# CIVILIAN POWER REACTOR PROGRAM

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Book 7

## PART III

# *Status Report on Organic-Cooled Power Reactors as of 1959*

UNITED STATES ATOMIC ENERGY COMMISSION

# DISCLAIMER

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## *Status Report on Organic-Cooled Power Reactors as of 1959*

Published: 1960

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# I

# SUMMARY

This report presents a brief survey of the current status of technology on organic-cooled reactors. It has been prepared by Atomics International under an Atomic Energy Commission contract. Included within the main body of the report is a summary of the work performed at Atomics International, a Division of North American Aviation, Inc., Brookhaven National Laboratory, Canadian General Electric Company, and Hanford Research Laboratories. Only the more important aspects of the technology are qualitatively reported but references are included where applicable so that the reader may obtain more detailed information.

At the request of the AEC, consideration has been given only to organic-cooled reactor plants in the 20- to 300-Mwe range applicable for central station power. The cost estimates prepared were developed under ground rules supplied by the AEC.

The report describes work completed and current work underway in the general research development program, the operational experience gained from the Organic Moderated Reactor Experiment (OMRE), a description of several typical organic-cooled reactor power plant designs, and a survey of the economics of such plants.

The organic concept was conceived during the wartime Manhattan project. Due to the lack of an immediate need for power reactors and the general unavailability of enriched uranium, serious consideration was not given to the organic concept until approximately 1953. At this time preliminary information on the radiation stability of typical organic compounds was being obtained on Van de Graaff machines and electron accelerators. This work was followed shortly by irradiations in in-pile test loops and culminated in a decision to construct the OMRE in 1955.

The Atomic Energy Commission has, since approximately 1953, continuously funded at a modest level an organic reactor development program. Due to the basic technical uncertainties associated with the use of an organic as a reactor coolant, a very large fraction of the development effort has been devoted to the determination of coolant property and stability information. It was not until the inauguration of the program for the City of Piqua, Ohio reactor that reasonably large-scale effort has been devoted to the development of system components and performance.

A brief summary of the status of several of the more important aspects of organic reactor technology are given on the following pages, with more detail in the main body of the report.

## 1. Physics

The physics of organic moderated reactors is similar to that of water reactors since the principle means of neutron energy degradation is by scattering collisions with hydrogen. Sufficient information is known from data on water critical experiments, the OMRE, on prototype water reactors, and from organic experimental work such that reliable extrapolation to large power reactors can be made. The physics of more sophisticated multiregion cores and cores in which power flattening techniques are used are not as advanced and require additional physics work to confirm the designs. Further work is also required in determining core performance as a function of fuel burnup.

### 2. Fuel and Material Properties

Initial work was directed toward the development of a low alloy metal fuel which would exhibit radiation stability at reasonable lifetimes. From these studies has evolved the U–3.5 wt. percent Mo plus 0.5 wt. percent Si, and U–3.5 wt. percent Mo+0.1 and 0.5 wt. percent Al alloys. These alloys have been operated up to 3,000 MWD/T without distortion and 10,000 MDW/T is expected to be attainable.

Recent work on organic reactor fuel elements has been devoted to an investigation of $UO_2$ clad with aluminum powder metalurgy (APM) materials. Tests to date indicate that these cladding materials exhibit significantly higher strength than aluminum alloys at elevated temperature, exhibit satisfactory radiation stability, are compatible with $UO_2$, do not suffer from porosity, can be fabricated into the desired shapes, and can be joined satisfactorily utilizing welding techniques. As of this date, full-size prototype fuel elements of $UO_2$ APM materials have not been fabricated nor has full-scale in-pile testing been started.

### 3. Heat Transfer and Fluid Flow

Correlations of heat transfer data have been obtained from limited duration tests over the range of surface temperatures from 600° to 900° F. These tests have indicated that under suitable conditions of forced convection heat transfer, the surface condition and temperature is stable. Limited tests on determining the burnout heat flux have been completed but much additional work remains. The determination of the true burnout heat flux is complicated by the fact that the organic, under reactor operating conditions, is a completely miscible variable mixture of organic compounds.

Limited nucleate boiling data have been obtained with one run of 1,500 hours which indicates there is an initial decrease in heat transfer coefficient but that after 900 to 1,000 hours, the coefficient stabilizes at a value approximately 10 to 12 percent below the initial value.

Considerable further work in all phases of forced convection and boiling heat transfer, including the accurate determination of burnout heat fluxes, must be completed prior to the operation of large organic-cooled power reactors.

### 4. Coolant Chemistry

The AEC-sponsored programs to date have yielded considerable information on the physical properties of materials useful as coolants. To date the investigations have been limited primarily to the polyphenyls, benzene derivitives. Information is available for both unirradiated and irradiated material. Operation of the OMRE has demonstrated the negligible activation of the coolant under operating conditions and the extremely small corrosion rates throughout the primary system.

### 5. Safety

Organic moderated reactors have large negative temperature coefficients, negative void coefficients, and negative power coefficients.

The physical properties of a coolant are such that there is negligible corrosion of either reactor or fuel materials; there are no exothermic chemical reactions between the coolant, fuel, or water; there is low induced radioactivity; and the system operates at low pressures due to the low coolant vapor pressure.

### 6. Component and Auxiliary Systems

Many components utilized in the organic system are of standard manufacture and have been utilized for several years in the petroleum industry. These items require no or very limited modification to be acceptable. Process system design results to date have been obtained primarily in laboratory scale mockups. Quarter-size mockups of the Piqua systems are now being completed for testing and evaluation. A magnetic jack control rod has been developed and successfully tested.

### 7. Fuel Handling

Work on fuel handling systems applicable to large organic power plants have been limited to design studies and the development of the Piqua refueling system. The Piqua refueling system has been mocked up and tested successfully. Further work is indicated in this general area prior to the operation of a large organic-cooled plant.

* * * * *

The only operating organic-cooled reactor, the OMRE, was placed into operation in 1957 and has been operated continually since except for a period of time to change to a second core loading. The operation of the reactor has demonstrated the organic radiation decomposition rates to be expected, the low induced activity, the low corrosion rates, and the technical feasibility of designing and operating organic cooled reactor plants. In all respects the plant has behaved as anticipated without occurrence of any unforeseen problems.

Design studies on organic-cooled reactors have been completed by Atomics International, Brookhaven, Hanford, and Canadian G.E. These studies encompass organic-cooled and -moderated reactors, graphite-moderated organic-cooled reactors, and heavy-water organic-cooled reactors. The design features of these plants are summarized in some detail in the main body of the report. It is significant to note however, that the latest design study on organic moderated and cooled reactors, based on the use of aluminum powder metallurgy-clad $UO_2$ fuel elements, having indicated significantly lower power costs, of the order of 7 to 7.5 mills/kwh for a 300-Mwe unit, than have generally been quoted previously.

At present the only organic-cooled reactor under construction is the Piqua plant, a unit rated at 11.4 Mwe. This plant is scheduled to go into operation the latter part of 1961. The Piqua plant is conservatively designed to operate under modest conditions. Steam is to be produced at 450 psia and 550° F. with a reactor coolant outlet temperature of 575° F. and a maximum fuel element surface temperature of 750° F. The operation of the Piqua plant will supply invaluable information on process system performance, plant control and stability characteristics, and further information on coolant and fuel element performance.

# II

# CONCEPT DESCRIPTION

## A. HISTORY

The use of an organic fluid as moderator, coolant, or combination moderator-coolant in a reactor has received consideration since the period of the work on the wartime Manhattan Project. In December 1944, Fermi and Szilard filed one of the first basic patents in the nuclear field (1) which contained the following:

> "... Diphenyl can also be used as a moderator and closely resembles light water giving a gain from 0.2 to 0.4 percent in k. With either, a slight enrichment of the uranium with one of the fissionable isotopes such as, for example $U^{233}$, $U^{235}$, $94^{239}$ will provide a k sufficiently greater than unity, to enable the construction of operating reactors. . . ."

The organic reactor concept was not actively pursued for almost 10 years, presumably due to the fact that this type of reactor cannot operate on natural uranium, and to the lack of knowledge concerning the degree of chemical instability of organic fluids in the combined thermal and radiation environment of a reactor core.

Interest in organic fluids for use in reactors was revived when enriched uranium became more available in the early 1950's. Work commenced independently at several laboratories in the United States to determine the stability of organics under the influence of radiation and high temperature. Experiments were conducted using radiation from $Co^{60}$, Van de Graaff generators, irradiated fuel elements and in-pile test facilities. Many different classes of organic materials were studied under temperature conditions ranging from room temperature to about 1,000° F.

The first general conference in the field of organics as applied to nuclear reactors was held in August 1953, in Downey, Calif. It was found that considerable qualitative agreement existed concerning the relative stability of organic compounds. The aromatic materials were reported to have exhibited the greatest stability under irradiation. The 1953 meeting marked the transition from the general exploratory phase to a better organized and more systematic study of the aromatic hydrocarbons. Since that time most attention has been devoted to the polyphenyls for possible use in nuclear reactors. These polyphenyls include diphenyl and the terphenyl isomers, as well as commercial mixtures of these compounds.

During the period from 1955 to 1958, test loops circulating organic fluids have been operated, both in-pile and out-of-pile. The most extensive in-pile loop experiments were performed at the Materials Testing Reactor (MTR) at the National Reactor Testing Station in Idaho (2, 3). Additional in-pile work was done by Monsanto Chemical Company at Brookhaven (4) and by Hanford Research Laboratories at Hanford (5). The out-of-pile loop experiments have been primarily directed toward the measurement of heat transfer and hydrodynamic characteristics of organic coolants. This work was done both at Atomics International (6) (forced convection studies) and Aerojet-General (1) (burnout studies).

In addition, a large scale test of an organic fluid has been conducted in the OMRE. This experience has proved the technical feasibility erated Reactor Experiment (OMRE). This of the use of an organic fluid as moderator, coolant, or both. Bulk temperatures in the range of 600° to 700° F. can be used with only negligible amounts of thermal decomposition of the organic.

Physical property changes resulting from radiation decomposition and the accompanying increase in the content of higher polymers have been measured, as well as the more important physical properties for the organic fluids of interest. Within the range studied, the decomposition products have been completely soluble in the original material. The radiation decomposition rates have been determined to decrease as the equilibrium polymer content increases. Reactor designs using organic fluids have always been based on operation with an organic fluid containing some significant amount, approximately 30 percent, of this higher polymer in the circulating fluid.

There has been no evidence of deposition on heat transfer surfaces which might result in decreased heat transfer rates where the surface temperature was maintained below about 850° F. and the fluid velocity exceeded a few feet per second. The heat transfer characteristics of the irradiated polyphenyls have been measured and determined to be predictable for long time operation within the range of reactor operating conditions of interest.

The design and construction of the OMRE was undertaken beginning in mid-1955 because of the recognized need for the test of an organic fluid under actual reactor operating conditions. The construction of the OMRE was completed 2 years later. The OMRE installation included no provisions for the generation of electrical power, and the heat produced is dissipated to the atmosphere in air-cooled exchangers. Maximum design power is 16 Mwt. Full-scale operation began in February 1958 following the critical experiment and low-power physics measurements, and by January 1, 1959, the unit had logged over 22 million kwh operation. A number of experiments have been conducted in the OMRE, and operation has been almost continuous, except for a period of several months near the end of 1958, when a new core was installed. Operation with this new core is presently underway at maximum design conditions.

Considerable information from the OMRE operation has been obtained on the organic coolant stability and on the heat transfer conditions in the core, as previously discussed. In addition, radiation levels around the plant have been determined to be extremely low, confirming the most optimistic predictions. Observations have also confirmed the fact that corrosion rates, even on the carbon steel used in the organic circulation system, are negligible. The electrical system for heating the piping and components containing organic was found simple and reliable in operation. Similarly, operation of the single stage distillation system for purifying the organic and maintaining equilibrium coolant composition has proved to be straightforward. For experimental purposes the polymer content in the organic was varied over a wide range, to as high as 40 percent. No unexpected difficulties of a significant nature have been encountered during the operation of the OMRE.

Construction of an Organic Moderated Reactor (OMR) for the City of Piqua, Ohio, is currently underway. The plant is to develop steam at 450 psia and 550° F., and at a flow equivalent to the generation of 11.4 net Mwe. A development program has been in progress for some time to develop certain information specifically needed for the Piqua OMR. This work has included investigations of the coolant material, fuels, core physics, heat transfer, and the design of certain components. Results of these investigations are referred to in subsequent sections of this report.

In addition to the development work for the Piqua OMR, a separate program, referred to as the Advanced OMR Program, is being conducted by Atomics International for the AEC. In general, the projects within this program are of a more basic or longer range nature, intended to develop technology required for the OMR concept. The AEC has also sponsored a limited amount of research and development work on organic fluids at installations other than Atomics International. The principal results of the Advanced OMR Program at Atomics International and of the investigations carried out on organic fluids by other organizations are referred to in subsequent sections of the present report.

In addition to the Piqua OMR program, a number of design studies, covering a range of plant sizes from 10 Mwe to 300 Mwe and extending into special applications such as ship propulsion and the utilization of alternate moderators, have been completed at Atomics International. The most recent of these, a joint effort of Atomics International and the Bechtel Corporation sponsored by the Atomic Energy Commission, resulted in the design of 75- and 300-Mwe capacity organic-cooled reactor plants. This project has shown that organic-moderated and -cooled reactor plants have excellent potential as large, baseload, central station power plants.

## B. CONCEPT

### 1. General Description

All of the OMR systems considered to date fall into the general category of "thermal converters." This is largely due to the fact that the parasitic absorption introduced by the use of hydrogen as a moderator causes a sufficient loss of neutrons to prevent either successful breeding or operation with natural uranium. Due to the presence of hydrogen in the core, the spectrum of the fission-causing neutrons lies primarily in the thermal region.

The excellent neutron moderating properties of the hydrogen in hydrocarbon liquids make possible compact core designs. Additional simplicity in core design is provided by utilizing the organic fluid both as the moderator and coolant. As a result of this simple and compact arrangement, costs for reactor structure and shielding in organic reactors can be maintained at a low level. Since the diffusion length in organic moderators is more than 1.5 times that in water, there is no mechanical limitation which prevents the utilization of optimum lattice spacing to achieve good nuclear performance in organic reactor cores. In addition, core operating pressures need not be high to attain temperatures consistent with high thermodynamic efficiency since liquid hydrocarbons have very low vapor pressures at elevated temperatures. This fact removes any size limitation from the design of organic reactors.

Use of the organic fluid permits a wide choice of nuclear fuels. Uranium can be used in the form of the metal or alloy, oxide, or carbide without introducing the potential hazards of exothermic chemical reactions. Corrosion rates on these materials are negligible. The use of high burnup ceramic fuels is particularly suitable to organic systems.

For cladding, principal attention has been given to aluminum alloys and aluminum powdered metal (APM). The greatest limitation in fuel element designs comes about as a result of the relatively poor heat transfer properties of the organic fluid. As mentioned previously, shapes integrally extruded with the aluminum cladding may be employed to alleviate this situation. Designs are being developed which use both nonboiling forced convection and subcooled nucleate boiling conditions in the core.

In all cases, heat from the reactor is carried by the organic fluid to heat exchangers where steam is produced and superheated. With this arrangement the steam is nonradioactive and can be produced at relatively high pressure and temperature conditions. The noncorrosive characteristics of the coolant permit the use of many conventional materials of construction. Piping and vessels are low-carbon steel joined by bolted flanges wherever convenient. Similarly, there are few special requirements for components used in the organic circulation system. This contributes to low maintenance costs as well as low initial capital investment.

The organic coolant does require that the plant design incorporate provision for degasification, purification, makeup, and eventual disposal of the used organics. The design and operation of the equipment required for these functions appears to be straightforward but admittedly adds complications. The terphenyl mixtures recommended as the virgin coolant are available in large quantities and are relatively inexpensive. As a result, the cost of this new makeup material in a practical power reactor is approximately 0.7 mills per kwhe, based on current prices. This contribution to power generation costs is expected to be reduced with future developments.

In any design the organic circulation system must be shielded, but the maximum radioactivity levels in the operating coolant are relatively low. This is one of the advantages of an easily purified coolant composed of carbon and hydrogen.

Like most organic materials, the polyphenyls are flammable, but because they have rather high spontaneous ignition temperatures (approximately 1,000° F.), they are not particularly hard to handle. Flammable mixtures of polyphenyl cannot be obtained in air by vaporization at normal ambient temperatures. There is insufficient vapor for ignition by a spark or flame at temperatures below 230° F. for diphenyl and 415° F. for terphenyl. Ordinary refinery practice and precautions are effective in preventing fires. Handling polyphenyls at normal ambient temperatures presents no health hazard since the atmospheric concentrations existing at these conditions are extremely low. Nominal precautions are required at high temperatures.

There is a basic limitation on the upper temperatures at which present-day organic materials may be used. This limit is in the 900° to 1,000° F. range, where thermal decomposition becomes excessive even without nuclear radiation. It appears that organic fluids will find their greatest use in nuclear reactors in the temperature range from 500° to 800° F.

## 2. Alternate Moderators

It is possible to consider the use of moderators other than an organic fluid when used in a reactor cooled by an organic. Such an arrangement has the advantage of decreasing the amount of organic material in the core, and hence reducing the cost of new makeup material. There is, of course, always the compensating factor of the additional complication required in the reactor design. Reactors employing organic as moderator as well as coolant are designated OMR's or OMCR's whereas OCR is a term applied to any reactor cooled with organic fluids.

In a recent study on a large optimized organic-cooled reactor, this problem of alternate moderators was considered. The possible use of graphite, heavy water, light water, beryllium, beryllium oxide, and zirconium hydride as moderators was considered in addition to that of the organic fluid itself. It was concluded that while the organic fluid offered the greatest potential, graphite as a moderator in an organic-cooled power reactor appeared superior to the remaining choices and capable of performance approaching that of the use of the organic. These selection studies are discussed in Section III.

A somewhat similar type of evaluation was conducted at the Brookhaven National Laboratory (8) investigating graphite and $D_2O$ in addition to organic fluids as possible moderators in an organic-cooled power reactor. The conclusions were quite similar to those obtained during the study just described, although the BNL evaluation gave a slight first preference to the use of $D_2O$ moderator.

Consideration has been given by the General Electric staff at Hanford (9) to the possibility of a large graphite moderated and organic cooled combination production and power reactor. These studies also show merit in the graphite-organic type of reactor.

In a study for the AEC of a large $D_2O$ moderated power reactor by Sargent and Lundy and Nuclear Development Associates (10), the possibility of alternate coolants was considered.

These coolants included heavy water, light water, gases, and organic fluids. The comparative figures developed showed the $D_2O$ moderated, organic-cooled system to be an inferior choice. Highest performance was estimated for a $D_2O$ moderated and cooled reactor in which the $D_2O$ coolant was permitted to boil. The different assumptions used in the course of this study make the results difficult to compare with others which have been obtained. The poor performance of the organic-cooled arrangement appeared to be largely due to the choice of coolant operating temperatures in a much lower range than has normally been considered for organic-cooled reactors.

Serious attention has been given to the $D_2O$ moderated, organic-cooled power reactor by the Canadian General Electric Company (11). Their design incorporates the use of high organic temperatures and is also based upon the use of natural uranium fuel. The performance claimed by the Canadian General Electric group for the $D_2O$-organic power reactor is very high but there are admittedly several unanswered development problems peculiar to this proposed design.

# III

# WORK STATUS

## A. RESEARCH AND DEVELOPMENT PROGRAM

### 1. Physics

#### *a. Work Completed*

The physics of organic-moderated reactors follows closely that of the water-moderated reactors. However, just as there is a decided distinction between nonboiling and boiling water reactors, so do the organic reactors differ from water reactors in the physics design. The hydrocarbons which have thus far been considered for organic coolant-moderators (principally mixtures of isomers of the polyphenyls) have approximately the same density as water, yet because of their molecular structure they have approximately half the hydrogen density of water (see figs. 1 and 2). Carbon, on the other hand, replaces the oxygen on a nearly equal basis. The difference in hydrogen density results in both a greater slowing-down length and a greater thermal-diffusion length. These two quantities have a pronounced effect on core design, particularly with regard to neutron leakage in the case of the former, and the geometrical arrangement and dimension of heterogeneous lattices in the case of the latter. Generally speaking, the optimum nuclear design of lattices results in a greater volume fraction of organic (5:1) than a comparable optimum nuclear design of a water lattice (1:1). Optimum lattice spacing is easily obtainable in organic-cooled reactors.

Much of the early work in the physics of organic-moderated reactors was necessarily directed toward the determination of age, $\tau$, and diffusion length, $L^2$. In a preliminary design study of an organic-moderated reactor, Fricke (12) of Argonne National Laboratory utilized the Marshak method (13) to determine the Fermi age of diphenyl. This work with adaptation to account for a mixture of diphenyl and stainless steel was used early in the analysis of the OMRE (14). Because of the small size of the OMRE and the obvious sensitivity of reactivity (or core loading) to the value of age, Atomics International undertook in 1956 the experimental determination of both age in pure diphenyl and the age in diphenyl-steel mixtures (15) up to organic-to-metal volume ratios of 5 to 1 (fig. 3). Conerty (16) of Knolls Atomic Power Laboratory compared calculated ages in diphenyl with those measured at Atomics International. The agreement with experiment was similar to that of water age comparison, wherein the consistent P–1 calculation ($\tau=46.3$ cm$^2$) is markedly lower than experiment ($\tau=54.2$ cm$^2$), while the Selengut-Goertzel approximation gives fair agreement with experiment ($\tau=52.2$ cm$^2$). In diphenyl at 600° F., $\tau=92$ cm$^2$ (14).

OMR flux distribution measurements have been made on two square lattices, one having 12 aluminum-clad, slightly-enriched (1.875 percent) uranium plates per 5¼-inch square element, the other having 10 such plates per element, and both having a 6-inch element spacing. Analysis of these measurements gives thermal utilization values of 0.832±0.004 and 0.812±0.003, respectively. For comparison, a calculation based on two-group diffusion theory gives 0.8447 and 0.8227 for these values.

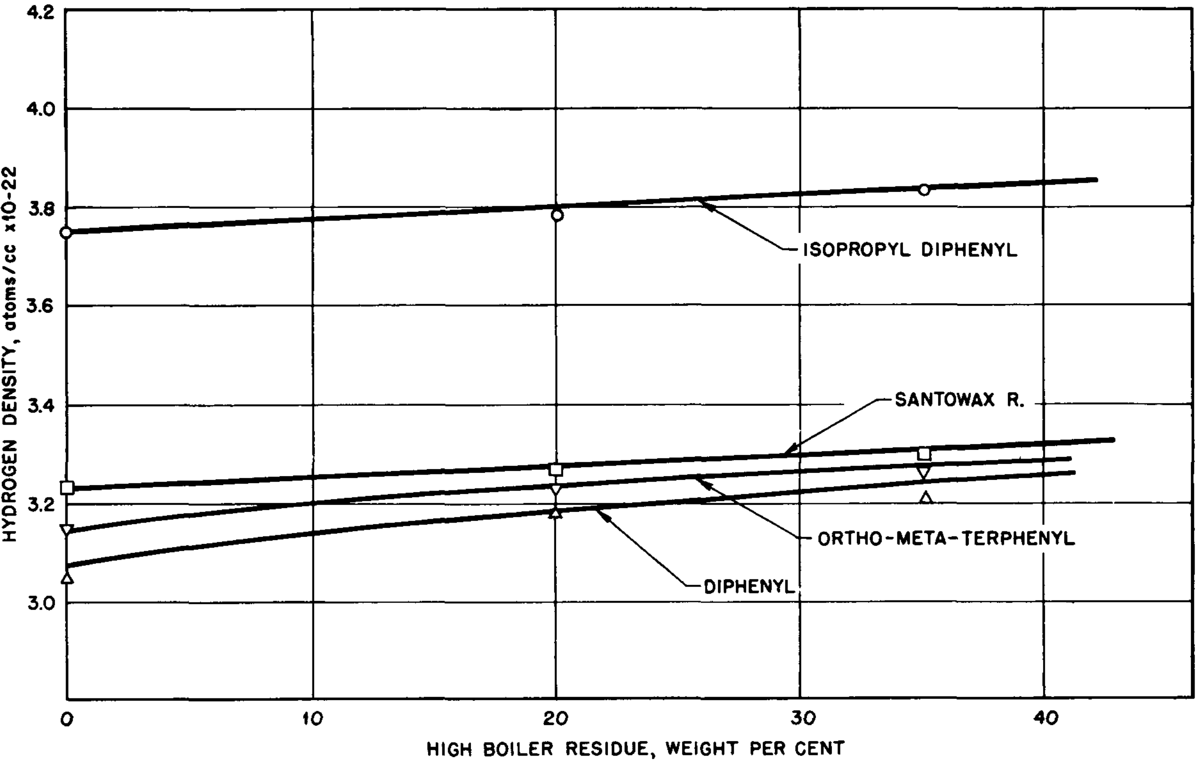

FIGURE 1.—*Hydrogen density of irradiated coolants.*

Critical mass estimates for the two lattices were made from inverse multiplication measurements, giving a critical size of 14.7 elements for the 12-plate lattice and 11 elements for the 10-plate lattice, corresponding to critical masses of 27.8 kg and 17.3 kg of U–235, respectively. Both of these values are lower limits. Theoretical calculations using two-group diffusion theory predict 12.85 elements and 12.82 elements, respectively. The critical mass of the 12-plate element lattice is higher than the critical mass for the 10-plate element lattice, even though the thermal utilization values would indicate the reverse. This is because the resonance escape probability is much lower for the 12-plate element. The diffusion length of the moderator was measured to be 4.32±0.12 cm. Theoretical calculations using measured cross section data give 4.25 cm. These values and those of the preceding two paragraphs are for a temperature of 27° C. (~80° F.). The moderator is a mixture of 68 percent terphenyl, 25 percent diphenyl, and 7 percent other polyphenyls (17).

The analysis of reactor power peaking has been based primarily on the results of machine calculations (IBM–709). A one-dimensional burnup code was used in conjunction with one- and two-dimensional steady-state reactor codes. The composite results of these calculations is shown in figure 4. The total power peaking factor for an OCR core is given as a function of operating time. For the initial hot, clean core the peak-to-average power ratio is 1.96. At the end of the first core life, this peaking factor has increased to 2.78. During the life of the subsequent core loadings, the total power peaking varies from 1.96 to 2.68.

