent.

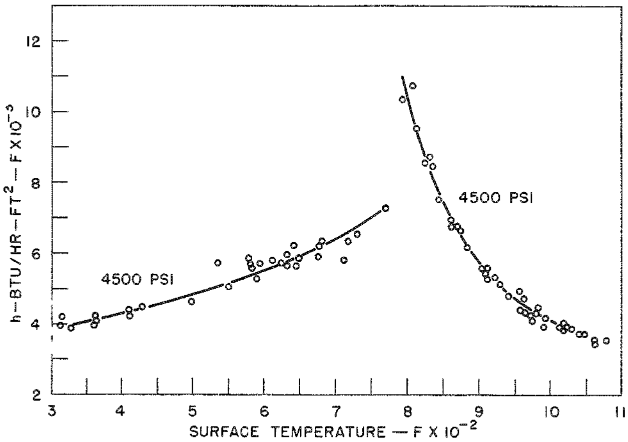

Figure 13

Variation of Film Conductance with Surface Temperature Data of Dickinson and Welch

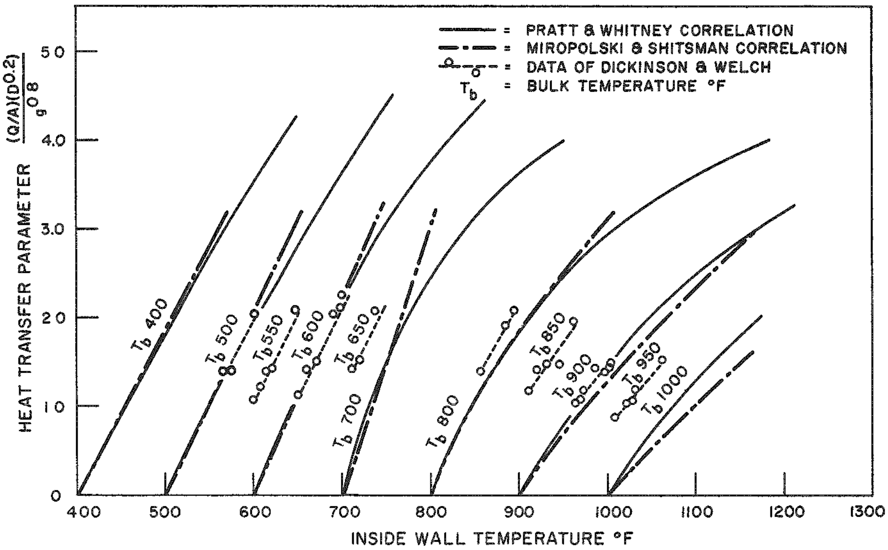

Figure 14

Comparison of the Correlations of Various Investigators for Supercritical Water-Heat Transfer

Miropolski and Shitsman(21) concluded that the data in the near critical region can be presented by the equation

$$Nu_B = 0.023\, Re_B^{0.8}\, Pr_0^{0.4} \quad ,$$

where the Prandtl number is evaluated at the bulk temperature or the wall temperature, whichever is less. The Nusselt and Reynolds numbers are evaluated at the bulk fluid temperature. This correlation is also compared in Figure 14. As can be seen, it breaks down at high values of $q''D^{0.2}/g^{0.8}$, as would be expected.

The heat transfer data available appear to be adequate for predicting heat transfer rate in the critical region. Studies of the property values of various investigators have been made[18] and some of the apparent inconsistencies explained. It seems that the possession of accurate property values may make it possible to produce a dimensionless correlation of the data. Some unexplained effects have been observed and should be further studied.

Measurements of friction factors in the supercritical region were also made and correlated in PWAC-109.[8] However, the scope of this study was quite limited.