The OMRE utilizes an adaptation of an Army Package Power Reactor (APPR, now designated SM–1) fuel element, the essential difference in core design being an organic space

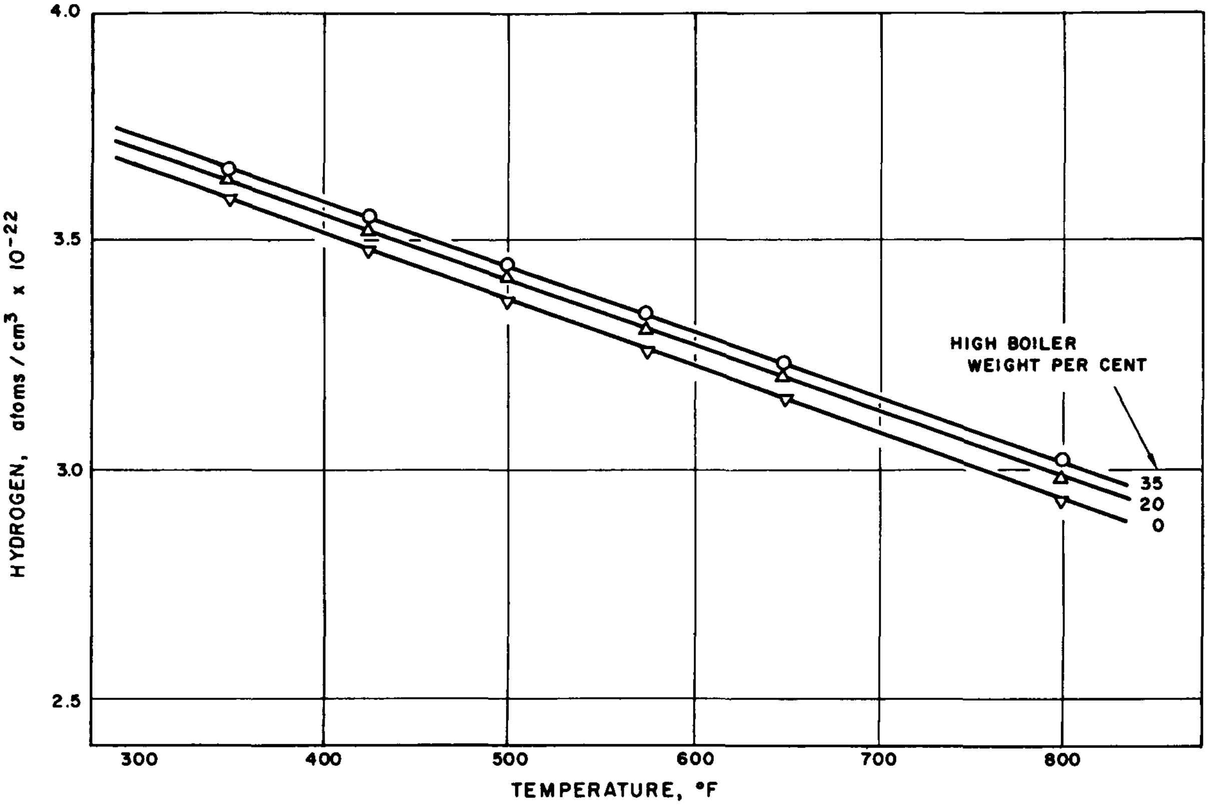

FIGURE 2.—*Hydrogen density of irradiated Santowax R.*

between fuel elements in the OMRE, and practically no space between elements in the SM–1. Additional volume of organic is necessary because of the greater migration area of the organic system. During the early operation of the OMRE, certain experiments were performed which provide some correlation with analysis. The critical mass of the OMRE was 16.5 kg, the calculated critical mass being 26 percent too low (18). Since this was the first critical assembly of an organic-moderated reactor, the lack of agreement was not unreasonable. Additional measurements performed on the OMRE were directed toward a rather detailed determination of temperature and power coefficients, the measurement of void and mass coefficients of reactivity, and the measurement of intracell fluxes. While it may generally be said that the agreement between analysis and experiment was satisfactory with respect to the design of the OMRE (18), the need for additional measurements in organic-moderated assemblies was certainly obvious.

Additional experimental work has taken two approaches. The measurement of bucklings and intracell fluxes in an exponential assembly provides much useful data for the comparison of analytical methods being utilized for the lattice analysis. On the other hand, a critical assembly provides data on temperature coefficients, control rod worths, critical masses and the like which provide even further comparison between experiment and theory.

Because of the immediate availability of the thermal column on the water boiler neutron source reactor, the bulk of the lattice studies which have been conducted to date have been of the exponential type. Buckling measurements have been made on both natural uranium assemblies and slightly enriched (0.912 a/o) fuel (15). These measurements are shown in figure 5. Comparison of measured cell fluxes with fluxes calculated in the $S_4$ approximation to the transport equation is shown in figure 6. Later, measurements of intracell fluxes in a slightly enriched flat plate fuel assembly were made and compared with the $S_4$ approximation. These results are shown in figure 7.

While the agreement between theory and experiment is seen to be rather satisfactory in these latter cases, they are simple geometries and the agreement does not ensure complete confidence in the analytical approaches presently being employed.

Comparison of the theoretical calculation of the multiplication factor, $k_{eff}$, to the measured one at the OMRE is shown in figure 8.

### *b. Work Underway*

With the completion of construction of the Organic-Moderated Reactor Critical Facility, the current experimental work is being directed toward the determination of critical masses, control rod worths, and temperature coefficients

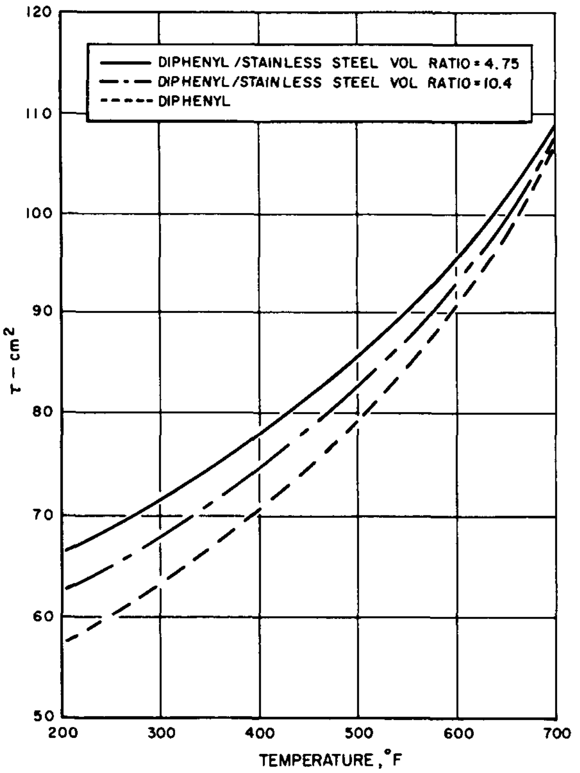

FIGURE 3.—*OMRE Fermi age.*

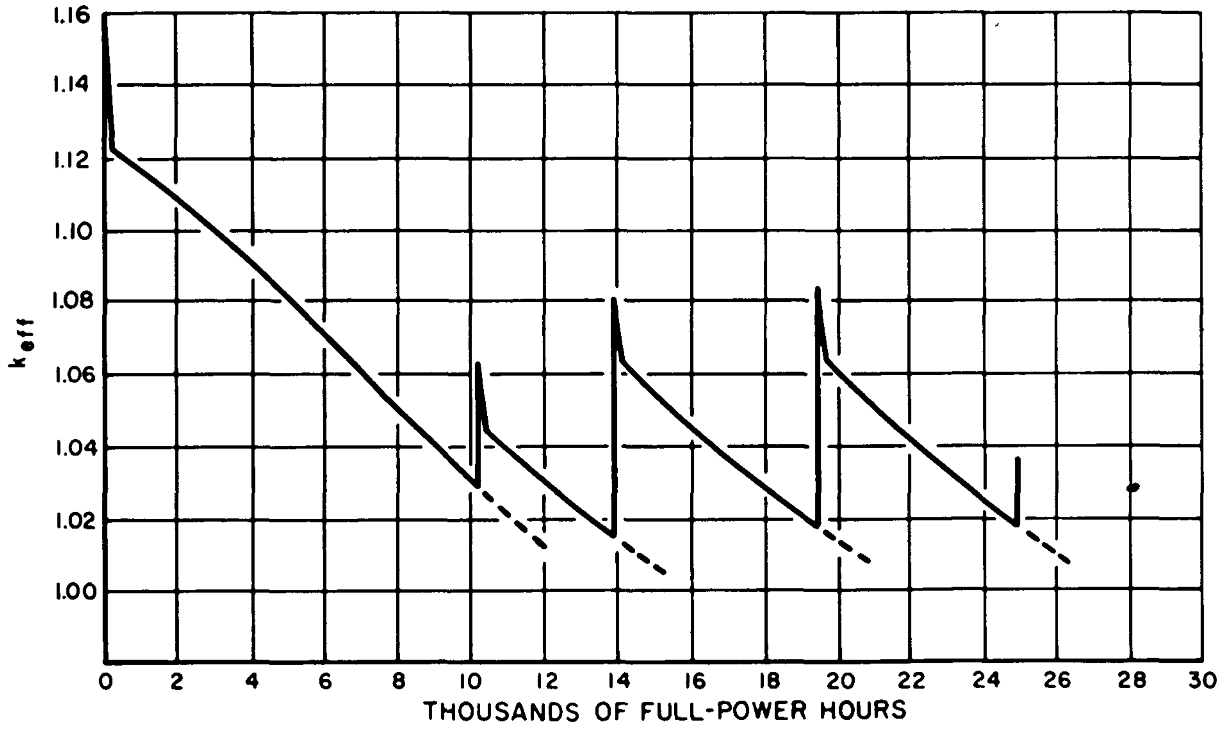

FIGURE 4.—*Effective multiplication during operation.*

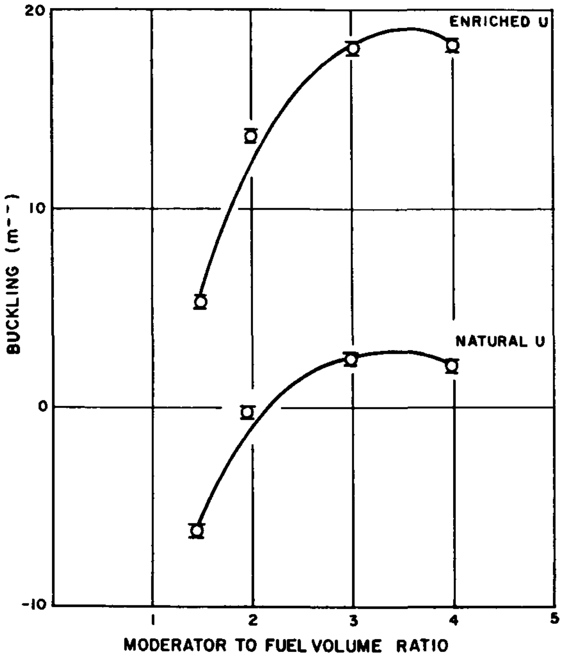

FIGURE 5.—*Buckling of diphenyl moderated uranium lattices.*

of reactivity in flat-plate fuel assemblies. The initial critical loading of the OMR critical facility was 15 percent higher than predicted, and analysis of the assembly is continuing to explain the observed differences in mass. Since the methods in current use for the analysis of the Piqua OMR and other OMR designs being conducted are essentially similar to those employed in the analysis of the critical assembly, the present work is still directed toward a more accurate prediction of reactivity and critical mass.

## 2. Fuel and Material Properties

### *a. Work Completed*

### (1) FUELS

### (a) *Uranium Alloy Fuels*

A proposed fuel element for organic moderated reactors consists of a finned, aluminum-clad fuel plate contained in a square steel box.

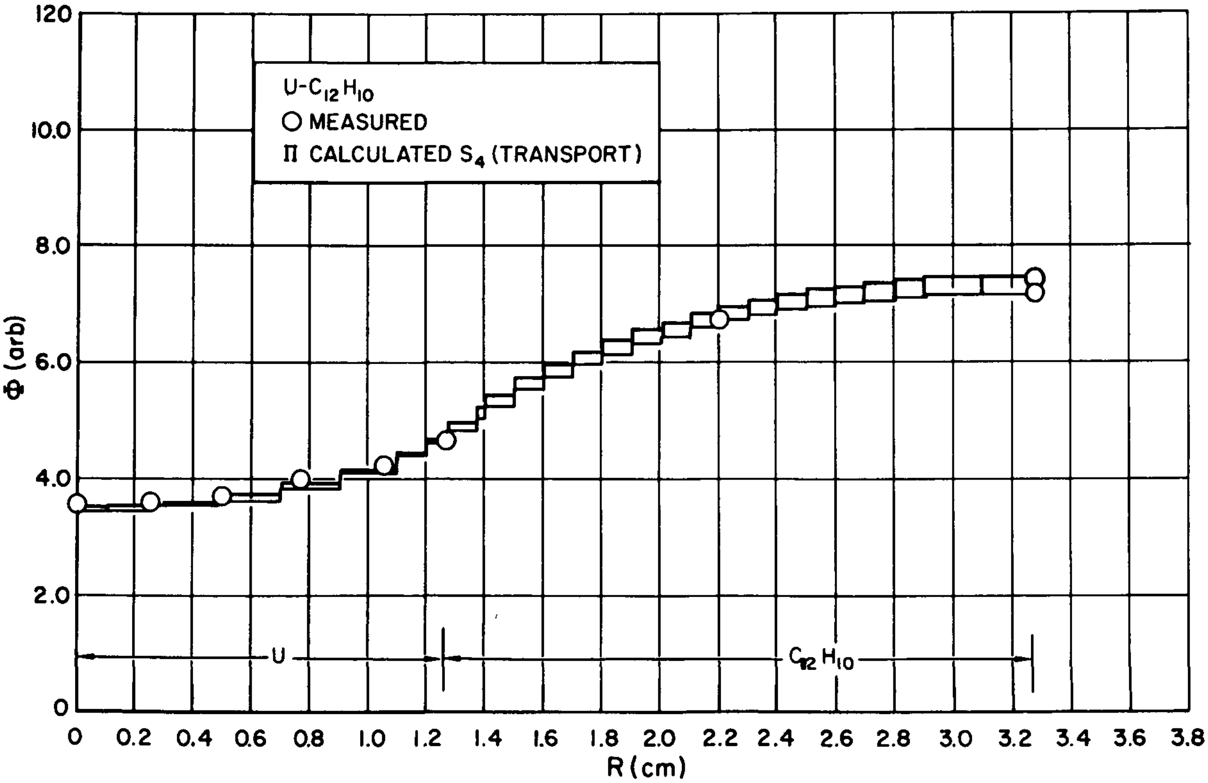

FIGURE 6.—*Flux distribution in a natural uranium rod in diphenyl.*

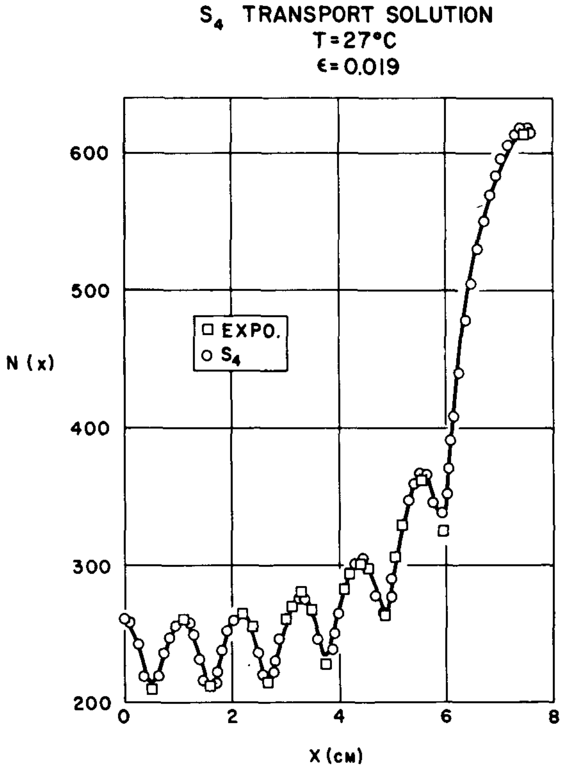

FIGURE 7.—*Flux distribution in an OMR 12-plate fuel element in diphenyl.*

Under OMR operating conditions, the maximum central temperature of the fuel will be about 850° F. Five uranium-molybdenum base alloys are being evaluated as potential fuels for these reactors. The nominal compositions are the binary U–3.5 wt percent Mo, U–3.5 wt percent Mo plus 0.1 and 0.5 wt percent Si, and U–3.5 wt percent Mo plus 0.1 and 0.5 wt percent Al. These alloys were cast as plates 2½ inches wide by 13 inches long of two thicknesses, 0.130 inch and 0.150 inch. Charges were melted in a MgZrO-washed graphite crucible and cast in a gang-type graphite mold, also coated with $MgZrO_2$. Six to eight plates were cast simultaneously from a single heat. These plates are cast to design thickness tolerances of ±0.003 inch for direct application in Al-clad extended-surface fuel plates without further sizing operations.

Some mechanical properties have been determined for these alloys in the as-cast, preirradiated condition. The results of creep and tensile tests at 900° F. plus hardness tests at room temperature are summarized in Table 1. The two Al-bearing alloys exhibited the highest resistance to creep, both having secondary creep rates of less than 0.003 percent per hour at stresses up to 20,000 psi, and the 0.1 percent Al alloy had a creep rate of 0.006 percent per hour at a stress of 40,000 psi. U–3.5 wt percent Mo–0.5 Si, U–3.5 wt percent Mo–0.1 wt percent Si, and the binary U–3.5 wt percent Mo followed in descending order. However, the creep resistance of all alloys exceeded that of unalloyed uranium by a factor of 5 or greater.

In tensile properties at 900° F., the U–3.5 wt percent Mo–0.1 wt percent Al alloy had the highest tensile strength, 110,000 psi, and yield strength, 80,600 psi (0.2 percent offset). However, all alloys exceeded the tensile and yield strength of unalloyed uranium (16,700 and 11,900 psi respectively) by a factor of 4 or greater. Ductility was low for all alloys, varying from about 4 percent in 2-inches for U–3.5 wt percent Mo to less than 0.2 percent for U–2.5 wt percent Mo–0.5 wt percent Al.

Thermal cycling tests were made for two temperature ranges: (1) between room temperature and 1,300° C., which included the phase transformation from alpha to gamma, and (2) between room temperature and 900° or 1,000°

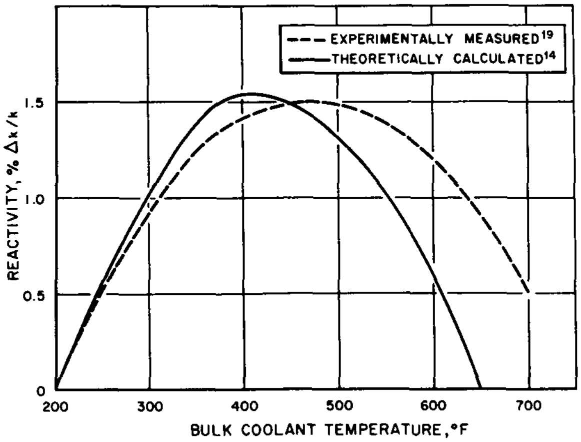

FIGURE 8.—*Effect of temperature on reactivity of OMRE core.*

### TABLE 1

### SUMMARY OF MECHANICAL PROPERTY DATA FOR U-3.5 W/O Mo BINARY AND TERNARY ALLOYS

| | U-3.5 Mo | U-3.5 Mo—X Si | | U-3.5 Mo—X Al | | Unalloyed U |
|---|---|---|---|---|---|---|
| | | 0.5 | 0.1 | 0.5 | 0.1 | |
| Secondary creep rates, %/100 hr for stress given at 900° F.: | | | | | | |
| 2,500 psi | | | | | | † 1. 9 |
| 5,000 psi | 0. 55 | | 0. 43 | | | † 3. 3 |
| 8,000 psi | 0. 70 | 0. 38 | 0. 95 | | | |
| 10,000 psi | 1. 35 | 0. 40 | 1. 81 | 0. 34 | 0. 25 | |
| 12,000 psi | 2. 28 | | | 0. 22 | 0. 25 | |
| 15,000 psi | | 0. 46 | | 0. 29 | | |
| 20,000 psi | | 0. 75 | | | 0. 27 | |
| 30,000 psi | | 2. 1 | | | 0. 29 | |
| 40,000 psi | | | | | 0. 61 | |
| 50 000 psi | | | | | 2. 60 | |
| Tensile properties at 900° F.: | | | | | | |
| Ultimate strength, psi | 87, 800 | 79, 500 | 71, 900 | 51, 900 | 110, 100 | 16, 700 |
| Yield strength, psi | | | | | | |
| 0.2% offset psi | 56, 100 | 59, 800 | 55, 000 | (*) | 80, 600 | 11, 900 |
| 0.1% offset psi | 45, 000 | 57, 700 | 42, 400 | (*) | 64, 800 | 10, 500 |
| 0.02% offset psi | 29, 900 | 35, 800 | 23, 600 | 45, 300 | 42, 800 | 9, 000 |
| Elongation in 2 in., percent | 3 | 1. 5 | 0. 5 | 0. 2 | 1. 4 | 14. 5 |
| As-cast hardness at room temperature | 38 $R_c$ | 42 $R_c$ | 45 $R_c$ | 45 $R_c$ | 43 $R_c$ | 90 $R_B$ |

*Not measurable because of low ductility.
†Reference BMI-1936 (Data for 500° C.).

F., which did not include any transformation but did more nearly simulate reactor conditions. U-3.5 wt percent Mo-0.5 wt percent Si exhibited the greatest thermal stability in these tests while the U-3.5 wt percent Mo and U-3.5 wt percent Mo-0.1 Al had the poorest stability of the alloys. No significant distortion or growth was observed for any of the alloys for the 900 to 1,000° F. test after 300 cycles, while reference specimens of unalloyed specimens were severely warped. In the more severe 1,300° F. test, the reference specimens of U-2 wt percent Zr—0.1 Al and unalloyed uranium were grossly distorted after 95 cycles along with significant change in dimensions, while no distortion occurred in Mo-bearing alloys and dimensional changes were less than 1 percent.

Two of these alloys, U-3.5 wt percent Mo and U-3.5 wt percent Mo-0.5 Si, were selected as the fuels for two OMR-type fuel elements tested in OMRE. The stability of these alloys under irradiation was evaluated early in 1959. This experience relates to the cladding failure of an OMR-Piqua element in the OMRE under conditions where the cladding melted due to a blocking of one of the cooling chambers. The core material was exposed to organic coolant at a maximum fuel surface temperature of 750° F. No catastrophic damage to the fuel was noted on hot-cell examination (25). A third alloy, U-3.5 wt percent Mo-0.1 wt percent Al, has been selected for another OMR-type fuel element presently in the OMRE. Table III-2 summarizes the effects of irradiation on low alloy U fuels.

### TABLE 2

### EFFECTS OF IRRADIATION ON BULK $UO_2$

(Zircaloy Clad)

| Specimen No. | Heat flux Btu/hr-sq. ft. × $10^{-3}$ | Burnup Mwd/t | Calculated central temperature (°F.) | Tubing OD | Overall length | Dimensional changes | | $UO_2$ center |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Diameter | Length | |
| 12H | 170 | 1, 800 | 2, 318 | 0. 402 | 5. 240 | 0 | 0 | Not melted. |
| 13H | 300 | 3, 800 | 3, 992 | 0. 401 | 5. 239 | 0 | 0 | Not melted. |
| 16H | 340 | 4, 200 | 4, 388 | 0. 402 | 5. 238 | 0 | 0 | Not melted. |
| 17H | 250 | 2, 700 | 3, 330 | p. 401 | 5. 238 | 0 | 0 | Not melted. |
| 14H | 220 | 4, 400 | 2, 912 | 0. 402 | 5. 249 | 0 | 0 | Not melted. |
| 15H | 370 | 10, 900 | 4, 802 | 0. 402 | 5. 237 | 0 | 0 | Not melted. |
| 18H | 420 | 13, 500 | 4, 982 | 0. 400 | 5. 240 | 0 | 0 | Not melted. |
| 19H | 300 | 6, 900 | 3, 992 | 0. 402 | 5. 238 | 0 | 0 | Not melted. |
| 82S | 330 | 14, 000 | 4, 320 | 0. 414 | 5. 205 | 0 | 0 | Not melted. |
| 83S | 540 | 22, 000 | 4, 982 | 0. 414 | 5. 222 | +0. 012 | 0 | 0.200 hole. |
| 84S | 600 | 25, 000 | 4, 982 | 0. 414 | 5. 224 | +0. 015 | 0 | 0.230 hole. |
| 85S | 300 | 12, 000 | 3, 992 | 0. 414 | 5. 206 | 0 | 0 | Not melted. |

### (*b*) *Oxide Fuels*

The characteristics that make $UO_2$ one of the most interesting fuel materials are by now well known, so the following enumeration of the most important ones should suffice:

(1) High melting point (~5,000° F.).
(2) Chemical stability with most reactor coolant,
(3) Compatibility with a wide variety of cladding materials, and
(4) An isotropic structure stable under irradiation at temperatures up to the melting point.

Unfortunately, $UO_2$ is far from being an ideal fuel material and has some serious shortcomings, among them a rather low content of uranium per unit of volume, namely, only 51 percent of uranium metal. This makes it necessary to densify $UO_2$ for fuel element use to at least 92 percent but preferably to over 95 percent of its theoretical density. There are a number of methods of densifying uranium dioxide. Among them are hot pressing and warm pressing both of which, while offering certain advantages, are uneconomical. Other methods are swaging or cold pressing and sintering.

Techniques for the fabrication of ceramic fuel elements by vibratory compaction and swaging of powders have been investigated. Vibratory packing studies, using a three-particle size system, resulted in a maximum vibrated density of 9 gm/cc or 82.2 percent of the theoretical density by warm swaging at 600° C.

Various binders, lubricants and granulations suitable for automatic pressing of $UO_2$ were investigated. 1 wt percent of polyvinyl-alcohol added dry, followed by granulation with approximately 10 wt percent water, drying at 80° C., passing through a 6-mesh screen, and coating with ¼ wt percent zinc stearate as a lubricant was found to give a granulation with the best pressing properties. Pellets pressed of this granulation with 10 tsi had, after sintering at 1,700° C. in hydrogen, a density of 95 to 96 percent of theoretical density.

High burnup oxide fuels are suitable to the organic concept because cladding surface temperature is the limiting parameter, not fuel temperature.

The effects of irradiation on bulk $UO_2$ (Zircaloy clad) are listed in table III–3.

### (c) *Uranium Carbide Fuels*

Uranium monocarbide shows great promise as a nuclear reactor fuel because of high thermal conductivity, which approaches that of uranium metal, and good irradiation characteristics. There is currently a good deal of interest in the utilization of UC as a reactor fuel. A substantial effort is presently under way to develop fabrication techniques and obtain physical-property, compatibility, and irradiation data.

TABLE 3

EFFECTS OF IRRADIATION ON U-LOW ALLOY FUELS

| Specimen (NAA-) | Composition (wt—%) | Measured central temperature (°F.) | | Calculated surface temperature (°F.) | | Burnup total a/o* | Max. increase in diameter (%) | Increase in volume (%)† |
|---|---|---|---|---|---|---|---|---|
| | | Range | Average | Range | Average | | | |
| 15-3-5 | U—1.2 Mo | 830–700 | 756 | 655–555 | 598 | 0.25 | 9.9 | 22 |
| 15-3-1 | U—1.2 Mo | 1,050–920 | 972 | 825–740 | 763 | 0.33 | 13 | 31 |
| 15-4-1 | U—1.2 Mo | 1,245–905 | 1,017 | 980–715 | 799 | 0.22 | 7.7 | 6.9 |
| 15-4-5 | U—1.2 Mo | 1,130–990 | 1,052 | 890–775 | 827 | 0.22 | 9.6 | 7.3 |
| 15-3-6 | U—2.0 Zr | 665–560 | 605 | 525–445 | 480 | 0.18 | 4.0 | 6.5 |

*Based on chemical analyses of some specimens and heat balance on all specimens.

†Based on density measurements of central sections.

Fabrication techniques have been developed for consistently producing ½-inch diameter by 3-inch slugs of high purity 97 to 98 percent dense UC. This is done by an arc melting and casting process. Slugs up to ¾-inch diameter by 6 inches long have been produced, but not consistently to date.

A preliminary survey of UC physical properties and irradiation characteristics was conducted at Battelle Memorial Institute. A 5.0 percent carbon UC sample was irradiated in the MTR to a burnup of approximately 6,000 Mwd/T. At this burnup there was a 2 percent density change. Some thermal migration of carbon to the outside of the slug was noted but the center of the slug was still UC. Some cracking of the slug occurred after encapsulation. It has not been determined if this is the result of thermal cycling or irradiation. Apparently only the excess carbon migrated. Compatibility tests of UC with sodium, NaK, stainless steel, and grinding coolants showed no reaction. Thermal conductivity and electrical resistivity values have been obtained for 5.2 percent carbon sample.

## (2) CLADDING

### (a) *Aluminum Powder Metallurgy* (*APM*)

The use of APM alloys in organic systems offers the potential of good high temperature strength along with low neutron absorption. Designs utilizing fuel elements clad with this material are capable of producing higher quality steam than plants using aluminum clad elements. In addition, the APM alloys are suitable cladding materials for ceramic fuels such as $UO_2$ which offer the potential of high fuel burnup and lower fuel cycle costs (see table 4). The APM alloys are also easily extruded in a variety of complex shapes. This is an important requirement for fuel cladding materials in organic-cooled systems since the low heat transfer coefficient of the coolant requires the use of extended surfaces.

Aluminum powder metallurgy products are produced in this country by the Aluminum

Company of America (Alcoa) and are designated as APM. The alloy M–257, containing 6 to 8 percent $Al_2O_3$, is the only alloy produced commercially by Alcoa. Similar alloys are also manufactured in Europe by the Swiss firm, Aluminum-Industrie-Aktien Gesellschaft (AIAG) and are known as Sintered Aluminum Powder (SAP) products. AIAG's commercial alloys contain 10 to 13 percent $Al_2O_3$. The terms APM and SAP are used, as appropriate, to designate the source of the alloys.

TABLE 4

PHYSICAL PROPERTIES OF $UO_2$ AND SAP

| Property | $UO_2$ | SAP |
|---|---|---|
| Melting point, °F | 5,072 | ~1,200 |
| Thermal conductivity (Btu/ft-hr-°F.) | 1.47 (at 1,200 °F.) | 114 |
| Density, gm/cm³: | | |
| Theoretical | 10.96 | 2.76 |
| Actual | 10.50 | 2.73 |
| Coefficient of thermal expansion, in./in.-°F. | $5.55 \times 10^{-6}$ (32 to 1,832 °F.) | (70 to 850° F.) |
| Specific heat, cal/gm-°C | 0.059 | ~0.21 |
| Tensile strength, psi | | 11,500 (at 850°F.) |
| Yield strength, psi | | 10,800 (at 850°F.) |

Published data on elevated temperature properties of AMP and SAP alloys indicated that the usable service temperature of these alloys is some 300° F. higher than for the best conventional wrought alloy, thus leading to the selection of M–257 as a possible cladding alloy for $UO_2$ fuel rods in OMR reactors. The principle fabrication effort has been aimed at the production of small diameter (0.300-inch I.D.), thin-wall (0.015-inch), tubing with external fins to promote heat transfer in organic media. To date, finned tubing from APM alloy M–257 has been produced by two commercial fabricators of aluminum alloys, and a third vendor is currently engaged in a similar fabrication effort. One vendor produced lengths of smooth-wall tubing 0.210-inch I.D.+0.020-inch wall; and tubing with eight external fins. These were all produced by cold impact extrusion techniques. The second vendor has produced M–257 tubing, 0.300-inch I.D.×0.020-inch wall with 16 external fins, by hot extrusion. While evaluation of the resultant tubes is incomplete the fabrication of APM alloys into intricate tubular configurations appears to be definitely feasible on a commercial basis. Tables 5 and 6 compare properties of M–257 to various cladding materials.

Joining of APM alloys is not readily accomplished by conventional techniques. Any fusion technique results in segregation of the oxide dispersion in the molten weld metal resulting in porosity and low joint efficiency. However, in fuel rod development effort unalloyed aluminum end plugs have been satisfactorily joined to M–257 tubing. Burst tests at 900° F. in which the 0.020-inch walled tubing ruptured before the end closure failed indicate that the strength of such weldments is greater than that of the tubing. Accordingly, end closures by the fusion welding of Al plugs in APM tubing appear to be a distinct possibility.

End closures have also been made by flash welding of APM end plugs to APM tubing. Evaluations of these joints are in progress. Recent Alcoa data on flash welded bar specimens indicate 96 percent joint efficiency at all temperatures up to 600° F.

Hot pressing is being evaluated and good metallurgical bonds have been attained when an intermediate AlSi or Ni layer is employed to promote diffusion. Satisfactory adoption of this technique to the fuel tube end closure problem is yet to be developed.

Ultrasonic welding is reported to offer good possibility for joining APM alloys, but much additional development is required before this technique can be seriously considered.

At this writing, it seems that joining of APM alloys is definitely feasible; however, a considerable effort is required to establish a practical, reliable end closure technique.

The compatability of APM and SAP alloys with organic coolant at 750° F. has been

## TABLE 5

## TENSILE AND YIELD STRENGTHS

| Temperature (°F.) | M-257 | | | 2024-T4 | | | 2618-T61 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Tensile (psi) (1,000 hr) | Yield (psi) (1,000 hr) | 1% Flow (10,000 hr) | Tensile (psi) (1,000 hr) | Yield (psi) (1,000 hr) | 1% Flow (10,000 hr) | Tensile (psi) (1,000 hr) | Yield (psi) (1,000 hr) | 1% Flow (10,000 hr) |
| 400 | 21,000 | 18,000 | | 31,000 | 27,000 | | 34,000 | 31,000 | |
| 600 | 17,000 | 15,000 | 8,800 | 8,000 | 5,500 | 1,500 | 9,000 | 6,000 | 1,600 |
| 800 | 12,000 | 11,000 | 5,400 | 1,700 | 1,100 | | 2,600 | 1,600 | |
| 1,000 | 7,500 | 7,000 | | | | | | | |

## TABLE 6

## PHYSICAL PROPERTIES OF VARIOUS MATERIALS AT 800° F.

| | APM type M-257 | 2S aluminum | 2024-T4 aluminum | Mg | SS type 347 | Carbon steel | Be | Zr |
|---|---|---|---|---|---|---|---|---|
| Tensile strength (psi). | 12,000 | 800 | 1,700 | | 75,000 | 50,000 | | |
| Yield strength (psi). | 11,000 | 600 | 1,100 | | 31,000 | 22,750 | | |
| Creep—(1% in 1,000 hr) psi. | 5,400 | 200 | | | 21,000 | 19,000 | | |
| Corrosion resistance to organic fluids. | Satisfactory. | Satisfactory. | Satisfactory. | Oxidizes | Satisfactory. | Satisfactory. | Not tested. | Hydrides. |
| Absorption cross section ($cm^{-1}$ at 2,200 m/sec). | 0.0113 | 0.0115 | 0.012 | | 0.229 | 0.22 | | |
| Conductivity (Btu/hr-ft-°F.). | 105 | 128 | | | 11 | 23.5 | | |
| Coefficient of Thermal expansion (in./in.-°F.). | $13.6\times 10^{-6}$ | $12.3\times 10^{-6}$ | $14.4\times 10^{-6}$ | | $10.1\times 10^{-6}$ | $7.65\times 10^{-6}$ | | |
| Melting point (°F.). | $\sim$1,200 | 1,220 | | $\sim$1,200 | 2,600 | 2,795 | | |
| Special problems | Joining | | | | | | Toxic | |
| Cost ($/lb) | 5.00* | 1.00 | 1.00 | | 5.00 | 0.40 | 100 | 25 |
| Compatible with fuels. | No reaction with bulk $UO_2$. | Reaction with $UO_2$ at $\sim$500° C. | Reaction with $UO_2$ at $\sim$500° C. | | Yes | | | |

*Production basis.

studied. The corrosion resistance of these alloys was found to be excellent, essentially the same as that of unalloyed aluminum.

APM (M–257) tubes with 0.020-inch wall have been found helium leak-tight under vacuum at temperatures up to 1,000° F. and pressure-tight for internal pressures of 15 psig at temperatures up to 900° F.

### (b) *Stainless Steel*

Due to their stability and proven capability, the 300 series austenitic stainless steels are of greatest interest. As a group they possess ample strength to serve as a clad and a structural material. Typical properties for types 304 and 347 stainless steel are shown in table 7.

Out-of-pile and in-pile tests of these materials with organics have demonstrated their corrosion resistance. Specimens removed from the tests still had their original luster and had negligible weight gains. The austenic stainless steels are not known to have any chemical reaction with $UO_2$. With uranium metal, stainless steel forms a low melting eutectic at approximately 2,000° F., but the cladding-fuel interface should not exceed 900° F. under conditions in the OCR reactor.

TABLE 7

PROPERTIES OF STAINLESS STEEL

| Temperature (°F.) | Type 304 | | | Type 347 | | |
|---|---|---|---|---|---|---|
| | Yield (psi) | Tensile (psi) | 1% Flow (10,000 hr) | Yield (psi) | Tensile (psi) | 1% Flow (10,000 hr) |
| Room | 30, 000 | 80, 000 | ------------ | 34, 000 | 80, 000 | ------------ |
| 1,000 | 18, 000 | 55, 000 | 17, 000 | 29, 000 | 60, 000 | 19, 000 |

Stainless steel can be fabricated in a variety of shapes and sizes by a wide range of techniques. Tubes from 1/16 inch in diameter and up can be produced either by extrusion or welding. Wall thicknesses down to 4.5 mils have been successfully fabricated. Plate is available down to 1 mil in thickness. All conventional joining processes can be used, including fusion welding and brazing. The thermal conductivity of stainless steel is approximately 11 Btu/hr-ft-° F. in the temperature range of interest, considerable less than that of aluminum. The effect of such a low conductivity is to preclude the use of extended surface fuel elements. By comparison, the thermal effectiveness of stainless steel and aluminum fins is respectively 0.45 and 0.9 for a length/thickness ratio of 2.5:1.

The stainless steels in general possess a relatively high cross section for neutron capture, the 2,200 m/sec macroscopic absorption cross section being 0.229 $cm^{-1}$. The cost of stainless steel is approximately $5 per pound in fabricated shapes.

### (c) *Zirconium*

Corrosion testing of zirconium metal in organics has shown that zirconium hydride is formed. With the formation of the hydride, the zirconium rapidly loses ductility and becomes brittle. For this reason zirconium, even though possessing other desirable properties, is not considered suitable for use in an organic cooled reactor. Zirconium alloys, e.g., Zircaloy 2, etc., exhibit the same corrosion behavior as zirconium.

### (d) *Mild or Low Alloy Steel*

Mild or low alloy steels used with organic coolants behave basically the same as the stainless steels. They possess satisfactory corrosion-resistance to organic coolants. There is no apparent chemical instability between mild and low alloy steels with uranium fuel at the normal temperatures expected in a reactor. However, this compatability has not been fully investigated. The thermal conductivity of mild steel is about twice that of stainless steel, allowing reasonably high thermal effectiveness of mild steel cladding with extended surfaces. The amount of iron employed in a core utilizing mild steel with extended surface would introduce a considerable amount of parasitic absorption, resulting in higher initial fuel enrichments and lower conversion ratios than would be obtained using materials with a lower absorption cross section. Also, the use of mild steel cladding would require special controlled environments during fuel handling to prevent corrosion.

### (e) *Aluminum*

While the strength of aluminum is satisfactory at room temperatures, at elevated temperatures the allowable stress rates are exceedingly low. Thus, aluminum metals as a group offer potential as a clad material only if the fuel alloy is structurally sound throughout its lifetime. Table III–8 compares the strength properties of alloys 2S and 2024–T4 aluminum.

TABLE 8

STRENGTH PROPERTIES OF ALUMINUM ALLOYS

| Temperature (°F.) | 2S | | | 2024–T4 | | |
|---|---|---|---|---|---|---|
| | Yield (psi) | Tensile (psi) | 1% Flow (10,000 hr) | Yield (psi) | Tensile (psi) | 1% Flow (10,000 hr) |
| Room | 5, 000 | 13, 000 | | 46, 000 | 68, 000 | |
| 400 (1,000 hr) | 3, 000 | 6, 000 | | 27, 000 | 31, 000 | |
| 600 (1,000 hr) | 1, 500 | 2, 500 | 300 | 5, 500 | 8, 000 | 1, 500 |

Because of the strength considerations, aluminum is not considered satisfactory as a cladding material for a $UO_2$ fuel element, but it is adequate as a cladding for stable uranium metal fuel at moderate burnups. The precipitation-hardened aluminum alloys, while possessing higher strengths in the lower temperature ranges, anneal over a period of time at temperatures above 500° to 600° F. with a continuing gradual decrease in all allowable stress levels. Type 2S aluminum has been tested both out-of-pile and in-pile for corrosion resistance to the polyphenyl coolants, and in all cases negligible weight gains were recorded. Subsequent examination of the test specimens indicated no localized attack or other adverse effects.

When used as a cladding for uranium metal fuel, aluminum is pressure bonded to an intermediate layer of nickel which acts as a diffusion barrier. When used as a cladding for $UO_2$, aluminum tends to reduce $UO_2$ at elevated temperatures, starting at approximately 900° F. When aluminum and $UO_2$ are intimately mixed, as in some test reactor plate-type fuel elements, the aluminum tends to reduce the $UO_2$ at temperatures around 840° to 930° F. The reaction rates between the two, when they are not intimately mixed, have not been definitely established but are known to be less.

Aluminum is one of the most versatile metals with respect to availability and diversity of fabricated shapes. Joining can be accomplished by all conventional techniques, including welding and brazing. The cost of aluminum in fabricated shapes is approximately $1 per pound. The 2,200 m/sec macroscopic cross section for normal 2S aluminum is approximately 0.012 cm.$^{-1}$

The use of aluminum cladding on the fuel elements in an organic reactor appears to be limited only by the low melting point, approximately 1,220° F., the lack of strength at elevated temperatures, and its chemical behavior with $UO_2$ at elevated temperatures.

### (3) Fuel Element Heat Transfer Studies

The two fuels most suitable for an organic moderated reactor at the present stage of technology are $UO_2$ and uranium metal alloys. The $UO_2$ is characterized by a high permissible center temperature, approximately 4,000° F., and a very low thermal conductivity, approximately 1 Btu/hr-ft-° F. Uranium metal alloys are center-temperature limited because of the beta phase transformation at approximately 1,200° F., but have a relatively high thermal conductivity of 16 Btu/hr-ft-°F. Therefore, taking rods as a reference design because of their well-developed technology, we may compute the maximum permissible power for both $UO_2$ and uranium metal. These results are summarized in table 9. For completeness, results for UC rods are also included. Due to the limitations on maximum surface heat fluxes, these maximum rod powers are unobtainable in practice unless an extended surface fuel element is utilized. The finning ratio, which is the ratio of the effective heat transfer surface* required (to be obtained by finning) to the area of a smooth tube of the diameter listed, for a maximum allowable heat flux of 155,000 Btu/hr-ft$^2$, is also given in table 9. (The heat flux of 155,000 Btu/hr-ft$^2$ was chosen to give a 2:1 ratio of burnout heat flux to maximum heat flux.) From design considerations, the maximum value of the finning ratio is approximately 2.5; thus, the allowable power for a $UO_2$ rod, a UC rod, or a uranium metal rod is approximately the same when the rod diameter is about 0.35 inch or less. It is therefore concluded that in an organic reactor, in which the heat transfer characteristics of the organic coolant restrict the power which may be removed from the fuel element, that the use of uranium metal does not offer any significant thermal improvement over that of $UO_2$. Indeed, as the fuel element surface temperatures can be raised, the thermal performance of the $UO_2$ would tend to surpass that of the metal. It should also be noted that due to the difference in densities of the $UO_2$ and uranium metal, the specific power of the $UO_2$ fuel element will be about 1.7 times that of a uranium metal element. The volumetric power of the two fuel elements will be approximately the same.

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*An effectiveness of 0.95 for the extended surface was used in the above table.

TABLE 9

MAXIMUM PERMISSIBLE POWER

| | $UO_2$ | | Uranium Metal | | UC | |
|---|---|---|---|---|---|---|
| Rod Diameter (in.) | Heat Flux (Btu/hr-ft$^2$) | Finning Ratio | Heat Flux (Btu/hr-ft$^2$) | Finning Ratio | Heat Flux (Btu/hr-ft$^2$) | Finning Ratio |
| 0. 2 | 587, 000 | 4. 00 | 1, 300, 000 | 8. 83 | 1, 250, 000 | 8. 50 |
| 0. 3 | 391, 000 | 2. 66 | 877, 000 | 5. 95 | 1, 160, 000 | 7. 88 |
| 0. 4 | 294, 000 | 2. 00 | 622, 000 | 4. 50 | 1, 085, 000 | 7. 37 |
| 0. 5 | 285, 000 | 1. 60 | 530, 000 | 3. 60 | 1, 020, 000 | 6. 93 |
| 0. 6 | 196, 000 | 1. 33 | 442, 000 | 3. 00 | 967, 000 | 6. 57 |
| 0. 7 | 168, 000 | 1. 14 | 378, 000 | 2. 57 | 913, 000 | 6. 20 |

***b. Work Underway***

### (1) OXIDE FUELS

Current research and development effort is involved with work in the following areas:

### (a) *Incorporation of Burnable Poisons Into $UO_2$*

In order to increase the burnup time of $UO_2$, the following burnable poisons were incorporated in amounts of 2 to 5 at. percent into $UO_2$: Gd, Sm, Er, Dy, and Eu. All these rare earth metals were incorporated in their oxide form. By careful blending a homogeneous mixture was achieved. Pellets made of this mixture were pressed and sintered under the same conditions as described for pure $UO_2$. The percentage of theoretical density was in most cases the same as, and in some cases even slightly higher than for pure $UO_2$ pellets. A uniform distribution of the rare earth oxide particles in the sintered pellets was established by metallographic investigation. This work is being continued using boron as poison.

### (b) *Compatibility Tests*

Experiments are in progress to establish the compatibility of $UO_2$ pure, and containing various burnable poisons with grade 1,100 Al and M-257 APM at 1,100° F. To date, no reaction has been found in tests up to 14 days' duration.

### (2) URANIUM CARBIDE FUELS

Techniques for fabricating UC slugs up to 1 inch diam by 6 inches long are presently under development. Facilities are being set up for pilot production of slugs by the arc melting and casting process.

Additional irradiation testing is under way and scheduled. An MTR capsule presently being irradiated is scheduled for a burnup of 18,000 Mwd/T. Three cluster type UC elements are scheduled for irradiation in the SRE to a burnup of 2,000 to 15,000 Mwd/T. MTR and ETR irradiation tests of 4,000 to 24,000 Mwd/T burnups are also scheduled.

Additional compatibility tests of UC with cladding materials are being prepared. Thermal conductivity of large samples of uranium carbides over the range of 4.2 to 5.6 percent carbon are about to start. Additional physical properties will be investigated.

Primary work (including the basic uranium metallurgy) is being done at Mallinkrodt Chemical and Davison Chemical Co. Fabrication of uranium fuels is being continued by BMI, Albany (Ore) Metals, Nuclear Metals, and Nuclear Material and Equipment Co.

### (3) ALUMINUM POWDER METALLURGY—CLADDING MATERIALS

Fuel element development programs are now in progress with the objective of developing fabrication, assembly, and inspection procedures for $UO_2$ and uranium alloy fuel elements for OMR reactors. These programs include the manufacture and testing of fuels, cladding alloys, and prototype fuel elements capable of operating at higher temperatures and for higher burnups. The use of APM alloys for cladding has not been tested in any reactor. These programs will stress the evaluation of APM alloys for this purpose; however, an alternate effort will be made on Al-clad zirconium tubing for this application.

Specific programs are under way to test the compatability of APM materials with $UO_2$ at elevated temperatures. Work is continuing on the evaluation of fusion welding, pressure bonding, ultra sonic welding and flash welding as a means of making end plug closures. The creep and rupture data reported in the literature for APM alloys is being checked by further laboratory tests designed to measure elevated temperature primary, secondary and tertiary creep strengths. Hot continuous extrusion work on shapes typical for fuel element use is continuing.

### 3. Heat Transfer and Fluid Flow

#### *a. Work Completed*

#### (1) Forced Convection Studies

Heat transfer coefficients have been measured for various polyphenyls flowing turbulently in a heated tube (6). The polyphenyls were: (*a*) diphenyl; (*b*) Santowax R (commercial mixture of terphenyl isomers); and (*c*) Santowax OM (a 2:1 mixture of ortho- and meta-terphenyls). The measurements were made in a stainless steel loop consisting of a centrifugal pump, strainer, turbine flowmeter, preheater, rotometer, test heater section, cooler, surge tank, and connecting piping and valves. The test heater section was a 0.375-inch O.D. by 0.016-inch wall type 304 stainless-steel tube having a heated length of 24⅛ inches. An unheated hydraulic entry length was provided upstream of the heated section. The heating was obtained by passing an alternating current through the tube wall.

The operating conditions were as follows:

| | |
|---|---|
| Fluid temperatures | 480 to 770° F. |
| Surface temperatures | 565 to 875° F. |
| Fluid velocities | 5 to 25 ft/sec. |
| Reynolds number | 20,000 to 300,000. |
| Heat flux | Uniform. |
| Heat fluxes | 40,000 to 290,000 Btu/hr-ft$^2$. |

Experimental heat transfer coefficients obtained at the above conditions ranged from 340 to 2,740 Btu/hr-ft$^2$-° F. The data obtained in this study were correlated by the relationship.

$$\frac{hd}{k}=0.015\left(\frac{vd\rho}{\mu}\right)^{0.85}\left(\frac{c\mu}{k}\right)^{0.3}$$

where

$c$=specific heat of coolant,
$d$=tube diameter,
$k$=thermal conductivity of the coolant,
$h$=heat transfer coefficient,
$v$=coolant velocity,
$\mu$=viscosity of the coolant, and
$\rho$=density of the coolant.

The physical properties of the coolant are taken at the bulk temperature. It has been found that when the above expression is used for organic coolants containing high-boiling compounds, it predicts a heat transfer coefficient that is lower than the measured coefficient. For example, the heat transfer coefficient calculated from this equation for Santowax R with 30 percent high boilers is 32.5 percent lower than for Santowax R with no high boilers, whereas experimental data indicate a 10 percent lower coefficient.

#### (2) Burnout Studies

Burnout heat fluxes have been measured for various polyphenyls flowing turbulently in an annular channel (7, 21). The polyphenyls were (*a*) diphenyl, (*b*) a polyphenyl mixture (15% diphenyl, 58% ortho-terphenyl, 24% meta-terphenyl, and 3% para-terphenyl), (*c*) Santowax R, and (*d*) mono-isopropylbiphenyl. The burnout heat fluxes were obtained in an electrically heated, ½-inch O.D. tube (0.020-inch wall) with an unheated rod (0.188-inch diameter) inserted concentrically to form an annular passage having an equivalent hydraulic diameter of 0.272-inch. The electrical power input (dc) to the tube was increased by increments until the tube was damaged and/or the tube wall temperatures rose rapidly to a high value (indicating film boiling). The coolant was pumped through the test section by nitrogen gas pressurization of a coolant tank connected to the upstream end of the test section. The coolant discharged from the test section into another tank. The test section was vertical and the flow was in the upward direction.

The burnout heat flux for diphenyl was correlated by the following equation:

$$\left(\frac{Q}{A}\right)_{\text{burnout}}=454\ T_{\text{sub}}\ V^{0.63}+116{,}000,\ \text{Btu/hr-ft}^2$$

where

$T_{\text{sub}}$=subcooling, °F.
$V$=velocity, ft/sec.
$(Q/A)_{\text{burnout}}$=burnout heat flux, Btu/hr-ft$^2$.

The operating conditions for diphenyl were as follows:

| | |
|---|---|
| System pressure | 23 to 406 psia. |
| Liquid bulk temperature | 510° to 831° F. |
| Liquid bulk velocity | 0.47 to 17.3 ft/sec. |
| Subcooling | 0° to 328° F. |
| Heat flux | 74,000 to 890,000 Btu/hr-ft$^2$. |

The burnout heat flux for Santowax R was correlated by the following equation:

$$\left(\frac{Q}{A}\right)_{\text{burnout}}=552\ T_{\text{sub}}\ V^{2/3}+152{,}000,\ \text{Btu/hr-ft}^2$$

The operating conditions for Santowax R were as follows:

| | |
|---|---|
| System pressure | 91 to 109 psi. |
| Liquid bulk temperature | 595° to 771° F. |
| Liquid bulk velocity | 49 to 15.3 ft/sec. |
| Subcooling | 174° to 334° F. |
| Heat flux | $0.416\times10^6$ to $1.287\times10^6$ Btu/hr-ft$^2$. |

A burnout heat flux correlation was also obtained for the polyphenyl mixture (see fig. 9).

### (3) Variation in Heat Transfer Coefficient

The extent of the decrease in heat transfer coefficients with time has been investigated in loops containing Santowax R, Santowax OM, and irradiated OMRE coolant containing 30 percent high boilers flowing turbulently in a heated tube (6, 22, 23). The method of investigation involved circulation of the coolant in the loop described in reference 1 over a period of time under fixed conditions of bulk temperature, heat flux and velocity and to note the change in heat transfer coefficient as indicated by the increase in wall temperature with time.

No change in surface temperature was observed with Santowax R in a 90-hour run under the conditions of 15 ft/sec velocity, 978° F. surface temperature, and 758° F. bulk temperature (6).

No increase in surface temperature was observed with Santowax OM for the following conditions (6).

| *Duration of run (hr)* | *Velocity (ft/sec)* | *Surface temperature (° F.)* | *Bulk temperature (° F.)* |
|---|---|---|---|
| 48 | 15 | 976 | 756 |
| 26 | 10 | 910 | 753 |
| 50 | 5.6 | 905 | 745 |
| 24.5 | 10 | 958 | 747 |
| 39 | 5.6 | 959 | 758 |

From the above test conditions it has been calculated that the rate of decrease in measured heat transfer coefficient for the irradiated OMRE coolant containing 30 percent high boilers would be as shown in Figure 10 (23). The rate of decrease in heat transfer coefficient becomes less with lower surface temperature and with increasing velocity.

### (4) Nucleate Boiling Studies

Some nucleate boiling heat transfer data have been obtained as a byproduct of the investigations on burnout heat flux. Preliminary data from these studies indicate that the heat transfer coefficient reaches equilibrium at between 25 and 45 percent above that for forced convection. The organics being studied exhibit the same general boiling characteristics as other common fluids.

## *b. Work Underway*

### (1) Forced Convection Studies

Measurements are being made of the local heat transfer coefficients in a Piqua-type extended surface channel. These data will permit a more accurate determination of fin efficiencies.

### (2) Burnout Studies

Burnout heat fluxes are being measured for Santowax R at velocities from 1 to 15 ft/sec, bulk temperatures from 500° to 700° F. and at pressures of 20, 150, and 300 psia (24). The test apparatus is similar to that described in reference 6. Burnout heat fluxes will be measured for both upward and downward flow.