Water Chemistry

Aspects of the water chemistry problem that would be particularly crucial in a supercritical water reactor system are (1) the deposition of crud on the reactor fuel elements and (2) deposition of radioactive substances in the external system. Of necessity, therefore, one must strive for and maintain "ultrapure" water in a supercritical system. As an example, the specifications for dissolved solids in the feedwater to the Philo #6 unit calls for a maximum of 500 ppb (parts per billion), and in the Eddystone #1 unit 50 ppb is the allowable maximum. By contrast, water containing up to 1 ppm is considered satisfactory for reactor systems at present.

There are three major sources of contamination for the supercritical water reactor cycle. They are: (1) pickup of metallic corrosion products from the reactor and external system, consisting primarily of compounds of iron, copper, chromium, nickel, etc., (2) dissolved solids in the makeup water, and (3) leakage of condenser cooling water into the condensate stream.

The quantity, nature, and location of deposits that would occur in a direct supercritical water reactor system cannot be specified at present. A number of experimental studies have been and are continuing to be carried out on the varying aspects of the water chemistry problem. The most comprehensive studies are being carried out by the commercial vendors and power utilities who are committed to the construction of supercritical boilers. Perhaps the most important information is being gained from the operation of the Philo #6 supercritical boiler. The data that have been obtained by the boiler industry have been summarized in a number of papers.[12,22-27] In addition to this information, some additional data on supercritical systems are available from the limited study made by Pratt and Whitney in conjunction with the ANP program. Some of the interesting information that has been gained from these sources is summarized very briefly below.

External Deposition. In the operation of the Philo plant, the dissolved solids have been kept well within the prescribed limits. No problem has existed in maintaining even lower values by passing a portion of the condensate stream through the demineralizers. Normal values obtained have been in the range from 100 to 200 ppb. During an outage in 1958, however, removal of the h-p turbine shells disclosed heavy deposits on the turbine buckets and diaphragms. The deposits were varied in nature: black, adherent and hard in the initial stages and loosely flaky beyond. The deposit thickness varied appreciably, due to flaking off of some portions. Also, the deposit varied in thickness from the leading to the trailing edges of the nozzles. Inspection of the reheat and l-p turbines also revealed both the black adherent deposit and a very slight, brownish deposit at various positions. Analyses of the deposits found in the h-p turbine showed the major portion of the deposits, or about 95% to be a mixture of cuprous and cupric oxides.

Magnetic iron oxide was a minor constituent, ranging from 3 to 8%. Other metallic oxides and silica were of no significance, all values being less than 0.1%. It was found that the cuprous oxide was more prevalent than cupric oxide. The distribution of the copper oxides obtained is shown in Figure 15. The deposits in the reheat turbines consisted essentially of a mixture of ferric and magnetic iron oxide together with cupric oxide. There was more silica in these deposits, the amount ranging from 5 to 10%. The faint deposits on the l-p turbine were found to have iron oxide as a major constituent.

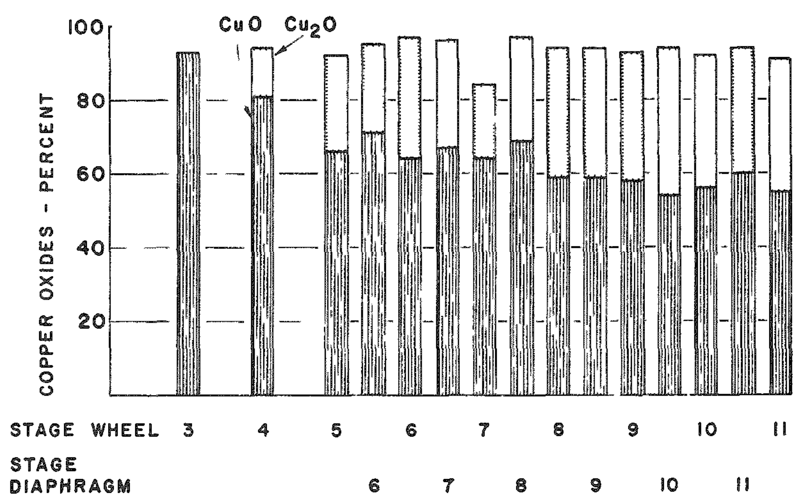

Figure 15

H-p Turbine Deposit Location and Composition

The nature, cause of pickup, carry through and deposition mechanism for the copper oxide have not been resolved. This is borne out by the following quotes taken from papers presented on Philo in 1958 and 1959.