Measurements of burnout fluxes for pool boiling of benzene have been initiated. Measurements of burnout heat fluxes for pool boiling of other organic fluids are planned. These

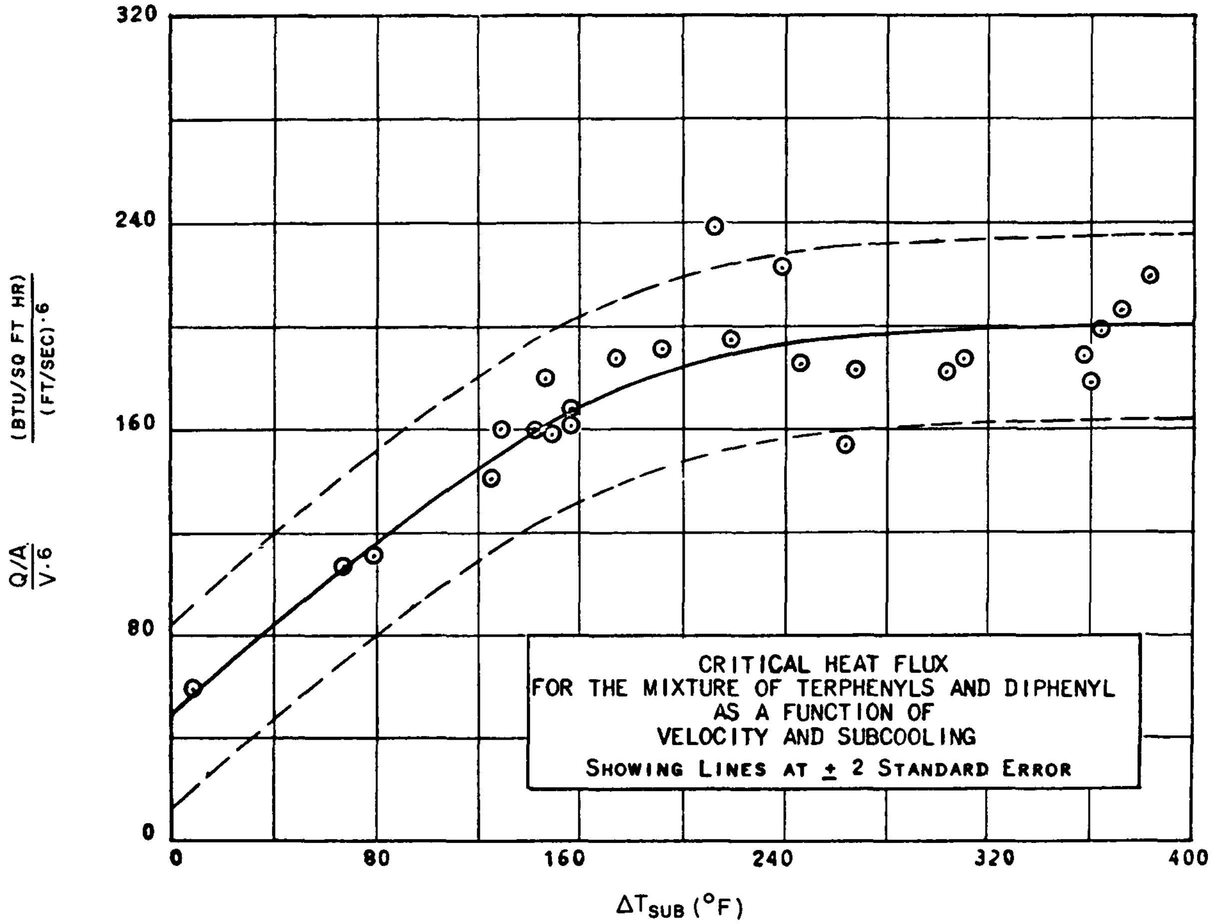


FIGURE 9.—*Critical heat flux.*

measurements will be made at pressures up to the critical pressure.

### (3) VARIATION OF THE HEAT TRANSFER COEFFICIENT

The rate of decrease in heat transfer coefficient observed with irradiated OMRE coolant having 30 percent boilers (with and without 16 percent diphenyl) flowing turbulently in a heated tube with subcooled nucleate boiling are being investigated (25). The method of investigation is to circulate the coolant in the loop described in reference 6 over an extended period of time under fixed conditions of bulk temperature, heat flux, and velocity, and to note the increase in wall temperature with time.

To date, five boiling runs have been made covering the following range of conditions:

| | |
|---|---|
| Surface temperature | 784° to 890° F. |
| Bulk temperature | 593° to 648° F. |
| Heat flux | 80,000 to 305,000 Btu/hr-ft$^2$. |
| Velocity | 5 to 10 ft/sec. |
| Duration | 154 to 500 hr. |

A sixth run which accumulated over 1,500 hours operated at a maximum initial surface temperature of 840° F., bulk temperature of 640° F., a maximum heat flux of 185,000 Btu/hr-ft$^2$, and a velocity of 5 ft/sec. The results from this run are shown in figure 11. It is significant to note that there is no decrease in the heat transfer coefficient after 1,100 hours. Forced convection heat transfer measurements immediately prior to and following some o the boiling runs indicate an increase in surface temperature which is less than that indicated by the decrease observed during the boiling runs.

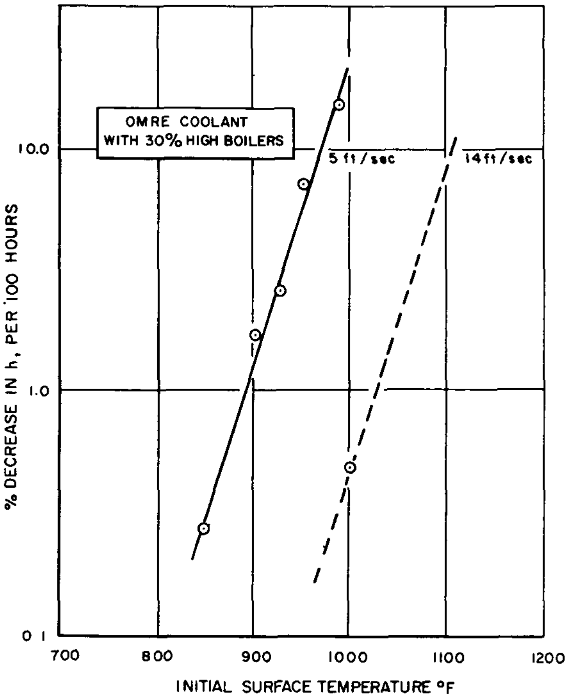


FIGURE 10.—*Change in heat transfer coefficient with time for various surface temperatures.*

### (4) NUCLEATE BOILING

Some subcooled, nucleate boiling heat transfer data are being obtained as a byproduct of the extended boiling runs described above.

## 4. Coolant Chemistry

### *a. Work Completed*

### (1) PHYSICAL PROPERTIES

Methods and techniques have been developed for the evaluation of the physical properties of organic materials (26). Measurements of these properties for many organic coolants of interest as reactor materials have been made. The results of these measurements for Santowax R have been compiled in tables 10 and 11. Similar data have been measured for the coolant in the Organic Moderated Reactor Experiment (OMRE) and its component organics—diphenyl, orthoterphenyl, metaterphenyl, and paraterphenyl (26, 27). Figure 12 shows the variation in coolant density as the HBC increases.

### (2) RADIATION EFFECTS AND COOLANT DECOMPOSITION

To determine the feasibility of organics as moderator and coolant in a reactor, it was nec-

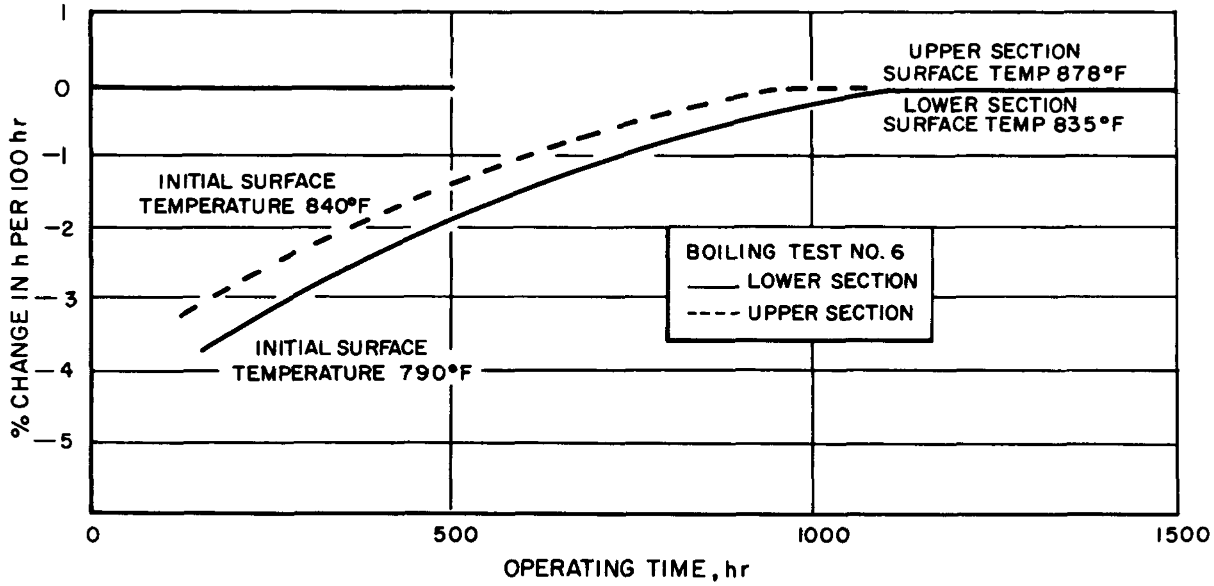


FIGURE 11.—*Rate of change in heat transfer coefficient as a function of operating time.*

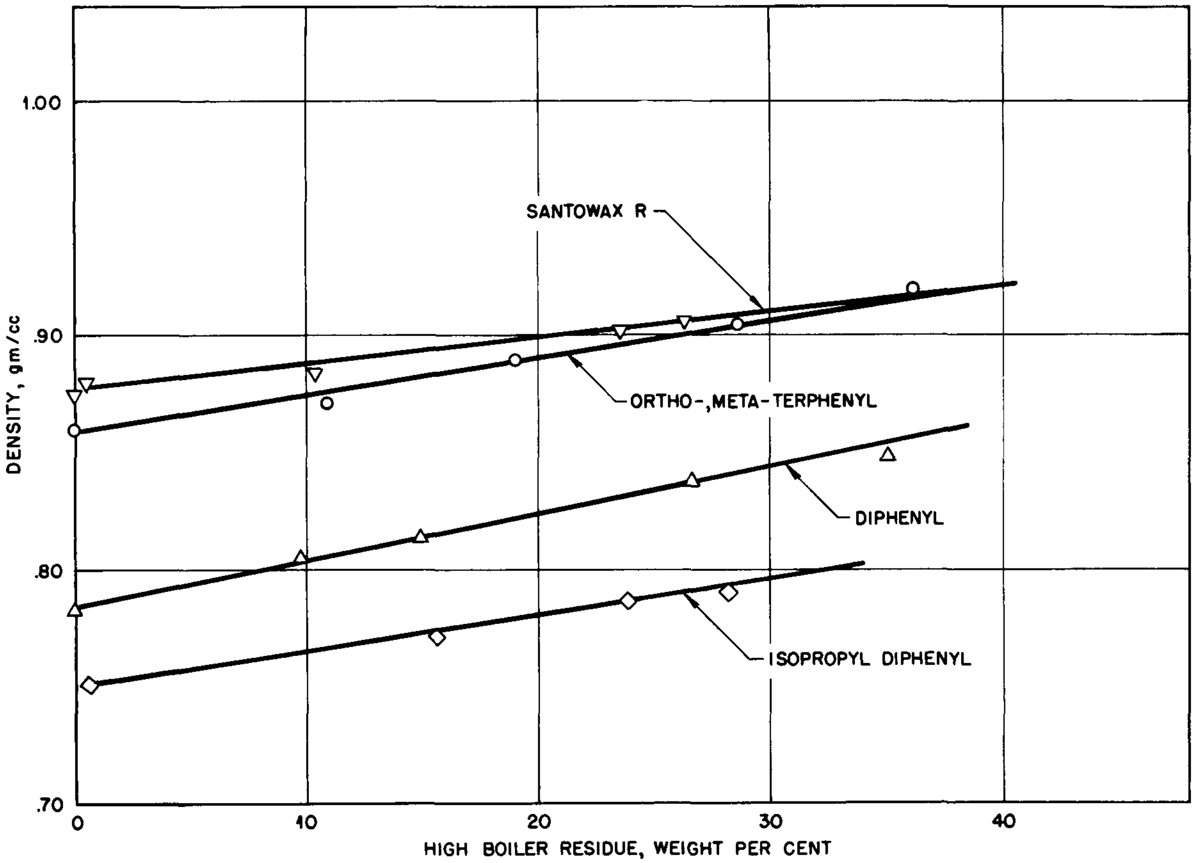


FIGURE 12.—*Density of irradiated coolants at 600° F.*

essary to evaluate the decomposition rate of these materials under intense radiation. In spite of the distinct advantages of low vapor pressure, low induced activity, and low corrosion with standard materials of construction, an excessive radiolytic decomposition rate would have rendered the use of organics uneconomical, due to coolant makeup costs. Since polyphenyls were known to be relatively stable to high temperature radiations, they have been investigated most extensively (28).

Many radiation sources were used in the evaluation of the coolant decomposition rate (28). Initial measurements were conducted with Van de Graaff electrons. Later determinations were made with in-pile test loops. More recent data were obtained from the operation of the OMRE.

The results of these investigations are presented in figures 13 and 14. These tests indicate that the coolant decomposition rate—and thus the coolant makeup cost—decreases with increasing high boiler (polymeric decomposition products) concentration.

A search was also made for an organic inhibitor which could be added to polyphenyl coolants to reduce the radiation decomposition rate (29). To date, 56 additives have been evaluated on the basis of gas evolution and polymer formation. These additives, in 2 percent concentration in OMRE coolant, received $4 \times 10^9$ r at 750° F. in the MTR gamma facility. Nine of these, as reported in table 12, proved to be effective in reducing G (polymer) by 20 percent or more.

TABLE 10

SUMMARY OF TEMPERATURE DEPENDENT PROPERTIES OF SANTOWAX R

| Property | Temperature (° F.) | High boiler residue content (wt. %) | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 10 | 20 | 30 | 100 |
| Density, liquid (gm/cm³) | 600 | 0. 874 | 0. 884 | 0. 896 | 0. 907 | 0. 982 |
| | 700 | 0. 827 | 0. 839 | 0. 851 | 0. 864 | 0. 952 |
| | 800 | 0. 777 | 0. 791 | 0. 804 | 0. 818 | 0. 922 |
| Vapor density (gm/cm³) | 600 | 0. 0013 | ---------- | ---------- | ---------- | ---------- |
| | 700 | 0. 0036 | ---------- | ---------- | ---------- | ---------- |
| | 800 | 0. 0088 | ---------- | ---------- | ---------- | ---------- |
| Hydrogen density (atoms/cm³ × 10⁻²²) | 600 | 3. 20 | 3. 22 | 3. 25 | 3. 27 | 3. 41 |
| | 700 | 3. 03 | 3. 06 | 3. 09 | 3. 12 | 3. 31 |
| | 800 | 2. 84 | 2. 88 | 2. 92 | 2. 95 | 3. 21 |
| Viscosity (centipoise) | 600 | 0. 32 | 0. 41 | 0. 53 | 0. 70 | 7. 8 |
| | 700 | 0. 23 | 0. 29 | 0. 38 | 0. 49 | 4. 1 |
| | 800 | 0. 18 | 0. 22 | 0. 28 | 0. 37 | 2. 4 |
| Enthalpy (base 300° F.), (Btu/lb) | 600 | 154 | ---------- | ---------- | ---------- | ---------- |
| | 700 | 207 | ---------- | ---------- | ---------- | ---------- |
| | 800 | 262 | ---------- | ---------- | ---------- | ---------- |
| Specific heat (Btu/lb-° F.) | 600 | 0. 530 | 0. 522 | 0. 515 | 0. 507 | ---------- |
| | 700 | 0. 542 | 0. 533 | 0. 524 | 0. 515 | ---------- |
| | 800 | 0. 555 | 0. 545 | 0. 534 | 0. 524 | ---------- |
| Thermal conductivity (Btu/hr-ft-°F.) | 600 | 0. 0660 | 0. 0660 | 0. 0660 | 0. 0660 | ---------- |
| | 700 | 0. 0645 | 0. 0645 | 0. 0645 | 0. 0645 | ---------- |
| | 800 | 0. 0610 | 0. 0610 | 0. 0610 | 0. 0610 | ---------- |
| Latent heat of vaporization (Btu/lb) | 600 | 124. 7 | ---------- | ---------- | ---------- | ---------- |
| | 700 | 120. 4 | ---------- | ---------- | ---------- | ---------- |
| | 800 | 113. 8 | ---------- | ---------- | ---------- | ---------- |
| Vapor pressure (psia) | 600 | 4. 0 | 2. 3 | 3. 3 | 4. 5 | ---------- |
| | 700 | 12. 7 | 9. 2 | 10. 9 | 13. 0 | ---------- |
| | 800 | 31. 8 | 27. 5 | 29. 7 | 32. 3 | ---------- |
| Surface tension (dynes/cm) | 600 | 21. 1 | ---------- | ---------- | ---------- | ---------- |
| | 700 | 17. 2 | ---------- | ---------- | ---------- | ---------- |
| | 800 | 13. 4 | ---------- | ---------- | ---------- | ---------- |

A concurrent search was conducted for a commercially available material which could serve as an organic coolant-moderator at reduced overall replenishment costs. Two new coolant materials were evaluated on the basis of gas evolution and polymer formation and were found to be considerably inferior to OMRE coolant (29). One of these, 1,1= ditolylethane, evolved 40 times as much gas as OMRE coolant and polymerized 4 times as rapidly. The other, a heat transfer fluid consisting of glycerides of unsaturated fatty acids in the $C_{16}$–$C_{26}$ range, evolved too much gas to be measured and was almost completely coked. Another material, anthracene oil, was investigated (30). It was concluded that its disadvantages—higher decomposition rate, higher vapor pressure, lower flash and fire points, toxicity, and high sulfur content—outweighed its lower costs.

### *b. Work Underway*

#### (1) PHYSICAL PROPERTIES

At the present time, physical properties such as density, viscosity, melting point, specific

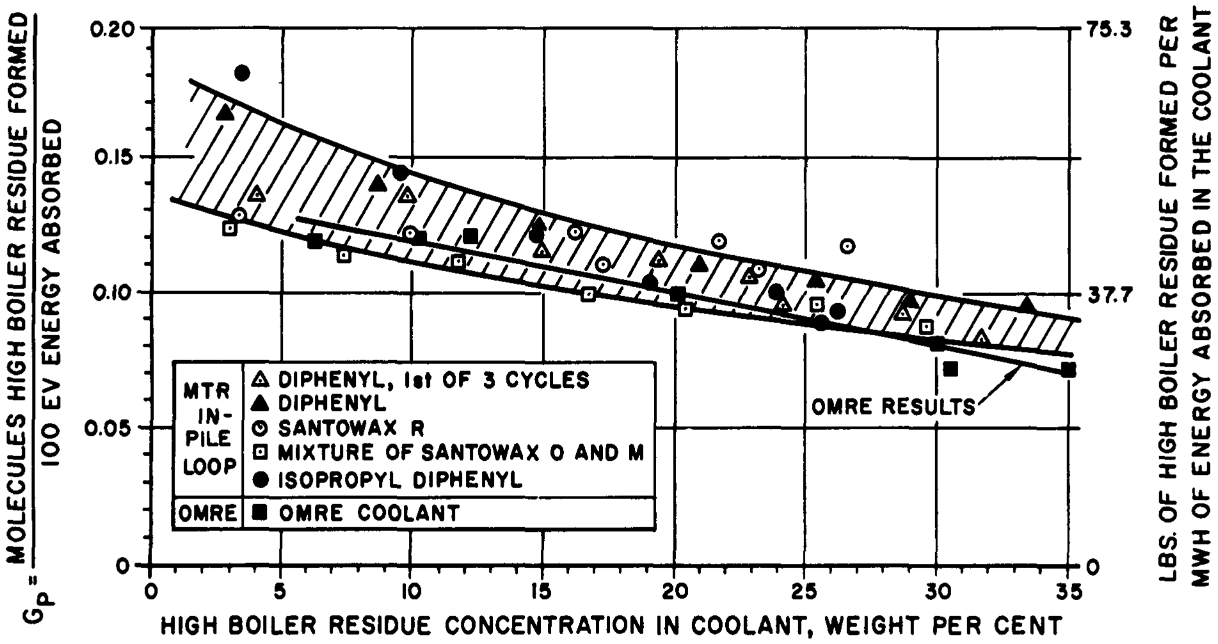


FIGURE 13.—*Decomposition rate of organic coolants.*

TABLE 11

SUMMARY OF MISCELLANEOUS PROPERTIES OF SANTOWAX R

| Property | High boiler residue content (wt. %) | | | | |
|---|---|---|---|---|---|
| | 0 | 10 | 20 | 30 | 100 |
| Final melting point (°F.) | 312 | 303 | 292 | 278 | 230 |
| Boiling point (°F.) | 713 | 739 | 728 | 713 | ---------- |
| Flash point (°F.) | 375 | ---------- | ---------- | ---------- | ---------- |
| Flame point (°F.) | 460 | ---------- | ---------- | ---------- | ---------- |
| Threshold temperature (°F.) | 835 | ---------- | ---------- | ---------- | ---------- |
| Auto-ignition temperature (°F.) | 1, 148 | ---------- | ---------- | ---------- | ---------- |
| Critical temperature (°F.) | 1, 241 | ---------- | ---------- | ---------- | ---------- |
| Critical pressure (psia) | 499 | ---------- | ---------- | ---------- | ---------- |
| Critical density (gm/cm$^3$) | 0. 306 | ---------- | ---------- | ---------- | ---------- |
| Heat of combustion (cal/gm at 20° C.) | 9, 604 | 9, 598 | 9, 593 | 9, 589 | ---------- |
| Latent heat of fusion (cal/gm) | 21 | ---------- | ---------- | ---------- | ---------- |
| Radiolytic gas evolution rate (molecules/100 ev at 660° F.) | ---------- | 0. 0068 | 0. 0043 | 0. 0028 | ---------- |
| Pyrolytic decomposition rate (wt. % HBR/hr at 650° F.) | $2.8\times10^{-4}$ | ---------- | ---------- | ---------- | ---------- |
| Radiolytic decomposition rate (lb HBR/Mwh absorbed at 600 to 650° F.) | 52. 0 | 44. 8 | 37. 6 | 30. 6 | ---------- |

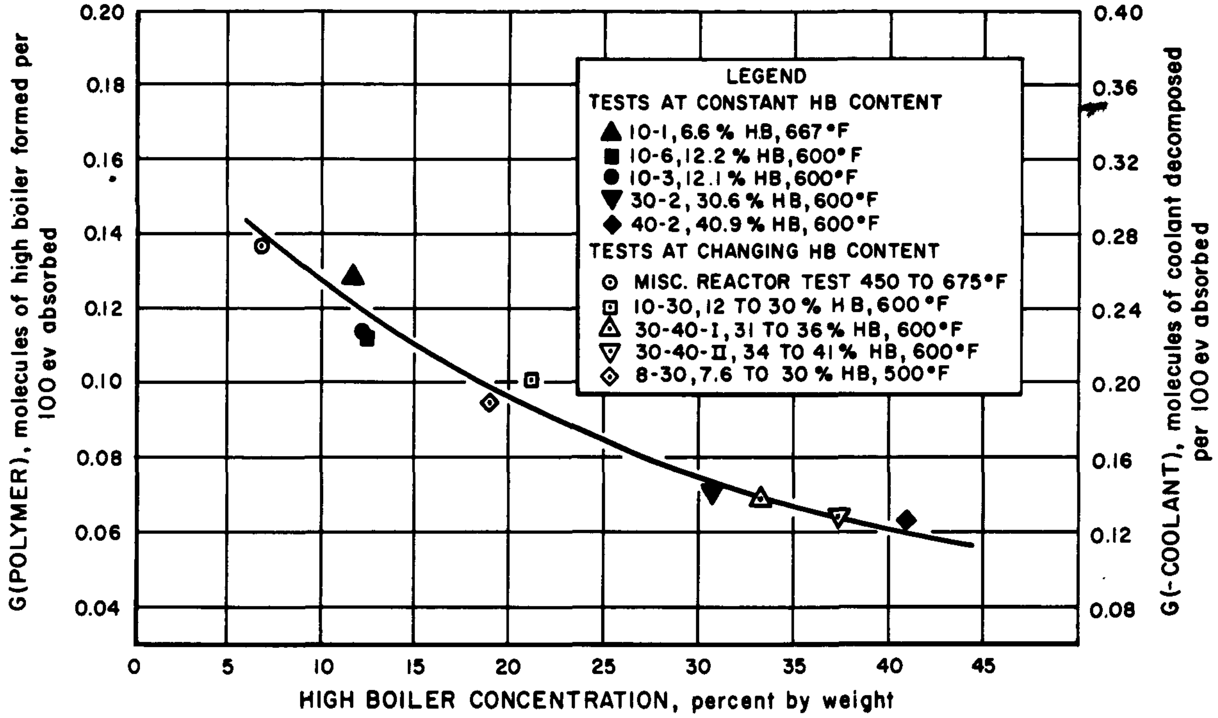


FIGURE 14.—*Decomposition rate of OMRE coolant.*

TABLE 12

ADDITIVES WHICH REDUCE RADIATION DECOMPOSITION RATE

| Additive | Reduction in G (polymer) (%) | Reduction in G (gas) (%) |
|---|---|---|
| 1,1,4,4-Tetraphenyl butadiene | 20 | 30 |
| 1,6-Diphenyl hexatriene | 25 | 30 |
| Tetraphenyl cyclopentadiene | 25 | 35 |
| Phenanthrene | 20 | 55 |
| Pyrene | 25 | 15 |
| 3,4-Benzpyrene | 50 | 50 |
| Alpha truxene | 30 | 10 |
| Triphenyl methane | 30 | 15 |
| 1,2,3,4,5,6,7,8-Octahydrophenanthrene | 30 | 10 |

heat, and dissolved gas content are measured periodically during the operation of the OMRE to provide current information for daily operations. Experimental programs to evaluate the critical density and temperature, thermal conductivity, water solubility, and explosibility characteristics of organic coolant materials are currently in progress. In addition, a design study to develop a PVT apparatus for high temperature application has been initiated.

### (2) RADIATION EFFECTS AND COOLANT DECOMPOSITION

A second high temperature screening test of additives and new coolants is being carried out. Thirty-nine new additive coolant samples are being tested and nine additives which reduced the rate of polymer formation in the first screen test are being retested. In addition, nine new coolant materials are being irradiated. The effect of the presence of the high boiling compounds formed by the irradiation of terphenyl coolant on the decomposition rate of terphenyls is being investigated. The possibility of regenerating terphenyls from the high boiling compounds with hydrogen under reactor conditions is being investigated.

In addition to this program, the OMRE is currently embarking on a long-time steady-state run at a high boiler concentration of 30 percent. This will establish the equilibrium conditions expected to prevail during constant operation of OMR power reactors. Steady state is expected to be achieved with respect to the detailed chemical composition of the high boiler fraction.

### (3) Chemical Properties

Work is underway to separate and identify the intermediate boilers, i.e., those compounds boiling between diphenyl and p-terphenyl; ozonization is being explored as a method for measuring olefin content of the coolant; the high boilers are being examined by mass spectrometry; the high boilers are being separated and identified; hydrogen density, particulate, water and acid content, and chemical composition of important components of the coolant and molecular weight of coolant and HB are being followed during operation of the OMRE.

## 5. Reactor Safety

### *a. Philosophy*

Organic cooled reactors possess the following characteristics which make them inherently safe plants:

(1) Negligible corrosion by the coolant of reactor construction and fuel materials ($<30$ $\mu g/cm^2$-month in the OMRE as compared to 2,000 $\mu g/cm^2$-month in pressurized water reactor systems) (31).

(2) No chemical incompatibilities between the coolant and either water or fuel materials.

(3) Low induced radioactivity of the coolant (150 mr/hr at 10 Mwt in the OMRE as compared to 17r/hr at 10 Mwt in the SM–1) (32).

(4) Low coolant vapor pressure (10 psia at 675° F.) (27) and hence, low operating pressure (150 psi in the OMRE) at temperatures in the range of interest for power reactors.

There are, however, certain hazards associated with the use of an organic fluid as coolant for nuclear reactors and certain plant-accident or equipment-failure situations wherein hazardous conditions may develop.

These hazards may be divided into two broad groups:

(1) Those arising from the presence of radioactivity or radioactive materials, such as direct radiation from the core or ingestion by humans of radioactive gases and vapors; and,

(2) Those arising from nonradioactive causes such as fires, fumes from coolant leaks, or chemical toxicity of the coolant.

Hazards in the first group are specific to reactor plant operation and those in the second group are typical of the chemical or petroleum industries.

Hazards in an organic reactor may be further classified as:

(1) Routine, i.e., coolant toxicity and fume hazards, or direct radiation from the core; and

(2) Plant accident situations, i.e., fires, large leaks of coolant, loss of coolant flow to the reactor core, or nuclear excursions in the reactor core.