"The major location for copper pickup has been established as the steam side of the heaters rather than the condensate or water side of the heaters."

"Tests have indicated that fifty percent or more of the copper in the feedwater deposits in the steam generator."

"Three theories of the carrythrough and deposition mechanism for copper oxide were considered........."

"In general the major source of copper pickup appears to be in the water side of the h-p heaters."

Needless to say, extensive test programs are currently underway to attempt to resolve the chemical and mechanical aspects of the problem. A large effort is also being devoted toward developing cleaning techniques for the removal of the deposits.

Internal Deposition on Heated Surfaces. The problem of internal deposition is equally important, since it can strongly affect the heat transfer characteristics of the system. If deposits are formed on the heating surfaces, hot spots occur, which could result in excessive temperatures and subsequent damage. Such deposits have occurred in supercritical loops used by Pratt and Whitney. The deposits have also occurred in the Philo steam generator but with no apparent increased surface temperatures. The Pratt and Whitney work was done in conjunction with the ANP program and is reported in PWAC-103.[2] Some of the significant information that was obtained from this study before it was terminated is as follows:

1. "Hot spots are caused by the deposition of material from water on the tube walls in region of high heat flux."

2. "Magnetite, hematite, silicate, and carbonate deposits have been identified at hot spot locations. Hematite has been found to exhibit a retrograde solubility at 700-800°F and at pressures below 11250 psi."

3. "Hot spots were produced with a variety of water sources ranging from tap water to distilled demineralized water, not demineralized downstream of the pump."

4. "No hot spots were ever observed when demineralized water was used and a final demineralizing operation was carried out between the high pressure pump and the preheater."

The Pratt and Whitney study was terminated before conclusive answers as to the causes and methods of preventing deposits (hot spots) could be obtained.

Interesting data on internal deposits have also been gained from the Philo plant. Even though the surface metal temperature showed no significant increase, a number of tubes were removed from the steam generator for laboratory analyses. Visual examination of these samples showed them to have black deposits generally less than one mil thick. The weight of these deposits decreased with increasing temperature. The heaviest deposits were found in the low-fluid-temperature positions of the steam generator, where thermocouples were not located. The deposits were identified as iron oxide. The copper content was less than 2 percent. The distribution of the deposits as a function of temperature is shown in Figure 16.

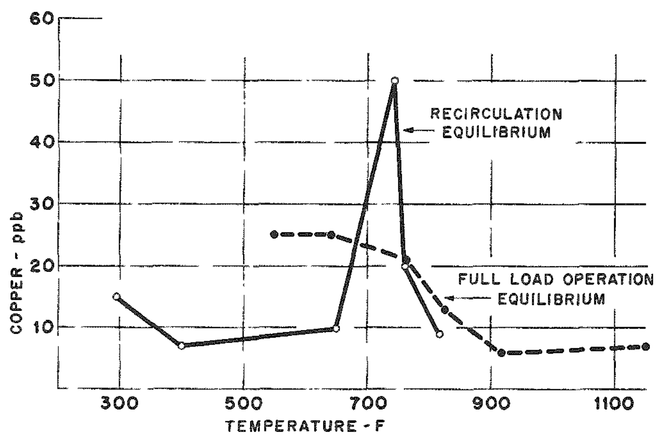

Figure 16

Copper Profile Across Steam Generator for Hydrazine Feed

The corrosion problem in a supercritical reactor system may possibly be resolved by utilizing conventional means of control of pH and oxygen. To reduce corrosion, ammonia is used in conventional systems for control of pH in the range 9.0-9.5, and hydrazine as an oxygen scavenger. Current practice in pressurized water systems calls for the addition of hydrogen to the primary system for oxygen control. In a reactor the problem is increased by the radiation-induced dissociation of water; in this case, excess hydrogen aids in recombination and pH is again maintained in the region 9-10. It is possible that these methods will suffice for a SCWR, but the problem needs study.

In retrospect, it should be borne in mind that the deposition problems described above could vary significantly between different systems, such as a reactor and boiler. The magnitude of the problem depends on a number of factors such as (1) type, quantity, and composition of various materials in the system, (2) temperature of various fluid streams, (3) the chemical treatment of the water, and (4) type and design of condenser.

Much more information is also required on the limits of tolerable impurities in nuclear systems. Some information of this type could be gained from the proposed PRTR high-pressure loop.(33) This loop is to be used for testing proposed high-pressure, high-temperature fuel elements. If constructed, the loop will give valuable information on the problems of maintaining water purity in a reactor atmosphere.

Property Information on Supercritical Water

The ASME Research Committee on Properties of Steam is presently cooperating in international research to extend the steam tables to 15,000 psi and 1500°F. Accurate knowledge of thermodynamic and transport properties of water in the critical region is required to analyze power cycles and reactor configurations. The empirical correlations for heat transfer will be of the greatest value if they are given in an equation involving dimensionless groups, such as Nusselt number, Prandtl number, and Reynolds number. The success of a correlation or any theoretical attempt to predict the results will depend on accurate and detailed information for the thermodynamic and transport properties of water, for instance, pressure, volume, temperature, enthalpy, specific heat at constant pressure, dynamic viscosity, and thermal conductivity.

A recent report(18) gives an excellent survey of the property values available for water and water vapor in the critical region. An important result of the study was the discovery that excellent agreement existed between the many PVT measurements for water, even though some of the data were obtained many years ago. Study of the existing thermal conductivity and viscosity data suggested that the Russian work was the most consistent. New measurements and studies of the existing data in the critical region are being made, and should result in adequate property information for supercritical water.

Power Cycles for Supercritical Reactor Power Plants

Whether or not the supercritical water reactor concept will appear attractive will depend to a large degree upon the ability of the designer to fit an attractive power cycle to the concept.

As mentioned previously, the major advantage of the supercritical water system is its potentially high thermal efficiencies. The cycle, as for any reactor system, will have to be optimized to obtain the lowest cost energy. Figure 17 gives an example of the cycle chosen for the Philo Plant of the Ohio Power Co. This cycle incorporates 7 stages of feedwater heating and 2 stages of reheat. A nuclear power plant operating on this cycle would have an overall plant efficiency of 46.7%.