Basic protection against these hazards is provided by incorporation of safety and protective features into the plant design based on consideration and analysis of potential hazards and accident situations. Additional protection for plant operating personnel is provided by the plant shielding and by the control of access to radioactive areas in the plant. Additional protection for the public is provided by restricting public access to the boundaries of the site, and by limiting the release of radioactive

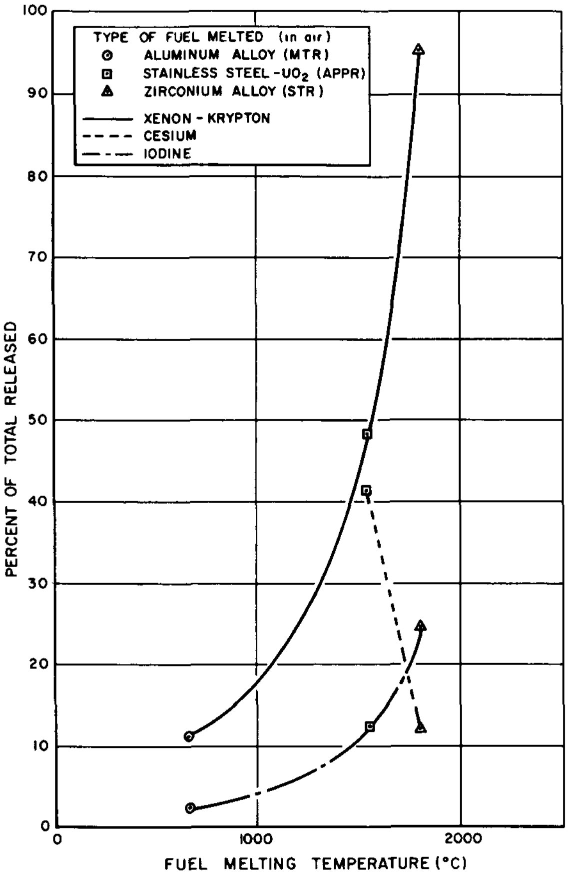


FIGURE 15.—*Correlation of percentage release of fission products with fuel melting temperatures.*

materials from the plant site to levels below the tolerance established by law.

***b. Containment Philosophy***

The basic consideration in reactor containment philosophy is to prevent the dispersal of hazardous amounts of radioactive materials as a result of any credible circumstance. This requires that the reactor plant design and its operating procedures give consideration to any and all conditions which might arise during normal or abnormal operation. In practice, adherence to this philosophy has resulted in including the following features which are typical of reactor plants:

(1) Some exclusion area surrounding the reactor plant.
(2) A stack used for discharge of gases released from the plant.
(3) Provisions included in the plant for the concentration and packaging of nongaseous radioactive wastes for subsequent disposal.
(4) Radiation shielding used around the reactor core and associated coolant system.
(5) Necessary containment features for radioactivity, including, in particular, the fuel element cladding and the coolant piping system.

In an OMR plant using a clad metallic fuel, it is possible to provide a design which will assure no fuel melting under any credible circumstance. In this instance, adequate containment is provided by the fuel element cladding itself. The amount of radioactivity which can be present in the coolant cannot form an external hazard, even in the event of a primary system rupture.

In OMR plant designs utilizing $UO_2$ fuel, the situation is different in that the accepted fuel element failures can lead to a much larger quantity of radioactivity circulating in the organic coolant. Figure 15 shows a correlation of percentage release of fission products with fuel melting temperature for fuel samples taken from the MTR, SM–1 and Submarine Thermal Reactor (STR) (33). The SM–1 stainless-steel clad—$UO_2$ elements released 52 percent of the Xe and Kr. Designs which permit operation with these higher coolant radioactivity levels have also been recommended to include a third containment barrier in the form of an external steel building shell. This shell would, of course, also serve to prevent the dispersal of radioactivity directly from the core in the event that some credible circumstance could not only rupture the organic coolant system but also cause melting of the fuel.

The inherent safety characteristics of the OMR system, in the form of negative temperature coefficients ($-5.0\times10^{-5}$ Δk/k-° F. at 600° F. in the OMRE), lack of potential exothermic chemical reactions, and a relatively low vapor pressure coolant result in a safe reactor plant. Containment would normally be provided by the fuel element cladding and by the coolant piping system. Additional containment provided by a third barrier in the form of a steel building shell is to be recommended only for unusual circumstances, such as location in a highly populated area or as a result of particular design features which could make the release of hazardous amounts of radioactivity conceivable. Even for particular locations or designs where containment provision by an external shell is recommended, an OMR plant only requires a shell capable of withstanding low internal pressures since no circumstances can result in the production of large amounts of gas within the reactor building.

#### *c. Work Completed*

##### (1) TOXICOLOGY OF POLYPHENYL COOLANTS

The toxicology of diphenyl and Dowtherm A (a commercially available mixture of diphenyl and diphenyl oxide used as an industrial heat transfer medium) has been extensively studied by Government laboratories and by the Mine Safety Appliances Company (34). The pharmacological inertness of these materials, as well as the terphenyls and similar polyphenyl compounds, has been established by these studies.

##### (2) FIRE AND EXPLOSION HAZARDS

Fundamental properties on flammability, explosive concentrations, self-ignition, and flame and flash points for various polyphenyl coolant materials have been determined by the U. S. Bureau of Mines (34, 35). This work has demonstrated that with proper precautions in design of organic reactor systems, fire and explosion hazards can be reduced in severity to those encountered in routine operation of petroleum refineries.

##### (3) CHEMICAL REACTIONS OF COOLANT WITH REACTOR MATERIALS

###### (a) *Fuel-Cladding Reactions*

Experimental information on chemical reactions between $UO_2$ fuel and aluminum indicated formation of an intermetallic compound between aluminum and uranium when intimately mixed in a dispension-type matrix, at temperatures above 900° F. Initial tests in which $UO^2$ pellets were sealed in a APM–257 tube and held at 900° F. for approximately 30 days indicate no reaction. While further tests are under way, it is presently believed that no chemical instability exists.

###### (b) *Coolant-Cladding Reactions*

Corrosion tests of APM and aluminum material in organic coolants at reactor operating conditions have indicated excellent corrosion resistance. Since the corrosion rate observed for aluminum cladding materials in organic coolants have been essentially negligible, the combination of APM cladding with coolant may be considered nonreactive.

###### (c) *Coolant-Fuel*

No problems of incompatibility between $UO_2$ fuel and organic coolant are known and none appear to exist. Corrosion tests of $UO_2$ in Santowax R at 750° F. indicate no significant weight changes in the fuel.

Although the work on chemical compatibility is not extensive, it serves to indicate the relative inertness of organic reactor material as compared to sodium—uranium or zirconium —uranium—water systems.

##### (4) TRANSIENT ANALYSES OF REACTOR ACCIDENTS

Each core design for an organic reactor prepared at AI has included detailed analysis of temperature, pressure, and power, transient phenomena which could occur to the reactor either during routine operation or in the event of a reactor accident. These analyses have guided the core and plant design by establishing the requirements for the plant protective systems, and determining limitations on maximum temperatures, heat fluxes, power densities, and thermal shocks and other transient conditions, on core and plant materials.

This analytical work has included study of the transients in the reactor core resulting from the following accident situations:

(*a*) Uncontrolled reactivity insertions, i.e., startup accidents, introduction of cold coolant into the core, continuous withdrawal of control rods.
(*b*) Loss of coolant flow accidents.
(*c*) Loss of pressure in the core and coolant system.
(*d*) Loss of electrical power in the reactor plant, with subsequent need for cooling of the core and removal of decay heat.

In addition, accident situations involving the plant as a whole have been analysed as follows:

(*a*) Effects of a large peak or spill of hot coolant caused by failure of a plant component or rupture of a coolant line.
(*b*) Effects of failure of a tube in a steam generator and introduction of steam and water from the steam system into the organic coolant system.
(*c*) Effects of a coolant fire.
(*d*) Additional effects of these accidents caused by contamination of the coolant with fission product activity.

### (5) OMRE FUEL ELEMENT FAILURE

The OMRE is a full-scale reactor experiment designed to demonstrate the technical and economic feasibility of an organic cooled and moderated reactor for power plant application. The plant has been in operation since September 1957. To date, the OMRE has accumulated about 1,000-Mw days of operation at power with coolant temperatures ranging from 500° to 700° F. and at power levels up to 12 Mw. Specific OMRE experience of interest to safety and hazards aspects of organic reactor follows:

#### (a) *Radiation Levels During Plant Operation*

Since the coolant does not become activated during operation, the OMRE is designed essentially as an unshielded plant. Except for protection against direct radiation from the core itself, no shielding is necessary for the plant process areas, and access to the plant equipment is possible during power operation. The radiation level in the region of the main coolant pumps during operation at 6–12 Mw is in the range of 50–150 mr/hr at a 1-foot distance from the 10-inch diameter main coolant piping.

#### (b) *Radioactivity in the Coolant*

Induced radioactivity in the coolant is due to activation of small quantities (about 5–10 ppm) of impurities and corrosion products circulating with the coolant. The major isotopes contributing to this activity are $Mn^{56}$, $Mg^{27}$, $Na^{24}$, and $As^{76}$ as coolant impurities and $Mn^{56}$, $Co^{58}$, $Cr^{51}$, and $Fe^{59}$ as corrosion products (36). The specific coolant activity during operation is about 0.08 to 0.10 $\mu$c/cc. Most of this activity is removed from the reactor by the purification system and is thereby concentrated in the high boiler compound.

#### (c) *Effects of Failure of Test Fuel Element*

In October 1958, a test fuel element, similar to the type proposed for the Piqua OMR, failed while operating in the OMRE. The element consisted of flat plates of slightly enriched, metallic uranium—molybdenum-alloy fuel material, clad with 2S aluminum. The failure was caused by plugging of the inlet end of the element with particulate material circulating in the coolant. The resulting flow stoppage in the element caused partial melting of the fuel and release of approximately 200 curies to the coolant system. Radiation levels before and after this incident were as follows:

| *Time* | *Radiation 1 ft from 10-in. diameter piping, r/hr* |
|---|---|
| Prior to failure | 0.04 |
| Instant of failure | 10 |
| 1 hour after failure | 2.4 |
| 1 day after failure | 0.05 |

Analysis of the coolant after the failure indicated that only gaseous and the more volatile fission products such as Xe, I, Br, La, Te, Kr, and Ra were released. No metallic fission product isotopes were found in the coolant. Subsequent operation of the reactor with the failed element still in place resulted in only further release of the same fission products. Cleanup of activity was accomplished by operation of the purification system.

### (6) FUEL ELEMENT MELTDOWN

Data from reference 4 (see fig. III–15) indicates that 52 percent of the volatile fission products will be released when an $UO_2$ fuel element melts. Therefore, one melted 300-Mwe OCR pin (100 pins per fuel rod) with 52 percent of the volatile fission products released, yields about 98.2 $\mu$c/cc in the coolant. However, the probability of completely melting a pin in the OCR is remote.

### (7) POSTIRRADIATION EXAMINATION OF ELEMENT OMRE–3

During the OMRE shutdown in June 1958, Element OMRE–3 was removed and sent to Battelle Memorial Institute for postirradiation examination and evaluation. The following is the evaluation taken verbatim from reference 20, BMI–1319:

> "The results of the postirradiation examination of Element OMRE–3 are generally encouraging to the organic moderated reactor concept. The organic moderator apparently did not produce any corrosion difficulties. The lack of heavy deposits of organic residues or obstructions in the coolant channels of the fuel element indicates the suitability of the Santowax OM moderator-coolant. As would be expected at the burnup and temperature experienced by this fuel element, the stainless steel—$UO_2$ fuel matrix exhibited very little radiation damage. The element design is also apparently satisfactory since major distortions or other defects were not found."

## *d. Work Underway*

Current Research and Development effort in the area of hazards and reactor safety falls primarily into the following two categories:

### (1) OPERATION OF THE OMRE

Operating data from the OMRE is evaluated on a continuous basis in terms of reactor hazards and safety. This includes:

(*a*) Determination of the degree of accessibility to various regions of the plant during operation at power and after shutdown.

(*b*) Analysis of radioactivity of coolant, waste gases, solid waste materials, and study of problems of disposal of radioactive waste materials.

(*c*) Determination of operating limitations on the plant as designed, and evaluation of improvements in operating procedures and plant design.

### (2) REACTOR PLANT CONTAINMENT STUDIES

The problem of leak-tightness of various reactor containment materials is being studied to determine how much, and in what manner, the cost for reactor containment can be reduced through proper selection and use of containment materials. An answer is being sought on the degree of leak-tightness necessary for reactor plant containment structures, how various materials (i.e., wood, concrete, plaster, steel) may be employed to attain this, what portion of leaked radioactive material may be safely considered to remain within a containment structure, and how a containment structure may be best designed to take full advantage of these features. Radiological implications of various leak rates are also under investigation in the study.

### 6. Components and Auxiliary Systems

#### *a. Work Completed*

##### (1) CONTROL RODS AND DRIVES

Two types of control safety rod drives have been developed for use in organic reactors. For the OMRE, a top-mounted rack-and-pinion type is used, with the drive motors mounted externally and driving through shaft seals. The moving parts contained inside the reactor tank are located near its top, in a nitrogen gas-filled expansion volume. The entire drive assembly is maintained at approximately 300° F. by means of a water-cooled heat exchanger, mounted between the tank lid and the drive housing. These rods have performed satisfactorily since early 1957.

For the Piqua reactor, a chief requirement was that the rods and drives do not interfere with refueling operations. For this reason, a magnetic-jack-driven "unitized" rod was developed for installation inside the reactor vessel. By restricting the diameter of the rod assembly to 6.25 inches, the fuel elements may be inserted or removed without removing the control rods. A prototype rod of this design has successfully undergone accelerated life tests, equivalent to several years of reactor operation.

For both of the rods described above, boron carbide is used as the neutron absorber. The $B_4C$ is used in tubes, designed to withstand pressures generated by the helium gas liberated in the n, *a* reactor in the boron. The tubes for the OMRE rods are 1¼-inch diameter, ⅛-inch wall thickness. The Piqua elements, being larger in diameter, are composed of a number of smaller tubes (¼-in. diam. $\frac{1}{32}$-in. wall), to minimize the metal required for pressure containment.

Preliminary design work has started on control rods utilizing a cruciform poison section varying from 6 to 12 feet in length, the blades of which are ¼-inch thick and measure from 3.5 to 4.5 inches from root to tip. The blades may be composed of 0.200 inch of either boron steel or $Eu_2O_3$-steel matrix clad by 0.025-inch thick stainless steel. The poison concentration may be adjusted—depending upon the rod location.

Cost optimization of control rods containing different poison materials, $Eu_2O_3$, $B^{10}$, $Sm_2O_3$, $Gd_2O_3$, and $Dy_2O_3$ have indicated that even though the initial cost of $Eu_2O_3$ rods is higher than that of the other poison materials, the increased lifetime more than compensates on the basis of minimum annual cost.

##### (2) DEGASIFICATION SYSTEMS

Due to the sources of water vapor and the continuous production or radiolytic gases, the necessity of a degasification system was recognized and work initiated in September 1957. A process was selected which depends upon the principle of a reduction in the solubility of these components with decreasing pressure. In order to examine the effect of the several parameters of the process upon the overall efficiency, a small scale loop was designed and constructed at Santa Susana.

The experimental program was divided into two areas and work in each proceeded simultaneously. In order to investigate the removal of water vapor from organics, it was anticipated that some means of water analysis would be required. Accordingly a review of existing methods and equipment showed that our requirements were too severe, hence modifications or new methods would be necessary. After thoroughly discussing our requirements with several instrument manufactures it was decided upon an instrument measuring the dielectric constant of the organic. The necessary work to revise the equipment to accommodate the temperatures and water range was initiated. This equipment with necessary additions to compensate for the change in dielectric constant with temperature was completed and delivered to us for evaluation.

The second area of this program consisted of examining the removal of the radiolytically produced gases (simulated by nitrogen) from isopropyl diphenyl and Santowax R. The parameters investigated included the system vacuum, the feed rate to the degasification system, the temperature of the feed, and the degree of atomization in the vacuum vessel. This information was summarized in an internal report (37).

Using the information obtained from the small-scale degasifier loop, a quarter-scale prototype of the Piqua degasification system was designed and is currently being constructed at Santa Susana.

### (3) Inorganic Impurities Removal

Operation of the OMRE has shown the importance of keeping the coolant in an OMR free of particulates and impurities. Buildup of solid impurities can result in restriction of flow through fuel plate coolant channels. Activation of impurities in the coolant can seriously limit access to process areas, increase shielding requirements, and complicate disposal of high boilers.

As a result of problems at the OMRE, work under the OMRE Purification Project has been expanded to include investigations of coolant impurities problems. Work to date has included laboratory filtration and absorption experiments. An experimental loop has been designed for testing of various removal devices including filters, absorbers, separators, and centrifuges. This loop is to be constructed and operated during fiscal year 1960 under the Advanced OMR Development Program.

An outline summary of work to date follows:

(*a*) First 6 months of OMRE operation showed a coolant activity of 80 mr/hr at 10 Mw at the surface of the 10-inch main coolant line.

(*b*) Melting of a fuel element at the OMRE introduced a large amount of contaminants into the system.

(*c*) Early efforts to determine source and cause of $S^{35}$, $p^{32}$, and $Mn^{56}$ were never completely resolved; however, it appears that much of the difficulty was due to uncleaned tanks and dregs from drums in which the feed material was delivered.

(*d*) A program was initiated in mid-March 1959 to develop methods of removing inorganic impurities from OMR systems.

(*e*) It has been established that much of the impurity content is fine particulates collected on the micron size filters.

(*f*) Adsorption methods have been tested but as yet have produced inconclusive results.

The project could lead to a significant reduction in the activity of the reactor coolant.

### (4) Coolant Purification

Research and development work began on the purification of irradiated OMR coolants as part of the OMRE design and development work in the latter part of 1955. Sample batch distillations of irradiated polyphenyl materials from the first in-pile loop (NAA-18) were conducted in the laboratory.

A single plate batch still was designed and constructed at the OMRE to provide for purification of OMRE coolant during reactor operation. Field operation and laboratory support on the OMRE Purification Project provided useful information concerning operating temperatures and pressures, decontamination factors, and manpower required to operate the still.

At the beginning of fiscal year 1958 (July 1957), a new research and development project for development of a purification system for the Piqua Reactor was initiated. It was apparent from OMRE experience that an automatic purification process system would be the most efficient and economical means of purifying OMR coolants used in power reactors. Various means of purification were studied as well as thermodynamic properties and physical properties in order to design an automatic process system for the Piqua Reactor. A combined flashing chamber and packed stripping column was designed. A full-scale prototype was constructed to evaluate optimum operating parameters and still performance.

A third project called OMRE Purification Modification was begun in December 1958 to cover the design of a new automatic purification processing system for the OMRE. This project utilized design information already avaliable under the two previously mentioned projects. The design of the new system has been completed, and procurement of equipment begun.

To date the Piqua OMR Purification Program has resulted in extensive measurements of physical properties such as latent heat of vaporization and vapor-liquid equilibria, and the design and construction of a prototype purification system to treat 1,000 lb/hr.

The results of the OMRE Purification Program indicate that reduction of coolant activation by removal of particular isotopes is possible. Decontamination factors of about 100 for $Mn^{56}$, $Mn^{54}$, and $P^{32}$ have been achieved by batch distillation. No reduction in $S^{35}$ contamination was possible. The operation of the OMRE still has also indicated that pyrolysis of high boilers (HB) becomes excessive at temperatures in excess of 800° F. Operation of stills containing high concentrations of HB should be limited to 700° to 750° F.

### (5) Waste Gas Treatment

The work objective to date has been to develop a processing system to prevent atmospheric contamination from organic vapors or from radioactivity present in waste gases produced during all phases of OMR operation. Principal sources of waste gases are decomposition gases from the degasification and purification systems and combustion gases from the residue burning system.

All work has been done under the Piqua Waste Gas Treatment Project, started in early 1957. Work completed to date includes:

(*a*) Waste gases from the OMRE were analyzed during the period March-November, 1958 for composition, generation rate and gross radioactivity.

(*b*) The composition of OMRE purification system off-gases was determined.

(*c*) Scrubbing and cold trapping of organic vapors have been investigated. Scrubbing of organic vapors from gas streams results in 90 to 95 percent particulate removal as expected from equipment of this type. The controlling factor is the temperature reduction of the gas that can be obtained by scrubbing system. The lowering of temperature results in condensation of the organic with subsequent knockdown of the particles. Cold traps have high initial efficiency, but if the heat transfer surface becomes coated with organic material the efficiency decreases rapidly. Cold traps also create dusts that will be carried through the trap unless efficient screens are present. The screen then tends to plug and increase the pressure drop.

(*d*) Removal of organic material from water has been studied. Screens and filters become high maintenance items, due to the plastic nature of the organic materials causing rapid increase in pressure drop. Settling is feasible if time is available because the specific gravity of the organic material is about 1.05 to 1.1. Tests indicate that 0.05 percent Santowax R will settle completely in 1½ to 2 hours when dispersed in water by a scrubbing system. Batch and continuous type centrifuges have been used successfully to remove the organic material.

(*e*) Scrubbing of residue burner combustion gases has been investigated. Scrubbing will remove 82 percent of the particulates on a weight basis and 92 percent on an activity basis. Scrubber efficiency on gaseous activity varied from 0 to 90 percent which is not at all significant for removal of $S^{35}O_2$. Measurements show that 87 percent of the activity was gaseous ($S^{35}O_2$). Scrubbing with wetting agents and alkaline solutions were not successful for removing $SO_2$

(*f*) Extraction of radioactivity into water and removal by ion-exchange has been studied. OMRE coolant and HBC was used in an attempt to extract activity in water. Unless a substantial amount of low boilers are present (1 percent or more) the activity cannot be extracted into the water. The activity was easily removed using Amberlite IRA–400 and IR–120 ion exchange resins.

(*g*) An experiment was conducted to evaluate the performance of absolute (CWS) filters and coarse prefilters in removal of coolant vapors. Organic vapors have been found to create a layer of solid material on prefilters with a large increase in pressure drop. The amount of organic materials that is carried through the prefilter is not sufficient to clog the absolute filter, but prefilters should be monitored for pressure drop. Most organic material through the prefilter is gaseous.

(*h*) The adsorption of diphenyl on activated carbon has been experimentally determined. Activated carbon was found to be an efficient adsorbent for removal of diphenyl vapor both with and without water vapor present. Cyclic tests have shown that the concentration of diphenyl can be reduced to below 0.9 mg/m$^3$ by activated carbon at 200° F. and 0 psi.

#### (6) WASTE DISPOSAL

The objective of this program has been to develop a processing system which will provide for disposal of the high boiler (HB) removed from the OMR coolant by the purification system.

Work under the Piqua Residue Handling Project has been confined almost entirely to disposal by means of burning. A water leaching test was conducted to obtain some indication of the feasibility of disposal of HB by uncontained burial in terrestrial pits. Leaching for 335 hours in a Soxhlet extractor showed no activity above background in the leach water. This would indicate that disposal of HB by burial is feasible.

#### (7) CONVENTIONAL EQUIPMENT

Equipment used in the organic reactors is standard and similar to that used in the petroleum industry. No research and development work has been started on pumps, valves, and piping.

### *b. Work Underway*

#### (1) COMPONENTS AND AUXILIARY SYSTEMS

#### (a) *Control Rods and Drives*

The first Piqua prototype unitized control-safety rod has been removed from the furnace after 6 months of accelerated life testing. This rod was originally designed for operation "dry" (gas-filled), and was modified for operation "wet", (organic-filled). A second prototype, designed for wet operation, has been assembled and has started life tests in the furnace.

#### (b) *Degasification Systems*

Work underway at the present time is centered in two areas: (*a*) the development of an instrument to measure continuously the concentration of water in organic coolants, and (*b*) the construction of a quarter-scale prototype of the degasification system for OMR Piqua.

The operation of the water analysis instrument is based on the change of dielectric constant of organic coolant with change in water content. The main problem in the development of this instrument is in the compensation for changes of organic temperature which also varies the dielectric constant of the mixture. An attempt is being made to calibrate the instrument by sending samples to an outside laboratory for analysis. The temperature compensator associated with the equipment now operates properly over a range of only 40° F.; steps are being taken to increase this range to 200° F.

Construction of the prototype equipment is nearly complete with equipment checkout to begin within the month. The objective of the operation of this equipment will be to obtain operating information for the Piqua reactor and to study the parameters of the degasification process on the Santowax R—water solubility problem.

#### (2) COOLANT PURIFICATION, IMPURITIES REMOVAL, COOLANT PURIFICATION, WASTE GAS TREATMENT, AND WASTE DISPOSAL

Current work in all of these areas is confined to the construction and operation of the Piqua plant prototype systems.

### 7. Fuel Handling

#### *a. Work Completed*

Fuel handling is done differently for tank-type, pile-type, and vertical-pressure-tube reactors. With tank-type reactors, the fuel reloading method may be either of the cask or wet type. The cask type requires a large refueling cask (approximately 50 tons by 35 feet high) with complete remote control and indexing.

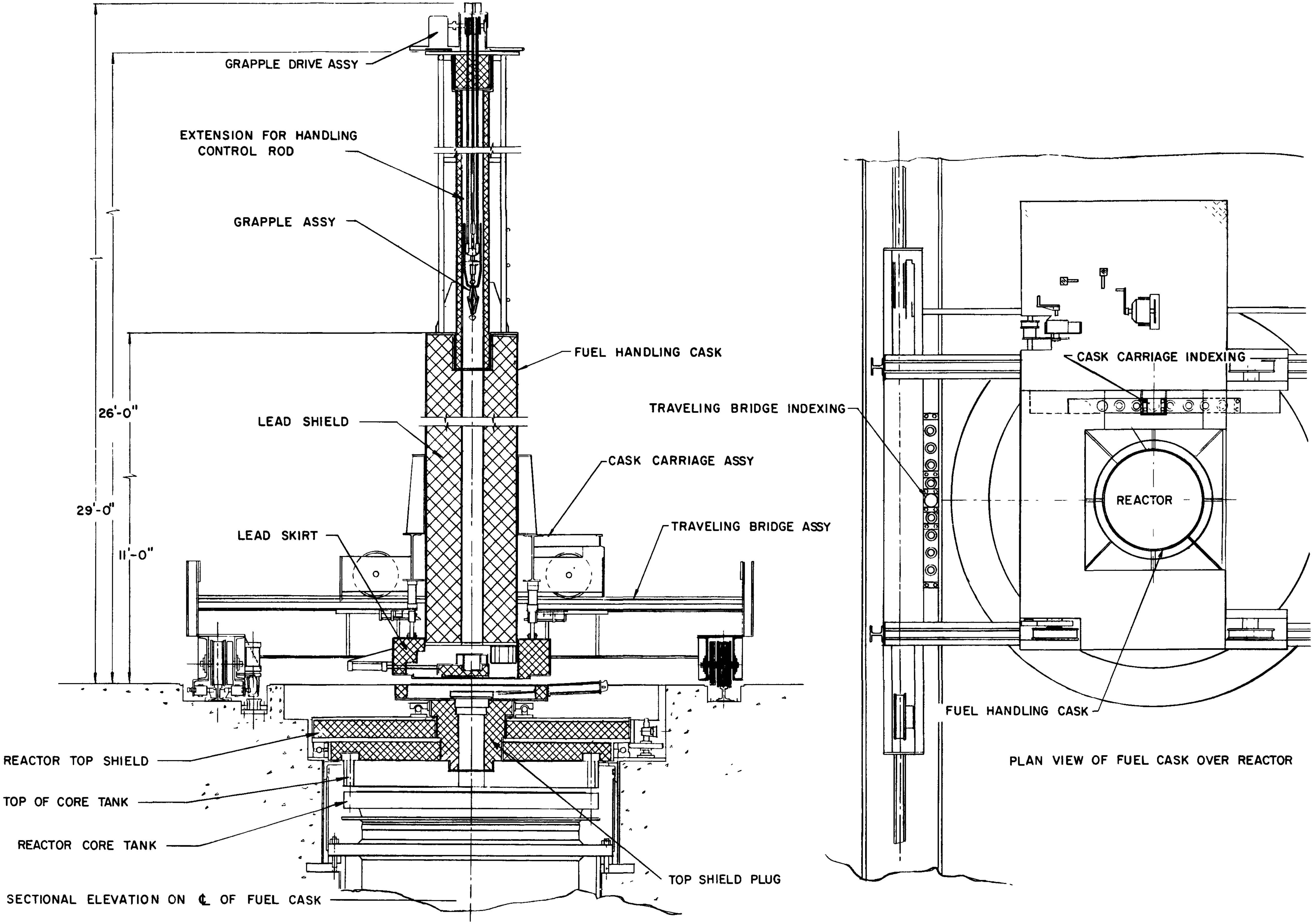
A typical example of the cask-type system is the one developed for the Piqua OMR as shown in figure 16.

A wet-type system developed for large OCR reactors is shown in figures 17 and 18. The element is in coolant at all times. The fuel element is raised until the lower end is free from interference with any core intervals and the upper end is covered by a minimum of 12 feet of organic. It is then placed on a tilt-table support guide. The support pivots about its lower end, until the whole assembly is in line with the fuel element transfer tube.

Proper sequencing of valves allows the fuel element to be inserted into the transfer tube, which is filled with organic. A solvent displaces the organic and cleans the fuel element. After the cleaning cycle is over, water displaces the solvent, and the fuel element is transferred to a rack in the water storage pool. Only one element can be transferred at a time. The tube transfer system can be modified to use a fuel element storage turret. This turret accommodates several elements before the solvent and water wash cycles are required.

#### *b. Work Underway*

The fuel handling procedure proposed for the OCR design is being reviewed in an attempt to simplify the procedure, improve the feasibility, simplify the design, and reduce the operating time and costs. A manipulator-type hoist replaces the above-core fuel handling machine and serves to lift an element from its in-core position and lower it into a combination pivot and wash chamber in the sub-pile room. The reactor top shield and core tank head remain in place; the fuel element remains vertical, and is constantly "locked" to the manipulator grapple throughout its downward descent. An above-pool traveling bridge is equipped with a downward-extended guide boom and a tape-suspended grapple by which the elements are lifted from the pivot-wash chamber into the pool for storage. Slightly inclined withdrawal of elements for this operation permits positive control and a simplified



SECTIONAL ELEVATION ON ℄ OF FUEL CASK

PLAN VIEW OF FUEL CASK OVER REACTOR

Figure 16.—*Fuel handling cask.*

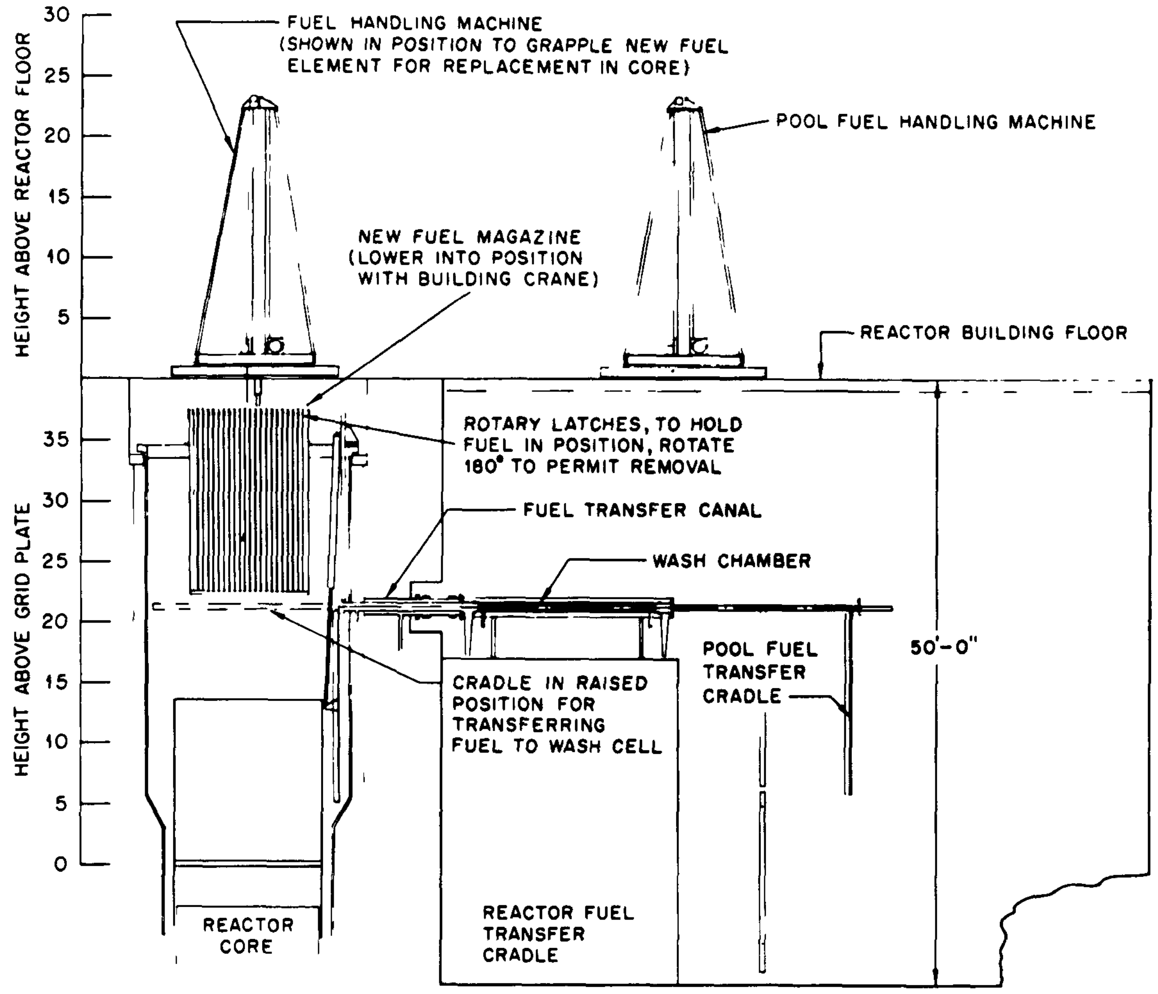


FIGURE 17.—*Fuel handling system.*

procedure for storing. It is believed that the advantages derived from the new fuel handling system warrant development of this fuel handling modification.

## B. EXPERIMENTAL REACTORS (OMRE)

### 1. Purpose

The reasons for the interest in the concept of an organic moderated and cooled power reactor and the advantages of this concept have already been described. All out-of-pile and in-pile capsule and loop tests had shown that the stability of some types of organic compounds is great enough to make their use not only technically attractive, but also economically attractive in nuclear power reactors. A full-scale reactor experiment was essential to establish the feasibility of the concept. This reactor experiment is the OMRE. It is not a prototype of a nuclear powerplant, but rather a full-scale irradiation facility designed to study the behavior of the most promising organic compounds under conditions similar to those encountered in power reactor applications.

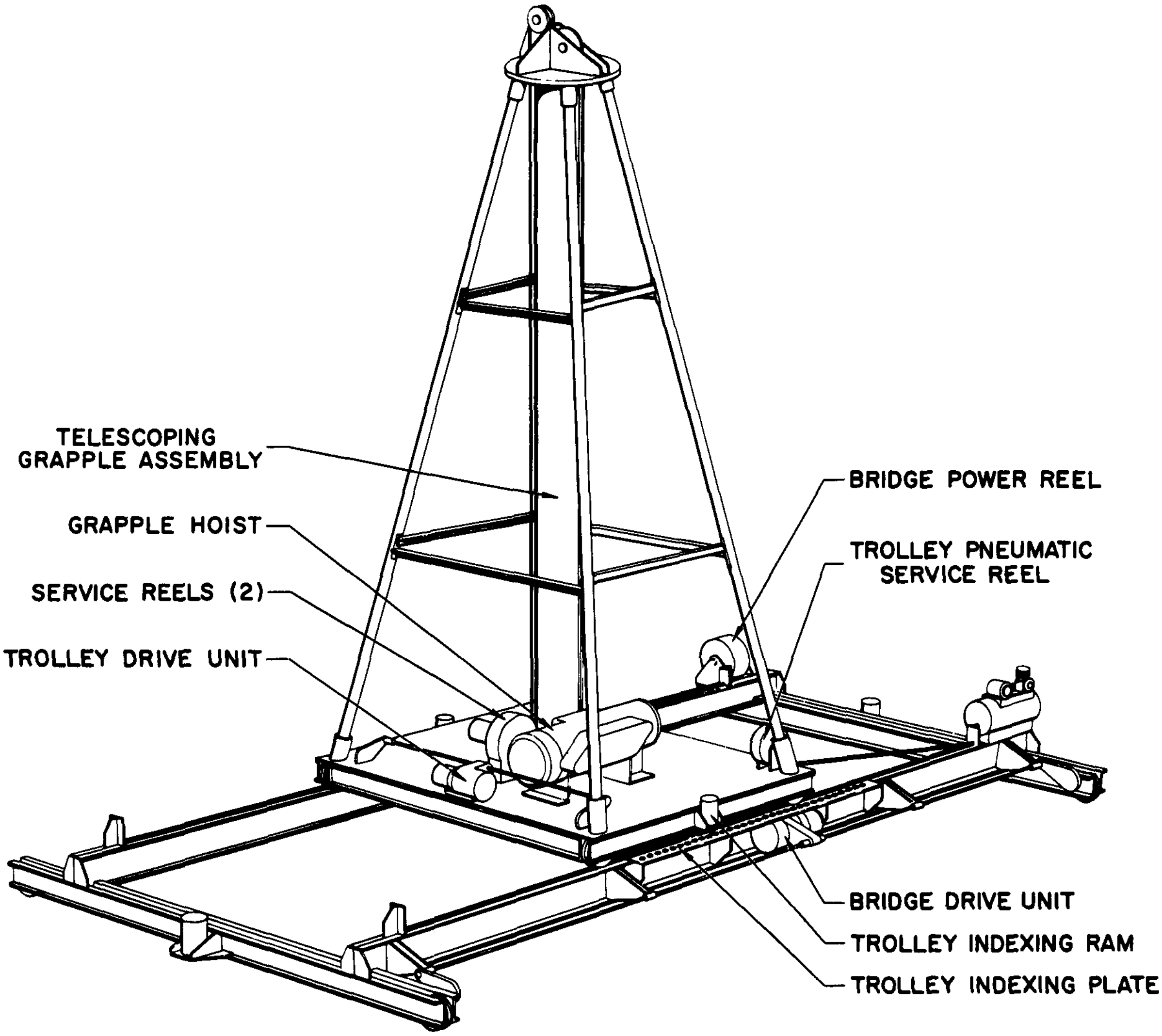


FIGURE 18.—*Fuel handling machine.*

It is the purpose of the OMRE to provide a conclusive test to demonstrate:

*a. The technical feasibility of the concept of an organic moderated and cooled power reactor.* The OMRE will show whether or not it is technically possible to operate this type of reactor continuously and reliably under steady state conditions without encountering unacceptable problems associated with the decomposition of the moderator coolant and possible deposition of high boiler material on the heat transfer surfaces in the system.

*b. The economic feasibility of this concept.* It is not sufficient to show that an organic moderated and cooled reactor can be operated successfully from a technical point of view. It is essential to know the hydrocarbon decomposition rates to be encountered in actual operation of such a power reactor, and the consequent coolant makeup rate requirements. The OMRE will provide this information, and thus permit an accurate estimate of the effect of the makeup cost of the hydrocarbon upon the cost of electrical power derived from this type of reactor.

*c. The possible advantages of the concept over other reactor types.* In addition to showing that the coolant makeup costs are reasonable, other factors which would affect the economics of the system can be investigated. These would be: (1) low operating pressures, (2) low corrosion rates with standard materials of construction, (3) low coolant activity, (4) simplicity of the overall system, (5) high degree of safety, and (6) the use of standard oil refinery equipment in the system. The OMRE can provide preliminary answers to some of these questions.

To provide this information, the OMRE was designed to meet the following criteria:

| | |
|---|---|
| Maximum fuel element surface temperature | 800° F. |
| Bulk coolant temperature | 500° to 700° F. |
| Maximum coolant velocity through core | 15 ft/sec. |

The limitation on the maximum temperature at the surface of the fuel elements was set at the time the OMRE was designed by the fact that even in the absence of radiation damage, pyrolytic cracking of hydrocarbons may become excessive above 800° F. A temperature of 500° F. is considered to be the lowest temperature of interest for power reactor applications, and the 700° F. upper limit on the bulk temperature is essential to allow a significant temperature driving force for heat transfer from the fuel elements to the coolant. The velocity of 15 ft/sec was determined by practical reasons to limit the amount of erosion in the piping system and keep the total flow rate of hydrocarbon in the OMRE within reasonable limits (9,200 gpm).

## 2. Chronology

The OMRE was authorized in 1955 to determine the economic and technical feasibility of the organic reactor concept. The reactor was designed, constructed, and placed into operation by Atomics International at the National Reactor Testing Station, Idaho.

The initial reactor design effort was started in July 1955. Construction was started in June 1956 and was completed in May 1957. The OMRE went critical in September 1957 and was followed by a few months of low power test and physics measurements. Full power operation began in February 1958 and by January 1959, the reactor had logged over 22 million kw of operation.

## 3. Description

### *a. Reactor*

Figure 19 shows a schematic flow diagram of the OMRE. The reactor core is located near the bottom of the reactor vessel and shielded by a 14-foot pool of hydrocarbon. A nitrogen blanket provides an inert atmosphere above the pool and maintains a 200-psig pressure on the system, corresponding to a saturation temperature of 920° F. for the OMRE coolant. A continuous purge of nitrogen over the surface of the coolant prevents a buildup of hydrogen and light hydrocarbon gases formed in the decomposition of the coolant under irradiation and sweeps these gases to the exhaust stack. An expansion tank is provided to take care of the large change in volume of the hydrocarbon during temperature transients (34 percent between 200° and 700° F.)

The cooling system circulates 9,200 gpm of coolant from the reactor to an airblast heat exchanger where the heat generated in the core is rejected to the atmosphere. An airblast heat exchanger is used as a heat sink in this experiment rather than a steam generator because it simplifies control of temperatures over the wide range of experimental operating conditions. Circulation is accomplished by means of two 4,600-gpm centrifugal hot-oil pumps operating in parallel. The mechanical seals on these pumps are cooled by recirculation of a small stream of cooled hydrocarbon from the discharge side of the pumps; a small leakage of coolant is considered permissible and is collected in drums for disposal. An auxiliary

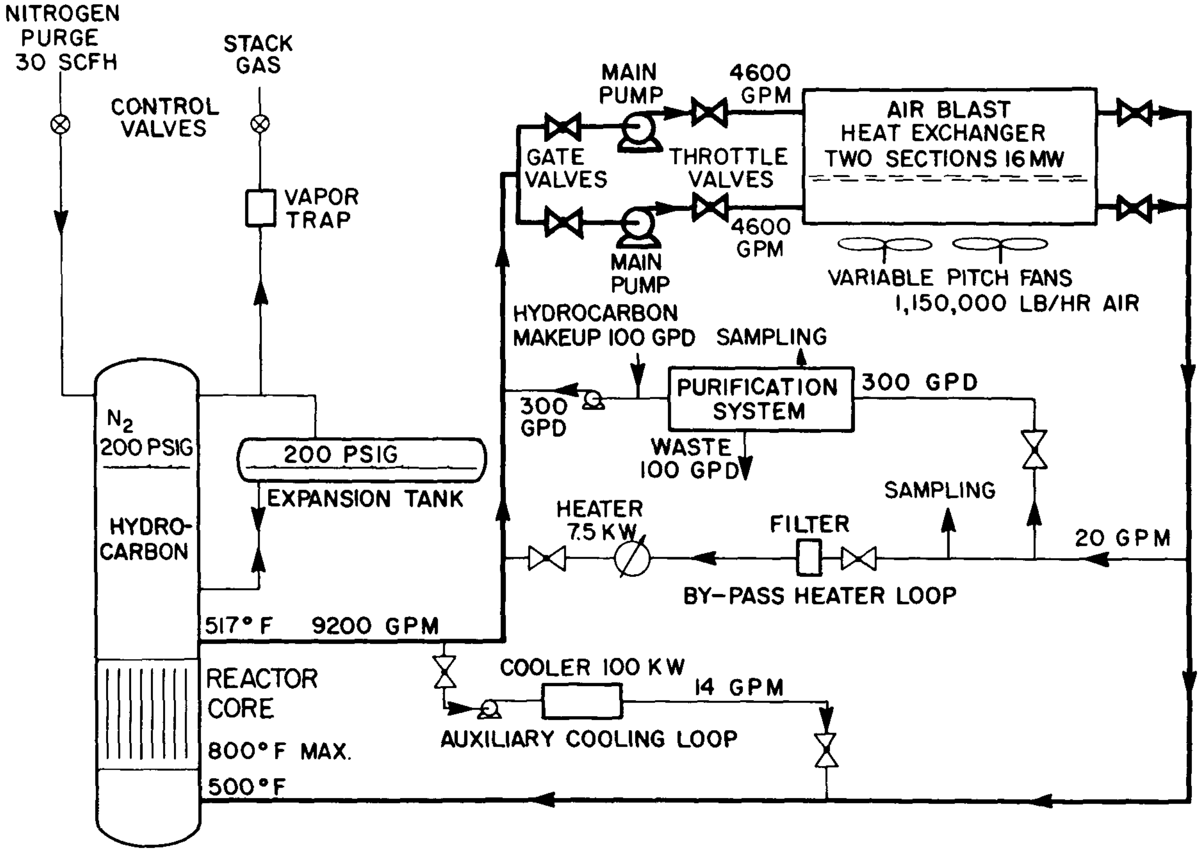


FIGURE 19.—*Schematic flow diagram.*

coolant system rated at 100 kw is provided to remove afterglow heat from the reactor during shutdown when the main coolant loop is inoperative. A spray cooler is used as the heat sink for this loop.

The bypass heater loop provides continuous information on the change in heat-transfer properties of the hydrocarbon during reactor operation. The test section of this loop consists of an electric heater plus temperature and flow instrumentation to allow determination of heat-transfer coefficients as a function of irradiation time of the coolant in the reactor, and to provide a convenient record of the effect of damage upon the heat-transfer behavior of the coolant outside of the reactor. A small self-cleaning filter is also provided for continuous removal of particulate matter from the coolant.

With the exception of the reactor vessel, which is made of mild alloy steel (½% molybdenum—1% chromium), and of the fuel elements, which are made of $UO_2$ in a matrix of stainless steel clad with stainless steel, the whole system is made of carbon steel. All components are provided with preheating equipment to bring the temperature of the system above the melting point of the coolant, and to maintain the coolant in a liquid state during extended shutdowns. Induction heating is used on the vessels and piping, the pumps are traced with heating cable, the airblast heat exchanger is provided with an oil furnace.

Figure 20 presents a perspective view of the overall arrangement of the OMRE facility at the National Reactor Testing Station in Idaho. The reactor vessel is shown in the

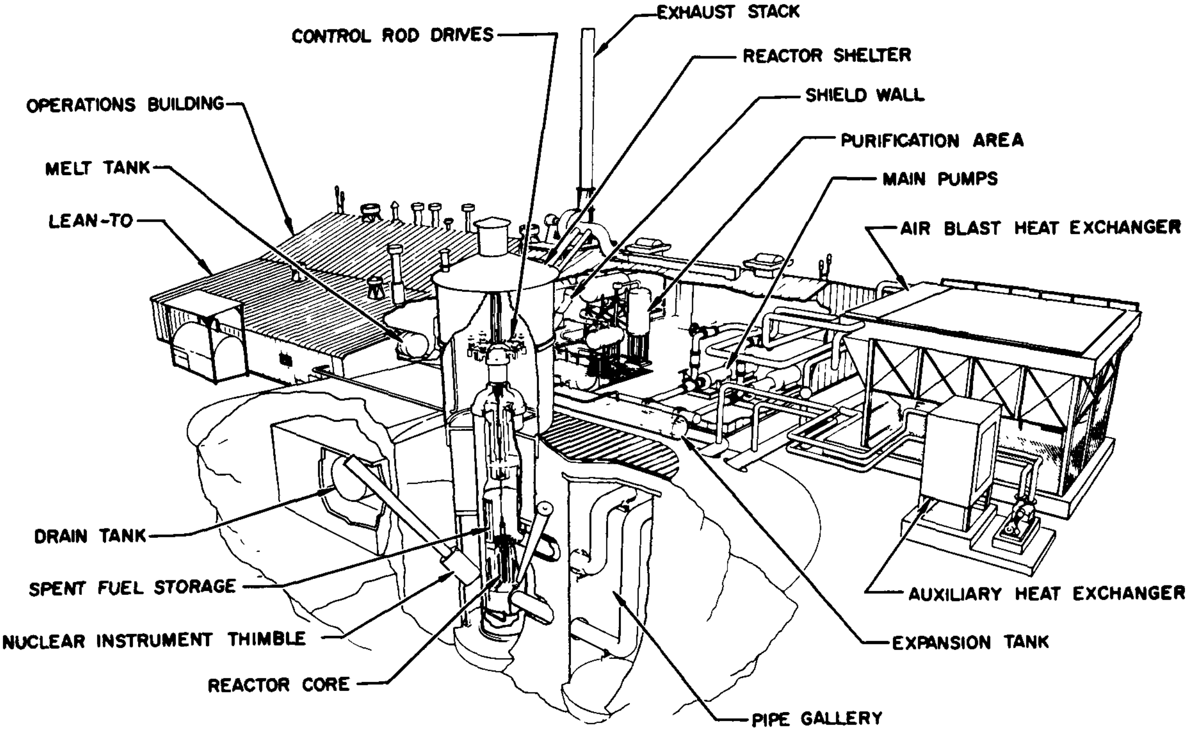


FIGURE 20.—*Perspective view of OMRE facility.*

foreground, the airblast heat exchanger to the right and the operations building in the background.

Figure 21 presents a cut-away view of the reactor vessel. Figures 22 and 23 present the core layout and the equipment layout. The major design and performance parameters for various coolant conditions are given below.

OMRE DESIGN PARAMETERS

Fuel enrichment—90%
Core size—34-inch diameter by 36 inches long
Reactor pressure—200 psia
Coolant—Santowax-OM
Moderator—Santowax-OM

| Bulk inlet temperature, °F | 500 | | 700 | |
|---|---|---|---|---|
| Peak/average flux ratio | 3. 16 | | 2. 80 | |
| High boiler compound, % | 0 | 35 | 0 | 35 |
| Thermal power rating, kw | 14, 800 | 10, 900 | 6, 200 | 4, 800 |
| Power density, kwt/ft | 695 | 512 | 291 | 225 |
| Central fuel temperature, °F | 750 | 750 | 800 | 800 |
| Core inventory, k to U-235 | 25. 5 | 25. 5 | 25. 5 | 25. 5 |
| $\Delta T$, °F across core | 25 | 18 | 10 | 8 |
| Viscostity ratio, $\mu/\mu_0$ | 1. 00 | 2. 43 | 1. 00 | 2. 20 |
| Avg specific power, kw/kg | 580 | 430 | 240 | 190 |
| Max specific power, kw/kg | 1, 830 | 1, 360 | 670 | 530 |
| Avg thermal neutron flux in fuel, n/cm²/sec | $2.0\times10^{13}$ | $1.5\times10^{13}$ | $9.5\times10^{12}$ | $7.4\times10^{12}$ |
| Max thermal neutron flux in fuel, n/cm²/sec | $6.5\times10^{13}$ | $4.8\times10^{13}$ | $2.7\times10^{13}$ | $2.1\times10^{13}$ |
| Avg heat flux, Btu/hr/ft² | 74, 000 | 55, 000 | 31, 000 | 24, 000 |
| Max heat flux, Btu/hr/ft² | 230, 000 | 174, 000 | 87, 000 | 68, 000 |

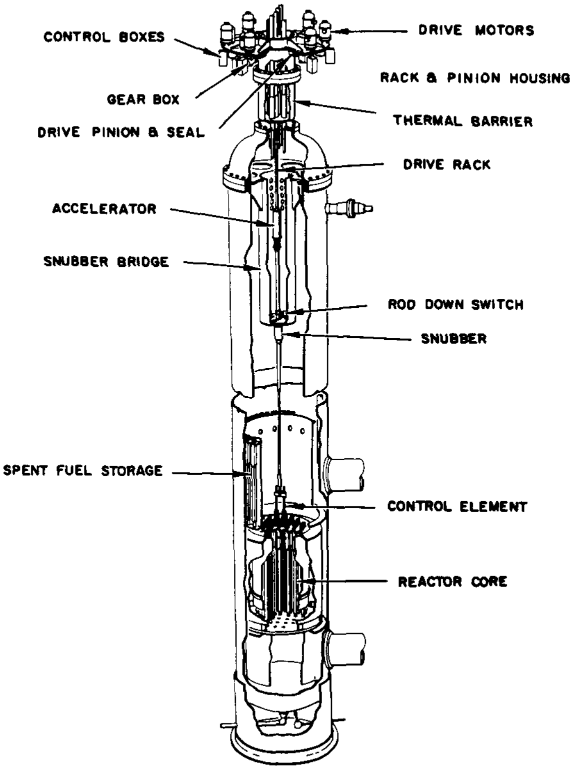


FIGURE 21.—*OMRE reactor vessel.*

***b. Process System***

The purification system removes a small batch of damaged hydrocarbon from the main coolant stream every day, purifies it, returns the purified material with additional fresh make-up to the reactor system, and rejects to waste storage the high boilers resulting from radiation damage. Purification is accomplished by means of low pressure distillation (20 mm Hg). A batch system is used because it allows the flexibility required by the large number of unknowns involved in such an experimental system. It is evident that a continuous system would be used in a full-scale power plant.

## 4. Operating Experience

***a. Operating Record***

### (1) LOW-POWER PHYSICS TESTS

A detailed description of the critical experiment, loading of excess reactivity, and other low-power physics tests have been presented previously, and is not included here.

### (2) POWER OPERATION

Sustained power operation began on February 1, 1958. Between this date and September 15, 1958, 765 MWD of power operation was accumulated during a series of tests to determine the radiolytic and thermal decomposition rates and the heat transfer properties of the coolant-moderator under a variety of operating conditions. During this period, tests were conducted at high boiler (HB) concentrations of approximately 12, 30, and 40 percent, and a bulk coolant temperatures of 600° F. (316° C.) and 700° F. (371° C.). The fuel-plate surface hot-spot temperature was maintained at 750° F. (399° C.) during the majority of this period. Decontamination of the coolant and new build-up of decomposition product concentration to 30 percent were continued from September 15 through November 24, 1958. The accumulated reactor power increased to 950 MWD during this period. The reactor was then shut down for complete cleanup and removal of inorganic particulate matter which had accumulated in the system, as well as installation of the second core loading. Figure 24 summarizes the operating history of the OMRE through January 1959.

The upper graph represents the concentration of the high boiling compounds in the coolant during various operating periods. The middle graph gives the integrated reactor power. The lower graph illustrates the operating power level, the maximum fuel element surface temperature, and the bulk coolant temperature during various operating periods.