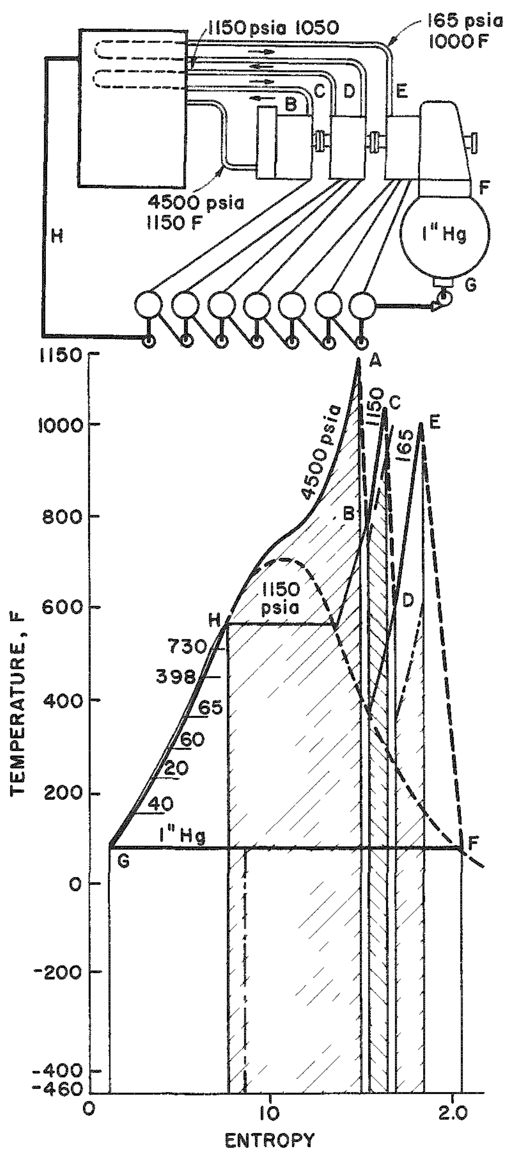

Figure 17

Power Cycle for Philo Plant - 2 Stages of Reheat and 7 Stages of Preheating

Figure 18 shows the simplest cycle that could be used with a super-critical water reactor power plant. This would be a direct cycle power plant with a no reheat and no feedwater heating. This cycle would give an overall plant efficiency of 37.2%. Figure 19 shows a cycle the same as the preceding except that it incorporates 7 stages of feedwater heating. The efficiency has increased to 44%. This illustrates the advantages to be gained from preheating on a cycle of this type. As can be seen by comparison with Figure 17, the efficiency is only increased an additional 2.7% by adding the two stages of reheat.

Depending on the working temperature and cycle chosen, there is probably an optimum pressure at which the reactor should operate. As an example, a 1000°F system with a single reheat has its maximum efficiency at 4100 psia.

In the final analysis, the choice of a cycle for a supercritical water plant will depend on the reactor system selected and on economic considerations. There is certainly an optimum cycle which will minimize costs and this cycle will not be the same for all designs.

Materials for Supercritical Pressure Reactor Power Plants

The design of a supercritical reactor will probably require the use of new high-temperature materials in order to avoid excessive thickness in tubes and stop valves. The requirements of a direct cycle plant may impose even more stringent materials problems than those of the conventional supercritical power plant. The major development work that is of interest is that done for the conventional supercritical power plants. A recent paper describes the high-temperature tests and the welding development for the Eddystone boiler,[30] which led to the selection of new materials for the supercritical panels. The following conclusions were reached.