The first test was a shakedown of the whole OMRE system at a moderate power level and moderately high temperature. The purification system was operated to maintain the high boiler concentration at 12 percent. This test showed that a few minor modifications were required in the purification and off-gas systems. A short shutdown period was taken to add two

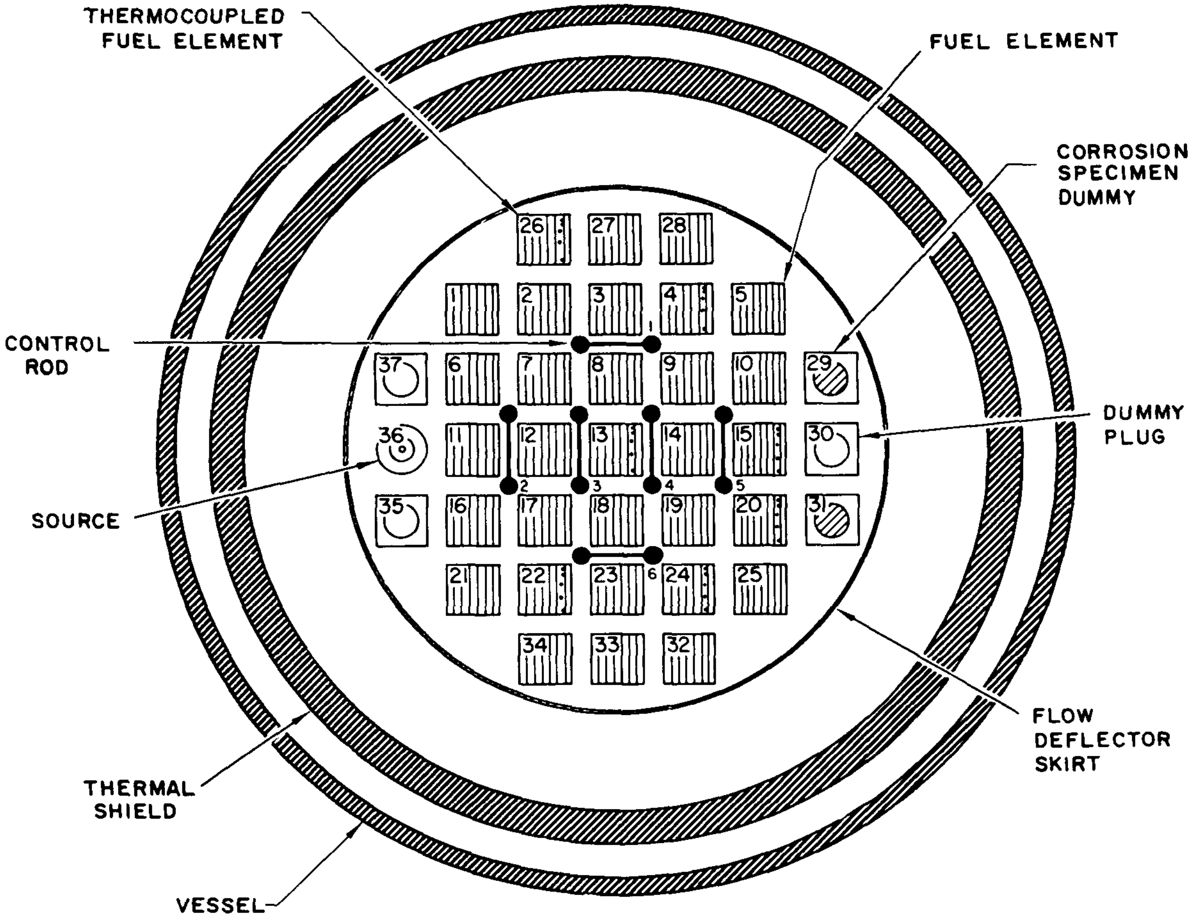


FIGURE 22.—*OMRE core layout.*

cold traps ahead of the vacuum pump. A larger vacuum pump was also installed.

The second test was done to check out the behavior of the system at a higher temperature [700° F. (371° C.) bulk coolant temperature]. No difficulty was encountered. Again the high boiler was held at 12 percent by periodic purification.

After the preliminary tests were completed, the reactor was operated at conditions similar to those which will be employed in initial operation of full-scale power plants. This operation consists of two tests, both at a bulk coolant temperature of 600° F. (316° C.). The first test, whose basic purpose was to determine the thermal stability of the coolant, was conducted at the minimum power level adequate to maintain the required bulk coolant temperature. This test showed that pyrolytic damage was insignificant at 600° F. (316° C.). The second test was performed with the fuel-plate surface hot-spot temperature at 750° F. (399° C.). The resultant power level was 6.0 Mw at full coolant flow. The main objective of this test was to determine the radiolytic damage rate at a high boiler concentration of 12 percent.

Purification was then stopped and the high boiler concentration was allowed to build up from 12 to 30 percent. The bulk coolant temperature was held at 600° F. (316° C.) and the maximum fuel-plate surface temperature was

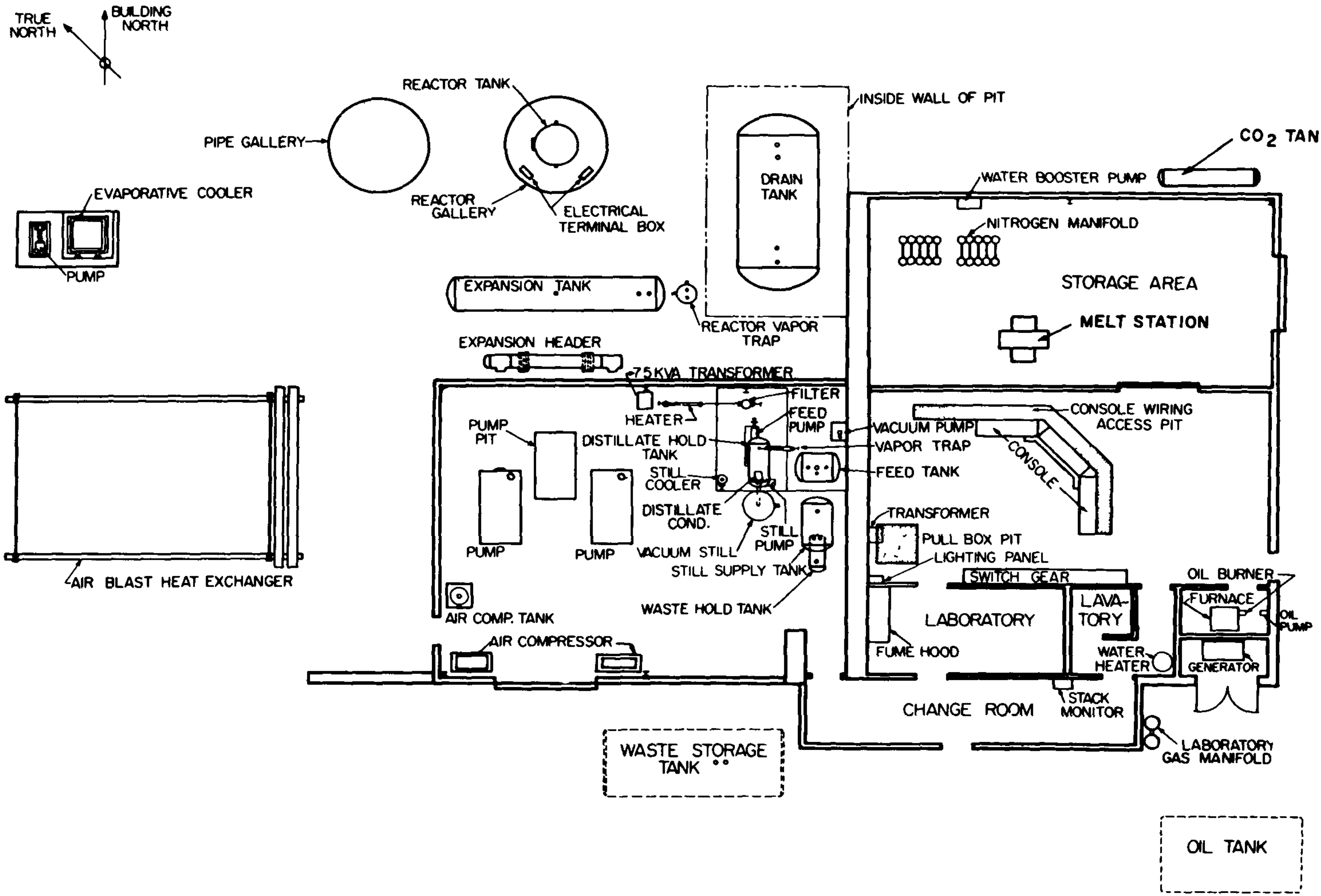


FIGURE 23.—*OMRE equipment layout plan.*

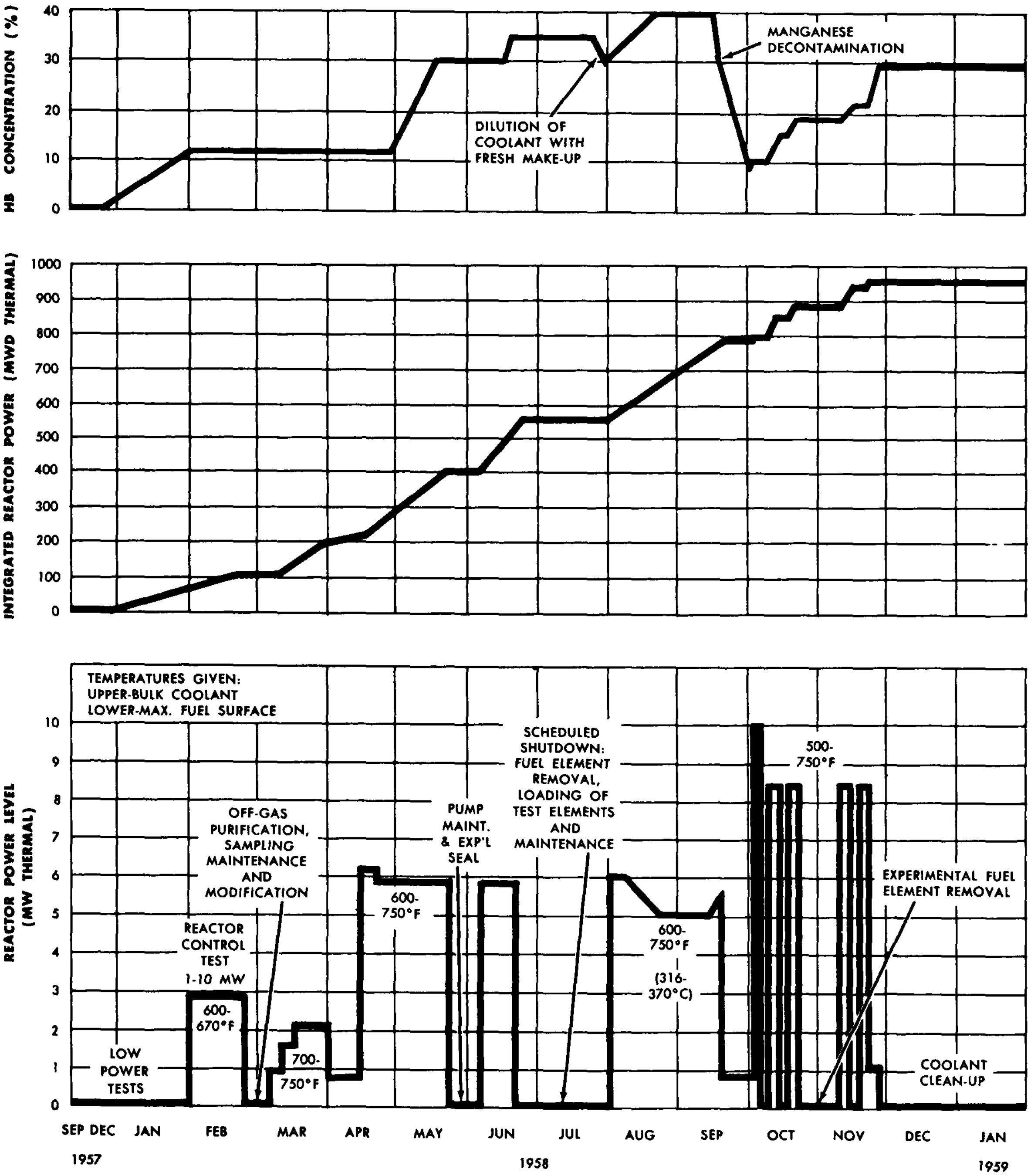


FIGURE 24.—*Operation of the OMRE September 17, 1957 to January 30, 1959.*

held at 750° F. (399° C.). The average power level during this run was 6.0 Mw.

With all reactor conditions the same as during the high boiler run, the purification system was started and the high boiler content maintained at 30 percent for a sustained period. This test was to determine the radiolytic damage rate at the higher high boiler concentration.

The purification system was again stopped and the high boiler concentration was allowed to build up to 41 percent. As the high boiler content increased, it was necessary to decrease the reactor power level to 5.3 Mw to maintain the maximum fuel-plate temperature at 750° F. (399° C.) with the bulk coolant temperature at 600° F. (316° C.). The decrease in power level was necessitated by a decrease in the coolant heat transfer coefficient.

When 41 percent high boiler concentration was reached, the purification system was put into operation to maintain this concentration for a duration run. As before, the coolant temperature was held at 600° F. (316° C.) and the fuel-plate surface temperature at 750° F. (399° C.), providing reactor power level of 5.3 Mw.

After a shutdown for fuel handling operations, the radiation levels at the coolant piping showed a marked increase. It was determined that $Mn^{56}$ was the source of this radioactivity. Since it was known that Mn and essentially all coolant impurities remained with the high boilers in the purification waste, the system was cleaned by extensive purification. With the reactor at a low power level (0.7 Mw) to provide heat for flashing in the purification still, the high boiler content was reduced from 41 to 8 percent. At comparative reactor power levels, the coolant piping radiation levels were reduced by a factor of 2.5 during these operations.

Previous operating experience indicated that a primary area of operating interest was at a coolant high boiler concentration of 30 percent. Therefore, in October a high boiler buildup run from 8 to 30 percent was initiated. To provide information at different thermal operating conditions, the bulk coolant temperature was maintained at 500° F. (260° C.) with the fuel-plate hot-spot temperature at 750° F. (399° C.). These conditions provided a reactor power level of 8.6 Mw throughout the run.

After the high boiler content had reached 24 percent in late October, the run was interrupted when fission products were released into the coolant from one of the experimental fuel elements which had been installed in June for testing purposes. The two experimental elements were then removed and the operations were continued until late November when a 30 percent high boiler content was reached. At this time operations were discontinued for system cleanup and installation of the second core loading. At the time of the shutdown in November, the reactor had accumulated 950 Mwd of operation.

#### ***b. Results***

##### (1) Coolant Decomposition Rates

The OMRE hydrocarbon decomposition rates as a function of the high boiler concentration are shown in figure 13 and are compared with the rates measured in in-pile loop experiments at the Materials Testing Reactor. Decomposition rates are expressed as weight of high boiling compounds formed per Mwh of energy absorbed in the coolant (by direct interaction of neutrons and gamma photons with the molecules of the hydrocarbon), and as molecules of high boiling compounds formed per 100 ev of energy absorbed (G-polymer is based on an average high boiler molecular weight of 460). The data, as plotted, are based on analytical calculations which indicate that 7.8 percent of the OMRE energy is absorbed in the moderator-coolant. As can be seen, the damage rates experienced at the OMRE agree well with those measured in the preliminary in-pile loop studies.

##### (2) Coolant Activation

As anticipated, the radiation levels at the coolant piping are due in major part to the inorganic impurities present in the virgin coolant or removed from the walls of the vessels and piping. The most important radioisotope impurities which have been observed are $Mn^{56}$, $Fe^{59}$, $P^{32}$, and $S^{35}$. These impurities result in low radiation levels at the surfaces of the reactor coolant piping and in the work area around the process equipment. Figure 25 shows the normal radiation level in the OMRE area during 10 Mw operation of the reactor.

### (3) COOLANT PROPERTIES

Changes in the physical and chemical properties of samples of reactor coolant during the operation of the OMRE have been determined on a routine basis. The initial results of this work have been previously described.

### (4) HEAT TRANSFER

Throughout this period of OMRE operation, the heat transfer coefficient of the irradiated OMRE coolant has been measured in an electrically heated bypass coolant loop. This loop contained a section of tubing with instruments to measure temperature and flow. Figure 26 presents the experimental results with the heat transfer coefficient plotted as a function of high boiler content in the coolant. All data points on this figure have been normalized to a fluid velocity of 14.6 fps (4.4 m/sec) at a temperature of 600° F. (316° C.). This curve clearly illustrates the slow and gradual decrease in heat transfer coefficient as the high boiler content increases to 40 percent. This decrease appears to be even smaller than would have been expected from the measured changes in the viscosity of the coolant. It is to be noted that the points shown on figure 26 represent data obtained both during buildup and during lowering of the concentration of decomposition products in the coolant. The loss in heat transfer properties of the coolant appears to be perfectly reversible, thus confirming the absence of significant deposits on the heat transfer surface.

Heat transfer measurements in the core of the reactor did not permit as detailed an evaluation as in the bypass heater. The data obtained, however, indicate that the heat transfer rate at the surface of the fuel elements approximated the changes observed on the bypass heater. It is therefore clear that the observed decrease in the core was smaller than would have been expected from changes in the viscosity of the coolant and that no appreciable insulation of the fuel element surfaces had taken place as a result of deposits of decomposition products on these surfaces. Actual measurements on the fuel plates of an element examined in a hot cell after 544 Mwd of reactor operation showed that the thickness of the film left on the surface of these plates ranged between only 0.12 and 0.38 mil (0.0032 to 0.0097 mm).

### (5) EXPERIMENTAL FUEL ELEMENTS

As part of a program to develop fuel elements suitable for organic power reactors, two developmental fuel elements were irradiated in the OMRE. These fuel elements had the same external dimensions as OMRE fuel elements and replaced two of them in the core lattice. The fuel material was comprised of plates of uranium-molybdenum alloy, clad with finned aluminum.

Each element was instrumented with thermocouples to measure the cladding temperature and the coolant stream temperature. An indication of the coolant flow was obtained with a hot-wire anemometer installed in the lower end-plug of each element.

Following failure of one of these developmental elements, both were removed from the reactor and examined in a hot cell. It was observed that mostly inorganic particulate materials from the organic coolant had plugged the entrance of the coolant channels. Although the organic coolant originally loaded into the OMRE had been distilled to remove particulate matter, later coolant additions were made without prior distillation. Furthermore, the mechanical operation of a filter unit installed in the coolant system was unsatisfactory, so the unit was removed. To prevent the recurrence of a clogged element, the following precautions have been taken:

(*a*) New filters of an improved design have been installed.

(*b*) All coolant additions will be made through the purification system to assure removal of any particulate impurities.

Due to the reduced coolant flow through the plugged coolant channels in the developmental fuel element, the temperature of some of the fuel plates increased enough to cause the aluminum cladding and some of the uranium fuel to melt, thus releasing some of the fuel into the coolant stream. During examination of the element it was also observed that, with the exception of the plates which melted due to the restricted coolant flow, the other fuel plates showed negligible dimensional change from radiation damage. The highest burnup estimated for these plates was 3,000 Mwd/T.

A description of this release of fission products follows.

### (6) Fission Product Release

During a period of steady operation on October 23, 1958, a very sudden increase took place in the radiation levels throughout the OMRE system. Fission products were identified in the coolant. They were completely contained in the system and there was no release to the atmosphere. It was later estimated that approximately 1,000 curies of fission product activity had been introduced into the coolant and gas blanket.

All of the fission products detected in both coolant and blanket gas samples immediately after the release were volatile or had volatile precursors. The iodine isotopes, although volatile, became chemically bonded and remained with the coolant. Since xenon was the only isotope detected in the blanket gas, it was vented to the atmosphere at a controlled rate under safe meteorological conditions. Within a few days the only fission products present in the coolant in any significant quantity were $I^{131}$, $Ba^{140}$, and $La^{140}$. The radiation levels from these fission products were sufficiently low to allow resumption of normal reactor and maintenance operation a few days later.

### (7) Component Performance

The overall component performance record for the OMRE has been excellent. As has been stated previously, the OMRE uses many components that are standard in the oil refinery industry, e.g., pumps and valves.

Pipes and vessels have presented no problems. Some difficulty was experienced at the first in getting perfectly leak-tight joints at pipe flanges. This problem was solved by using soft iron gaskets at the flanges in place of the spiral asbestos-metal gaskets originally specified. Standard steel valves have worked well in all cases. Valves that have had some stem leakage have been repacked with standard asbestos packing which works satisfactorily. On the larger valves some stem leakage has been tolerated because the leakage can be caught in open buckets. In all cases the leakage has been very small.

The main loop and auxiliary pumps, which are commercial hot-oil pumps, have given excellent service. Some difficulty has been experienced in getting perfectly leak-tight mechanical seals, but again, small amounts of leakage can be tolerated. One mechanical seal ran for over a year with less than 10 pounds of leakage.

A self-cleaning disc-type filter that was installed in the bypass loop proved unsuitable for the purpose. The discs would bind when the temperature reached 400° F., thus stopping the self-cleaning action. This filter has been replaced by two sintered stainless-steel filters which were installed in the auxiliary loop.

### *c. Novel Features of OMRE Operation*

The operation of the OMRE is unique in many respects. With good quality control of the virgin coolant makeup, few impurities are added to the coolant system. To date, there has been no indication of significant corrosion to the piping and equipment, and the radiation levels encountered about the coolant system are quite low so that contact maintenance of all equipment, except the reactor core, could be performed at all times during full power reactor operation.

Since the coolant has a relatively low vapor pressure, coolant leaks at valve packings, flanges, and pump seals have presented no problem. The leakage is usually trapped in buckets or similar containers and recovered. For piping connections, bolted flanges used in conjunction with soft iron gaskets have proved to be leakproof when properly installed.

Since all of the plant components are constructed of standard, conventional materials of construction, reactors of this type can be built at a moderate cost and readily maintained by workers with normal abilities and with conventional working tools. The entire system, with the exception of the fuel elements, is made of mild steel and is of relatively lightweight material (the piping is Schedule 40), allowing maintenance work to be accomplished quickly and easily.

As was previously mentioned, the decomposition product compounds are easily removed from the coolant by a single-plate, low-pressure flash distillation. Most of the coolant impurities remain with the still bottoms which are removed from the still into conventional steel oil drums at 500° F. (260° C.) and atmospheric pressure. Some radioactivity is, of course, encountered in this operation, since the distillation waste has been the only outlet for coolant impurities. Burning studies of the high boiling compounds are now underway.

#### *d. Conclusion*

To date, the results obtained from the operation of the OMRE have conclusively demonstrated the feasibility of an organic moderated and cooled power reactor. The low decomposition rates of the coolant and the absence of deposited decomposition products on the heat transfer and other system surfaces have assured the practicality of the concept. The operation has provided the operating experience necessary to verify the predicted novel construction and operating features: low operating pressure, reactor stability and safety, use of standard, lightweight materials of construction, low induced activity in the moderator-coolant, and ease and simplicity of operation and maintenance. Operation of the OMRE will continue to provide necessary additional information for the design requirements of full-scale Organic Reactors.

### 5. Developmental Organic Reactor (DOR)

The Developmental Organic Reactor (DOR) has been proposed as the next logical step in the orderly development of the organic concept. The DOR would supplement the OMRE and provide information in certain areas that the OMRE is unable to supply because of its limited flexibility. The OMRE was built as a low cost experiment designed to study the behavior of the most promising organic coolants under conditions similar to those encountered in power reactor operations. As such, it is not easily adaptable to the insertion of coolant test loops, or full-size test elements into the reactor core.

The DOR, as now conceived, is a 20 Mwt organic moderated and cooled experimental reactor. It consists of a reactor vessel, heat transfer system, and coolant processing system. The core consists of plate-type fully enriched fuel elements with provisions for test thimbles in the high flux region between the elements. The heat generated in the core is removed by a circulating polyphenyl which is pumped through steam generators. The steam produced is condensed in an air-cooled condenser, returning as feedwater to the generator.

The DOR will provide a facility where various engineering aspects of organic coolant technology can be explored and full-size fuel elements can be tested for extended periods under temperature, flow, pressure, and irradiation conditions to be encountered in power reactors. It will also be a source of information on corrosion, equipment life, heat transfer, and other engineering requirements. Certain instrumentation and control problems associated with a steam-generator system may also be studied in this plant.

(Since this report was written, the Commission has initiated work on a 20 to 40 Mwt Experimental Organic Cooled Reactor (EOCR), to be constructed at the National Reactor Testing Station, Idaho. In some respects the EOCR is similar to the DOR described herein.)

## C. DESIGN STUDIES

### 1. Summary

Design studies of intermediate and large organic-cooled power plants have been conducted since approximately 1956. Because there are no overriding safety or other considerations which dictate the choice of a particular fuel in an organic-cooled system, the ultimate selection can be based strictly on economic performance. The earlier design contemplated the use of low alloy metallic uranium fuel. The earlier research and development program therefore emphasized metallic fuels and a design of a finned aluminum-clad uranium metal fuel element evolved. Later design studies have considered the use of $UO_2$ as a basic fuel material. Since the thermal and environmental condition in an organic-cooled reactor core are markedly different from those existing in water reactors, the utilization of "conventional" Zircaloy and stainless-steel cladding materials is not feasible. Present development work with $UO_2$ fuels is based on APM as cladding.

The majority of design studies conducted to date have investigated organic cooled and moderated systems. However, other systems cooled with organics and moderated with heavy water and graphite have been considered by Hanford, Canadian G.E., and NDA.

Organic moderated and cooled reactors fueled with metal are characterized by several common design features. Included among these is the use of relatively few control rods since large reactivity changes with burnup do not occur. Cask-type refueling systems have been utilized since the low core specific power and large heat capacity of the metallic uranium permits transfer of spent elements in air without supplementary cooling. Lower temperature conditions exist within the core due to the use of aluminum cladding materials. The external systems design and plant hazards analysis have been based on low activity levels in the coolant resulting in less shielding and in modified containment criteria.

Later design organic-moderated cooled reactors utilizing $UO_2$ fuel differ from the metallic fuel units primarily in the core configuration. A large number of cruciform-type control rods, utilizing poison material of high epithermal worth, are required to compensate for changes in reactivity due to burnup. The cask-type refueling systems have been superceded by wet systems in which the transfer of spent fuel is handled at all times within a fluid cooling media. Increased temperature conditions within the core are permissible due to the higher strength of the APM cladding. The design of the reactor external auxiliary systems is based on the supposition that some fission products will continually circulate in the coolant (see figs. 25 and 26).

The current status of technology is such that the metallic fuel reactors can be constructed today with a concurrent research and development program. The fuel elements required for the oxide fuel design still require further research and development effort prior to the initiation of plant construction.