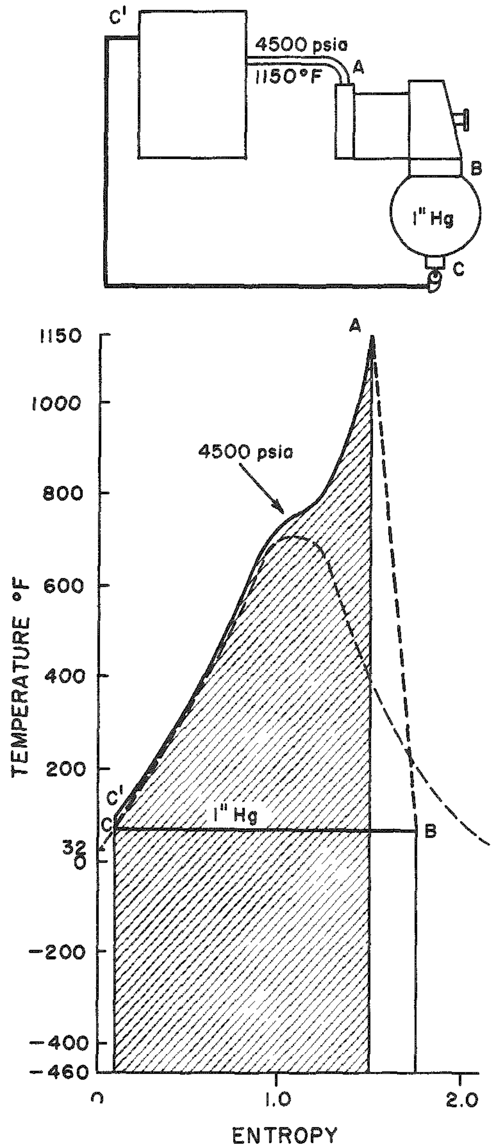

Figure 18

Simplest Possible Supercritical Water Power Cycle

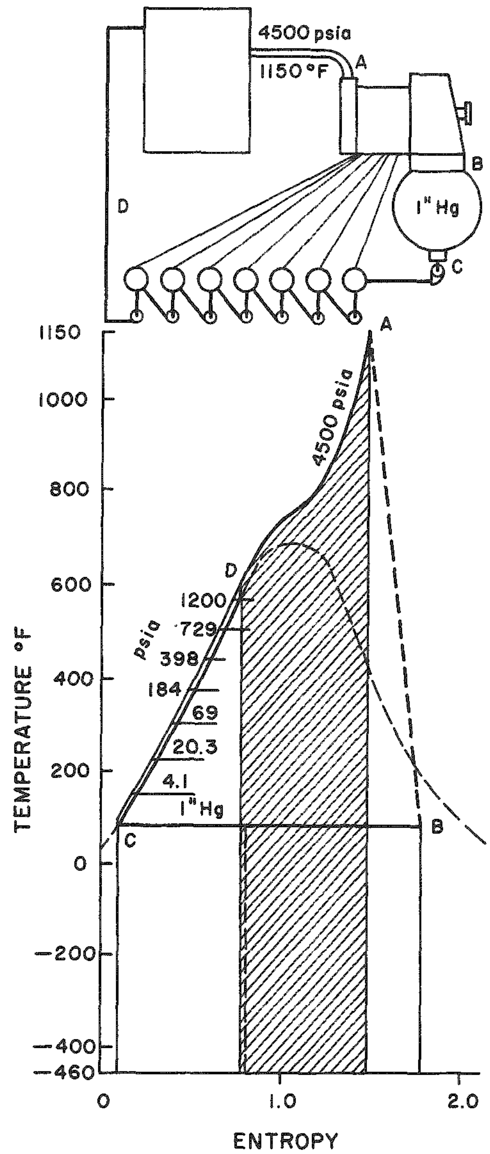

Figure 19

Simple Cycle with 7 Stages of Feedwater Heating Added

1. 17-24 CuMo steel has high-temperature strength superior to the strength of the ASME-approved austenitic steels, and tubes of this composition can be made using conventional steel mill procedure. Tubes of this alloy can be fabricated without difficulty, provided close control of heat treatment is exercised.

2. Type 316 is a very satisfactory alloy for fabricating and has high-temperature properties which seem to testify to present stress code values.

3. The Fox CN-16/13 Co electrode appears to possess characteristics and provide high-temperature properties in deposited metal superior to any known American welding electrode. Satisfactory welds, completely austenitic, are possible, and this is an important and unusual achievement. Design features and fabricating procedures for tubes and valves are presented.

WCAP-543[12] presents an excellent materials summary as of 1957. A discussion of the materials used in the Philo plant is included. The main steam piping for the Philo plant was Type 347 stainless steel. This was chosen as the most suitable material for this line and valves. Welds in the main steam lines were made with the consumable backing ring process. The main steam piping in the Eddystone No. 1 unit will be 316 stainless steel made by the forged and bored process. A typical size of this piping will be 10.312 inches OD with 2.656-inch walls.

Type 347 and 316 stainless steel are currently approved by the ASME Boiler Code. Until recently, there has been no urgent need to use such alloy compositions for steam plant piping; these materials are of relatively recent development and their cost is high. It is expected that as the use of high temperatures and high pressures becomes more common other alloy materials of a similar nature will be covered by the boiler code.

Supercritical pressure reactor systems will undoubtedly have additional materials problems. Greater care will need to be exercised in the selection of materials because of the peculiar problems of reactor plants. The choice of materials will be affected by the desire to keep corrosion products, and hence deposited activity in the installed components, to a minimum.

<u>Component Development for Supercritical Water Systems</u>

Considerable development has been done in the past decade on components for supercritical water power plants. As a consequence, components such as valves, piping, turbines, feedwater pumps and heaters have been developed to the point where they are considered suitable for commercial application. An excellent summary of component parts as of 1957 is also given in WCAP-543.[12] In addition to the Philo plant which is in operation, five other large plants are under construction.

The Philo No. 6 unit of the Ohio Power Company has been in operation for three years. Steam conditions are 4500 psi and 1150°F. The electrical output of the plant is 125 Mw. The plant was designed as a prototype pilot plant for the larger units being constructed by the American Gas and Electric System. The operating experience with the plant is well documented in a series of papers.[16,17,22,23]

The Breed and Philip Sporn Units, for which the Philo Plant is a prototype, are identical in the important design details. The steam conditions will be 3500 psi and 1050°F. The electrical output of the plants will be 450 Mw.

The Philadelphia Electric Company is constructing two supercritical units. The first, Eddystone No. 1 will utilize steam at the highest pressure and temperature yet considered, 5000 psi and 1150°F, ultimately to be increased to 1200°F. The output of the unit will be 325 Mw electrical. Eddystone No. 2 will operate at a lower temperature and pressure. Steam conditions will be 3500 psi and 1050°F. The output will also be 325 Mw.

The Avon No. 8 plant of the Cleveland Electric Illuminating Co. will provide 250 Mw electrical. The steam conditions will be 3500 psi and 1100°F. A series of recent papers,[25-31] document the current status of the design and research for Eddystone No. 1. The problems in selection of materials for the boilers, main steam piping, and turbine elements are discussed, as are problems of water treatment.

Supercritical Pressure Steam Turbines. In the proposed plants utilizing steam at supercritical conditions of pressure and temperature, the "supercritical" turbine is physically only a small part of the entire turbine unit, yet this element develops approximately 1/8 of the entire output of the turbine-generator set. Because of this, "already, a 350-Mw turbine-generator set for 3500 psi costs several hundred thousand dollars less than one for 2400 psi and the same temperature."[32]

The supercritical turbines for the plants so far proposed are for use on cycles utilizing several stages of feedwater heating and double reheat. Consequently, the turbine-generator sets are of the cross-compound, double reheat type The turbines consist of several high-pressure elements operating at 3600 rpm and an 1800-rpm double-flow low-pressure element. The main flow of steam from the turbine stop valves is, in series, through the superpressure and the very high-pressure element, the first reheat stage, the high-pressure turbine stages the second reheat stage, and finally through the intermediate and low-pressure turbines to the condenser.

Feedwater Pumps. For a SCWR utilizing the once-through concept or natural circulation, the only pumps that will depart from conventional practice are the feedwater pumps. In the pressure ranges being considered, it becomes increasingly advantageous to consider pumps with rotor speeds in excess of 3600 rpm. This is because of the significant reduction in the number of stages and the impeller diameter for the high-speed pump, and the subsequent increase in reliability. In the past, motor drives have been used for a number of reasons. Most important of these was the better station economy gained by expanding the steam in the high-efficiency main turbine. With the increase in pump speeds and driver sizes, direct steam-turbine drives become more interesting. This is because turbine efficiency increases rapidly with speed. A turbine has the added advantage of variable speed. Some development work of direct interest is the work of Pratt and Whitney reported in PWAC-108.(7) The work was done under subcontract to Aerojet-General, Worthington Corp., and Nash Engineering Company.

The main development work for the supercritical water plant feed pumps has been done by the suppliers of the units for the plants now under construction. Experience with the feed pumps for the Philo station has not been good, but developing technology and experience should enable pumps to be supplied as standard components.

Circulating Compressors. In the case of a reactor where it would be desirable to circulate the fluid at temperature, a considerable amount of development work would have to be done on circulating compressors for high-pressure, high-temperature application. The combination of high pressure, high temperature and low density makes the design of a satisfactory compressor a difficult job. No development work has been done on units for this type of service and designers should try to avoid their use.

Pressure Vessel. A major limitation of supercritical water reactors which use an enclosing pressure vessel of the conventional type will be the size of vessel that can be constructed. Limitations on pressure vessel size in turn impose design limits on reactor power. Manufacturers have indicated that vessels up to 6 ft ID can be constructed with available materials by conventional means. Vessels of this type will probably have to be of laminated construction. Very much larger vessels are probably out of the range of present technology, though advances may make larger vessels feasible and economical. The sealing and gasketing of these vessels will also be a major problem.

SCWR POTENTIAL

The results of the Westinghouse and Hanford studies are in direct contradiction in regard to the potential of a supercritical water reactor. The conclusions reached in the Westinghouse study are summed up in the following quote, "It became evident that the high pressure and temperature, but the low density of supercritical water, gave rise to design complications and expensive construction which would detract significantly, if not outweigh, the potentially attractive thermodynamic efficiency being sought through the use of supercritical water. In view of these unpromising findings it was concluded with the Maritime Reactors Branch's concurrence that it would be inappropriate to perform the detail work as defined under Phase III." The conclusion drawn in the opinion of the authors cannot be applied to the supercritical water reactor in general. The study served to illustrate the penalties that are accrued through the use of the indirect cycle. The overall efficiency of the supercritical plant turned out to be only 30.3%, a slight incremental gain over the subcritical boiling and pressurized water concepts. In addition to the much lower thermal efficiencies, the system is, as was concluded, further penalized by the increased complexity of the external plant, which is in turn reflected in increased capital costs resulting from the supercritical pressure. The Westinghouse study merely showed that the design selected, an indirect cycle, forced-circulation supercritical water system with a separate moderator, is an uneconomical concept. Since no major changes in technology have occurred in the past few years, this opinion is still probably valid today. No serious attempt was made to evaluate other possible concepts and cycles. Also, it appears that some of the extreme pessimism in the conclusion could possibly be attributed to conservatism of the designers.

The projected power costs obtained from the Hanford study of a direct cycle system on the other hand certainly are very attractive. It appears, however, that a fair degree of optimism has been included in the cost estimation of this design study. This is especially true in connection with the fuel cycle costs cited. They do not appear to reflect the complexity of the fuel elements selected nor of the handling system. Also, it appears that a more detailed design may make capital costs rise. As an example, it may be necessary to have more stringent requirements on the materials used and a more complex auxiliary system to keep the contamination in the primary system at tolerable levels. In fact, the contamination problem was apparently not even considered. The study does, however, show the benefits of the direct cycle.

It is the opinion of the authors that the direct cycle concept offers the best possibility for achieving economic power from the supercritical water reactor. The realization of this goal will depend to a large degree on the ingenuity of the designer for achieving a basic simplicity in reactor design and in developing concepts which can operate on attractive power cycles.

There are additional reactor systems that may be fitted to a supercritical water cycle. An example of one concept that suggests itself would be an extension of the boiling reactor into the range of supercritical pressures, that is, a direct cycle natural-circulation system. Such a system is possible since at constant pressure the density of supercritical water decreases very rapidly with increasing temperature. The change resembles the change from water to steam at subcritical pressures. Thus the recirculation of the coolant through the core is derived from the density differential created by the injection of the cold makeup water to the hot recirculating fluid in the downcomer. No attempt has been made at a detailed design or economic study of this concept. It is merely mentioned here to illustrate another supercritical water concept that may be promising.

NOMENCLATURE

h	Heat Transfer Coefficient	μ	Viscosity
D	Diameter	T	Temperature
k	Thermal Conductivity	g	Mass Velocity
q"	Heat Flux		
Pr	Prandtl Number		**Subscripts**
Re	Reynolds Number	B	Refers to Bulk Temperature
Nu	Nusselt Number	o	Defined in the text
C_p	Specific Heat	W	Refers to Wall Temperature

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