### 2. Metal Fueled OMR's

Design studies on metal fueled OMR's encompass the range from 10 to 150 Mwe. All of these plants utilize a metal fuel of either

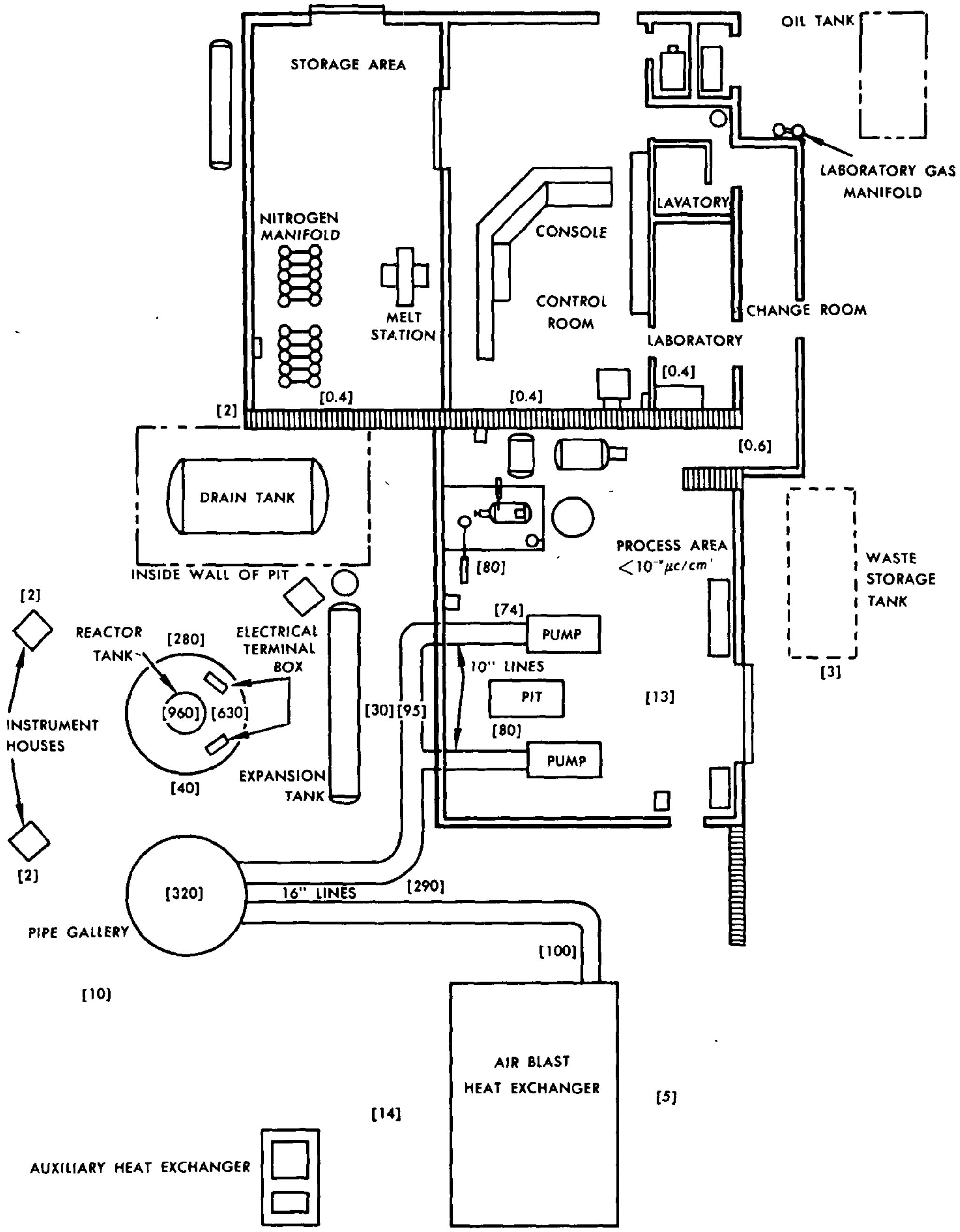


FIGURE 25.—*Radiation survey of OMRE area.*

uranium 3.5 wt percent Mo–0.5 wt percent Si or U–10 wt percent Mo in the shape of flat plates or circular segments similar to the Piqua development. 2S aluminum cladding has been utilized on all designs. Surface temperatures have been limited in each case to 750° F., partly because this represents a conservative temperature to minimize changes in the heat transfer characteristics with time and partly due to a limitation imposed by the aluminum. Identical process systems, including those for degasification and pressurization, coolant purification, waste gas handling, organic residue disposal, and other plant auxiliary systems. Table 13 summarizes the performance characteristics of several of these designs.

## Table 13

## METALLIC FUELS

| | Units | Piqua<br>(Report NAA-SR-3757) | 10 Mw-OMR<br>(Report NAA-SR-3792) | 20 Mw-OMR<br>(Report NAA-SR-3832) | 40 Mw-OMR<br>(Report NAA-SR-3792) | BNL OMR<br>(Eval of OCR's final report) | BNL GMR<br>(Eval of OCR's final report) | BNL DMR<br>(Eval of OCR's final report) | BNL WMR<br>(Eval of OCR's final report) |
|---|---|---|---|---|---|---|---|---|---|
| Net electrical power rating | Mwe | 11 4 | 10 | 20 | 40 | 75 | 75 | 75 | 75 |
| Thermal power rating | Mwt | 45 5 | 38 | 73 | 148 | 300 | 300 | 300 | 300 |
| Thermal efficiency | % | | 23 3 | | 27 0 | | | | |
| Number of loops | | 1 | 2 | 2 | 2 | | | | |
| Moderator | | Terphenyl | Santowax R | Santowax R | Santowax R | Santowax R | Graphite | $D_2O$ | $H_2O$ |
| Coolant | | Terphenyl | Santowax R | Santowax R | Santowax R | Santowax R | Santoxwax R | Santowax R | Santowax R |
| Coolant pressure | Psia. | 120 | 120 | 135 | 150 | | | | |
| Coolant flow | lb/hr | 5 5×$10^6$ | 4 6×$10^6$ | 6 5×$10^6$ | 12 5×$10^6$ | | | | |
| Coolant core velocity | ft/sec | 14 6 | 15 3 | 15 3 | 15 3 | 15 | 15 | 15 | 15 |
| Coolant core inlet temperature | °F | 523 | 565 | 552 | 538 | 540 | 450 | 475 | 475 |
| Coolant core outlet temperature | °F | 575 | 625 | 625 | 625 | 600 | 600 | 600 | 600 |
| Coolant core average ΔT | °F | 52 | 60 | 73 | 87 | 60 | 150 | 125 | 125 |
| Cladding material | | Al-Finned | Al-Finned | Al-Finned | Al Finned | Finned | -Finned | Finned | -Finned |
| Cladding thickness | in. | 0 035 | 0 035 | 0 035 | 0 035 | | | | |
| Cladding maximum surface temperature | °F | 750 | 750 | 750 | 750 | 800 | 800 | 800 | 800 |
| Fuel material | | U-3 5 Mo | U-3 5 Mo | U-3 5 Mo | U-3 5 Mo | U-metal | U-metal | U-metal | U-metal |
| Fuel shape | | Conc tubes | Conc tubes | Conc tubes | Conc tubes | Plates | Plates | Plates | Plates |
| Fuel diameter | in | 5 25 OD<br>3 10 ID | 5 25 OD<br>3 10 ID | 5 25 OD<br>3 10 ID | 3 25 OD<br>3 10 ID | 4 8×4 8 | 4 8×4 8 | 4 8×4 8 | 4 8×4 8 |
| Fuel height | in | 54 | 60 | 78 | 108 | 96 | 144 | 120 | 120 |
| Fuel inventory | MTU | 6 55 | 5 88 | 11 8 | 28 1 | | | | |
| Fuel initial enrichment | % | 1 8 | 1 80 | 1 70 | 1 60 | | | | |
| Fuel depleted enrichment | % | | 1 32 | 1 23 | 1 17 | | | | |
| Fuel maximum center temperature | °F | 850 | 850 | 850 | 850 | | | | |
| Core height | ft | 6 15 | 5 0 | 6 5 | 9 0 | 8 | 12 | 10 | 10 |
| Core diameter—equiv | ft | 5 00 | 4 4 | 6 0 | 7 2 | 9 | 15 | 14 | 9 5 |
| Average heat flux | Btu/$ft^2$-hr | 34,300 | 36,200 | 32,400 | 29,200 | 31,000 | 32,800 | 32,800 | 32,800 |
| Maximum heat flux | Btu/$ft^2$-hr | 132,000 | 163,000 | 212,000 | 146,000 | 103,000 | 109,000 | 109,000 | 109,000 |
| Peak to average power ratio | | 3 85 | 4 5 | 6 55 | 5 0 | | | | |
| Average power density | kwt/$ft^3$ | 375 | 500 | 400 | 405 | | | | |
| Specific power | kwt/MT | 6950 | 6470 | 6200 | 5260 | | | | |
| Initial conversion ratio | | ~0 60 | 0 56 | | 0 60 | | | | |
| Hot channel factors | | | | | | | | | |
| FΔt | | 2 05 | | 1 79 | | 1 6 | 1 6 | 1 6 | 1 6 |
| Fθ | | 2 47 | | 1 91 | | 2 1 | 2 1 | 2 1 | 2 1 |
| Fϕ | | 1 79 | | 1 39 | | | | | |
| Control rods | | 7 | 7 | 12 | 17 | | | | |

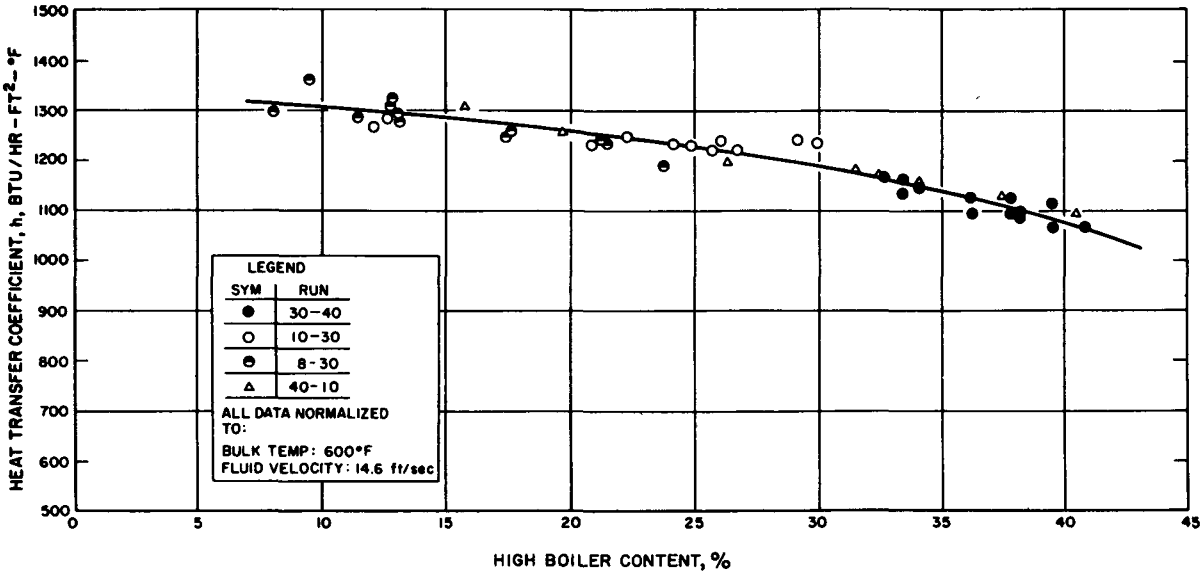


FIGURE 26.—*Experimental heat transfer coefficient of irradiated OMRE coolant.*

In the following section a more detailed description is given for a typical 20-Mwe reactor plant (see figs. 27 through 29).

### *a. 20,000 Kilowatt OMR (38)*

The nuclear power plant described in this document utilizes an organic moderated and cooled reactor (OMR) as the primary heat source to develop 20,000 net electrical kilowatts of power.

Simple in concept and straightforward in design, the OMR uses a high-boiling symmetric hydrocarbon oil as both the moderator and coolant. Operating at low pressure, the reactor provides heat for generating the superheated steam used to drive the turbine generators.

The low-pressure coolant, operating at temperatures below its atmospheric pressure boiling point, does not enter into hazardous chemical reactions with any of the materials in the fuel elements or reactor core. A negative temperature coefficient of reactivity ensures stability during load variations, while the low-level coolant radioactivity permits personnel access for inspection and maintenance of the heat transfer and process systems during operation.

The low coolant radioactivity, in addition to protecting operating personnel, simplifies maintenance and minimizes the required shielding. There is no corrosion in the reactor or heat transfer system, since the coolant is compatible with the steel of the systems components and with the fuel element cladding and does not react with either water or the fuel.

### *b. Summary of Plant Characteristics*

The plant can utilize a site with an exclusion radius of about 1000 ft. The reactor-steam system and the turbine-generator are housed in two separate buildings of conventional construction. As stated previously, no pressure-type secondary containment vessel is required for the reactor building; however, controlled air circulation is provided for this structure.

The reactor has a rating of 73 Mwt and, in conjunction with steam generating equipment, produces 272,000 lb/hr of steam for use in the turbine generator. Approximately 20 Mwe net is generated from the steam produced when the reactor plant is operating at full power. The reactor uses fuel elements of slightly en-

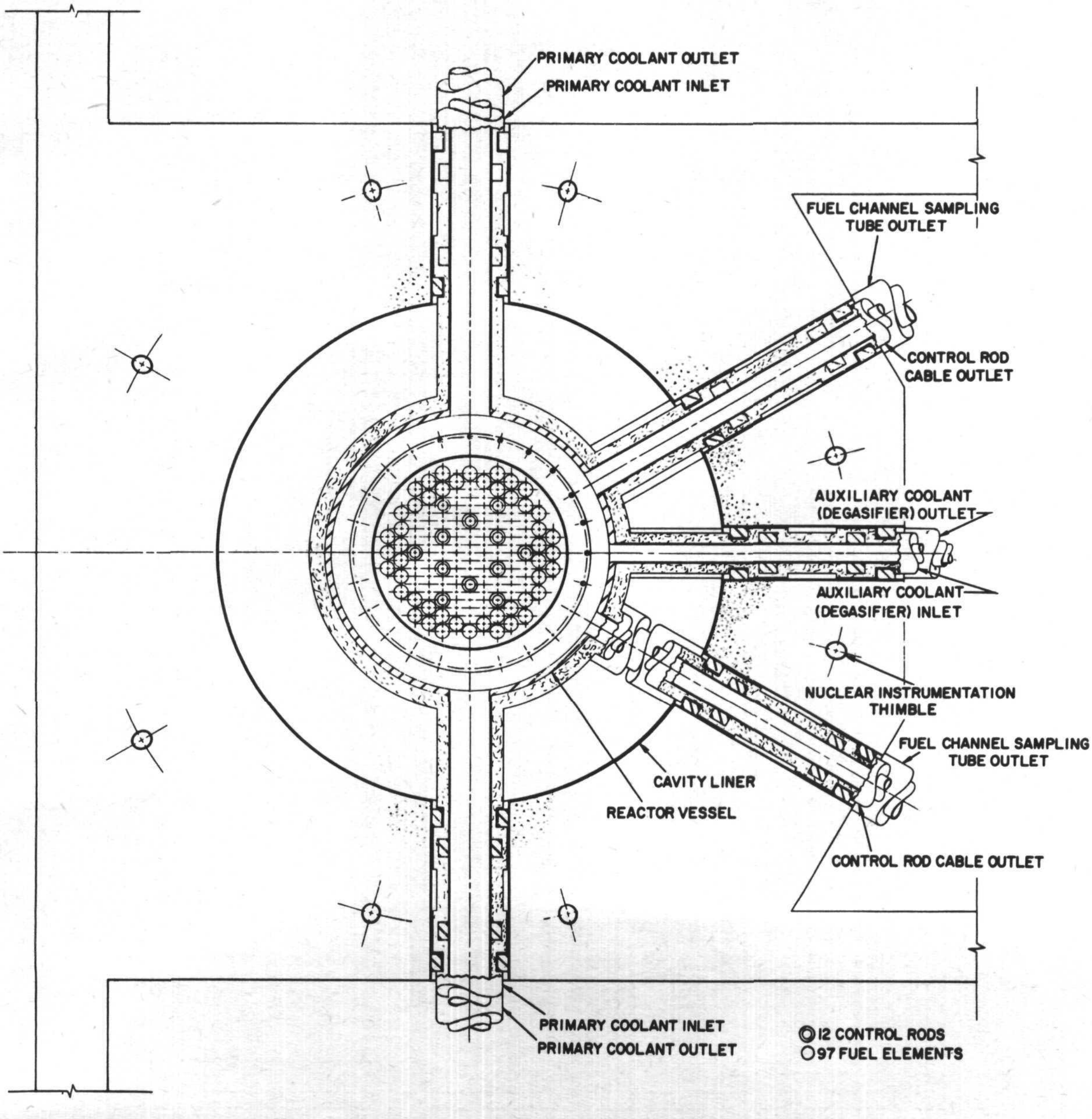
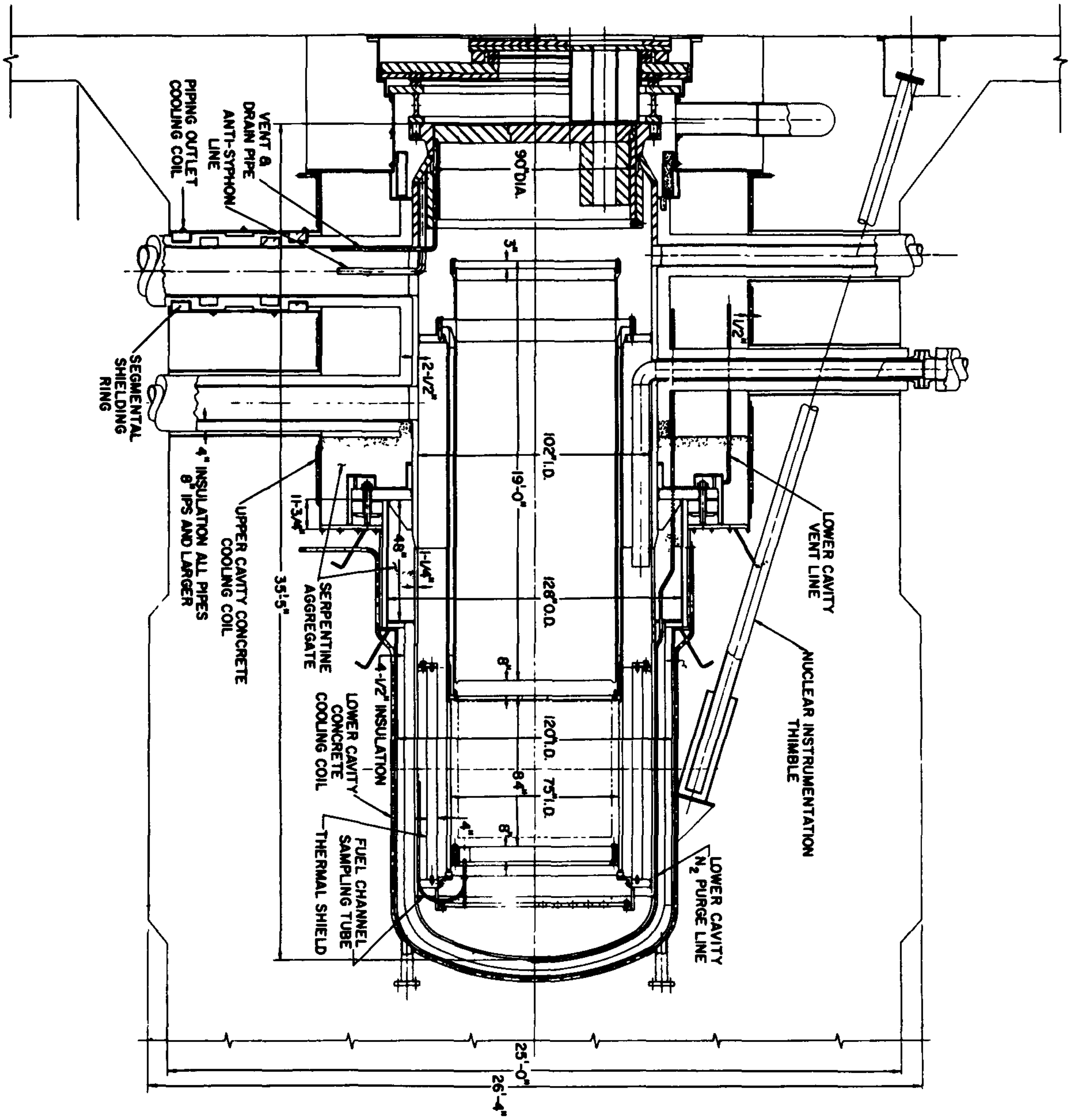


FIGURE 27.—*Reactor plan cross section (20,000-kw OMR).*

riched uranium and is cooled and moderated by an organic hydrocarbon liquid. The coolant used is a commercially available mixture of polyphenyls.

The coolant is circulated through two heat transfer loops from the reactor core to steam generators where superheated steam is produced. The full-power flow rate of coolant in the plant is $6.75 \times 10^6$ lb/hr. The coolant leaves the core at 625° F. and leaves the steam generators to return to the core at 552° F. Superheated steam is produced by the plant at a constant pressure for all load conditions. It is supplied to the steam header at 815 psia and 580° F. Plant design characteristics are listed in table 14.



NOTE PIPING IN ELEVATION VIEW IS NOT SHOWN IN TRUE RADIAL ORIENTATION

FIGURE 28.—*Reactor elevation cross section (20,000-kw OMR).*

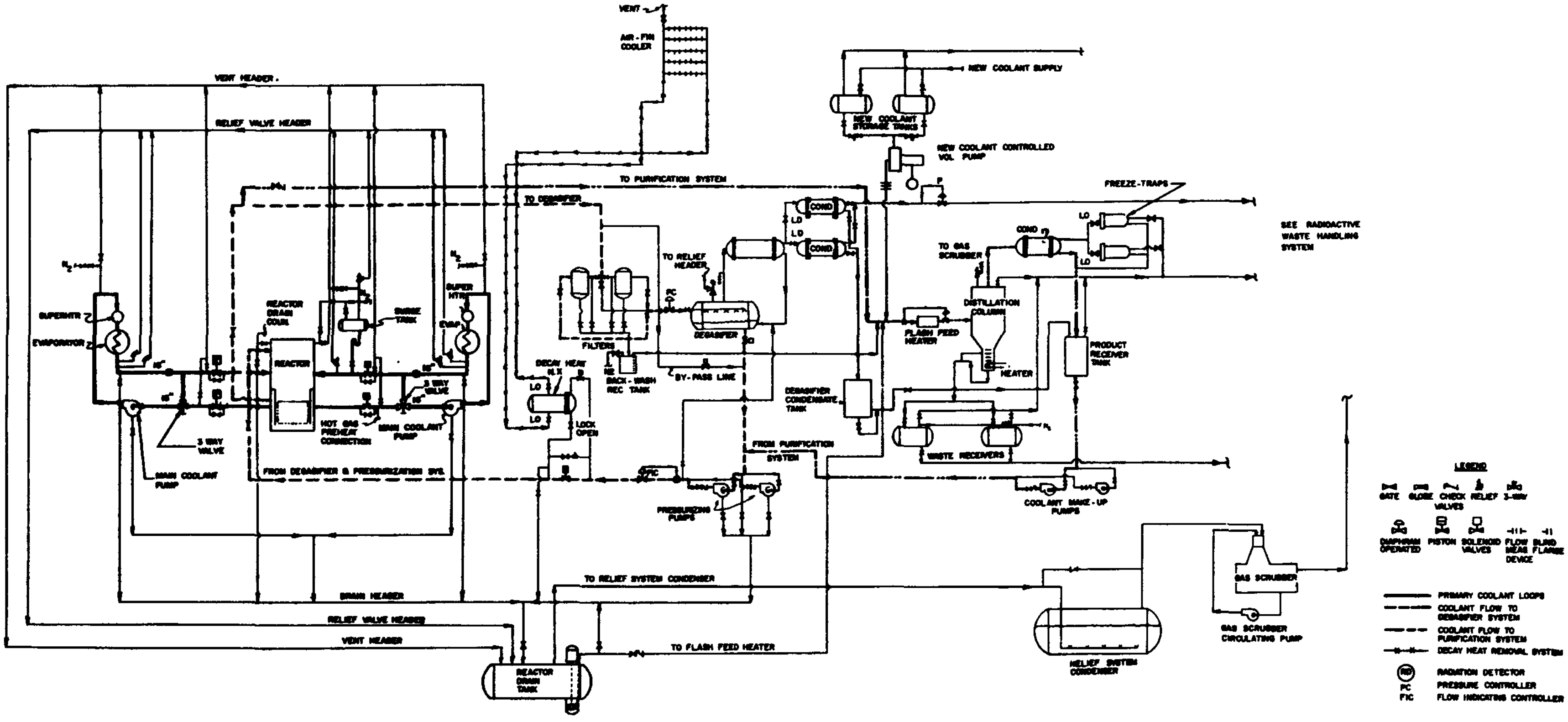


FIGURE 29.—*Main coolant system, composite diagram (20,000-kw OMR).*

TABLE 14

OXIDE FUELS

| | Units | Maritime (Report NAA-SR-3859) | 75 Mw-OCR (Report BCPI-1 Vol IV) | 300 Mw-OCR (Report BCPI-1 Supl 2) | GOCR (Report BCPI-1 Vol III) | Canadian GE [A/Conf 15/P/210 (AECL-620)] |
|---|---|---|---|---|---|---|
| Net electrical power rating | Mwe | 30,000<br>SHP | 75 | 300 | 284 7 | 150 |
| Thermal power rating | Mwt | 93 | 229 | 934 | 937 3 | 480 |
| Thermal efficiency | % | --- | | | 31 8 | 32 |
| Number of loops | | 2 | 3 | 3 | | 2 |
| Moderator | | Santowax R | Santowax R | Santowax R | Graphite | $D_2O$ |
| Coolant | | Santowax R | Santowax R | Santowax R | Santowax R | Organic |
| Coolant pressure | psia | 34 | 33 | 50 | 165 | 43 |
| Coolant flow | lb/hr | $11\ 3\times10^6$ | $21\ 5\times10^6$ | $54\ 45\times10^6$ | $50\ 5\times10^6$ | $9\ 5\times10^6$ |
| Coolant core velocity | ft/sec | 6 9 | 6 79 | 7 22 | 17 | 28 2 |
| Coolant core inlet temp | ° F | 620 | 600 | 550 | 550 | 575 |
| Coolant core outlet temp | ° F | 675 | 675 | 675 | 675 | 800 |
| Coolant core average ΔT | ° F | 55 | 75 | 125 | | 225 |
| Cladding material | | APM-finned | APM-finned | APM-finned | APM-finned | SAP-finned |
| Cladding thickness | in | 0 015 | 0 015 | 0 015 | | 0 030 |
| Cladding max surface temp | ° F | 825 | 850 | 850 | 850 | 830 |
| Fuel material | | $UO_2$ | $UO_2$ | $UO_2$ | $UO_2$ | $UO_2$ |
| Fuel shape | | Cyl pellets | Cyl pellets | Cyl pellets | | Conc tubes |
| Fuel diameter | in | 0 33 | 0 30 | 0 30 | 0 30 | 2 35 |
| Fuel height | in | | 0 60 | 0 60 | 0 60 | 80 4 |
| Fuel inventory | MTU | 6 85 | 13 95 | 46 5 | 46 | 32 1 |
| Fuel initial enrichment | % | 3 7 | 2 8 | 2 1 | 1 8 | |
| Fuel depleted enrichment | % | | | | 49 9 | |
| Fuel max center temp | ° F | 4000 | 4000 | 4000 | 4000 | |
| Core height | ft | 5 0 | 7′5″ | 12 0 | | 13 7 |
| Core diameter equivalent | ft | 5 0 | 7′4″ | 10 33 | | 15 5 |
| Average heat flux | Btu/ft²-hr | 28,700 | 46,500 | 33,600 | 56,000 | |
| Maximum heat flux | Btu/ft²-hr | 125,000 | 123,000 | 96,300 | 197,000 | 450,000 |
| Peak-to-average power ratio | | 4 35 | 2 64 initial<br>3 32 final | 2 55 initial<br>3 37 final | 3 52 | |
| Average power density | kwt/ft³ | 930 | 770 | 889 | 69 4 | 186 |
| Specific power | kwt/MTU | 13,500 | 16,400 | 20,000 | 20,000 | 14,900 |
| Initial conversion ratio | | 0 614 | 0 58 | 0 69 | 0 54 | |
| Hot channel factors | | | | | | |
| FΔt | | 1 25 | 1 25 | 1 25 | | |
| Fθ | | 1 56 | 1 56 | 1 56 | | |
| Fφ | | 1 25 | 1 25 | 1 25 | | |
| Control rods | | 21 | 25 | 57 | 60 | |

Major systems in the reactor plant, in addition to the heat transfer loops, include the degasification and pressurizing system, the coolant purification system, the pressure-relief system, and the decay heat removal system. Other systems are provided for preheating, venting and draining, coolant storage and make-up waste disposal, and other auxiliary services.

The reactor plant components and piping are constructed primarily of ordinary carbon steel. Most of the plant is located below ground level to reduce the shielding requirements. Complete fuel-handling facilities are included for removing and replacing individual fuel elements in the reactor, and for storing spent and fresh fuel elements in the plant.

The plant control system automatically controls the plant when the load is between 10 and 110 percent of full load. Manual operation is provided for control at all loads. In addition, a plant protective system provides for rapid detection of abnormal operating conditions and automatically takes corrective action as needed.

## 3. Oxide Fueled OMR's

### *a. Range of Design Studies*

Under a Commission contract, Atomics International, in cooperation with the Bechtel Corporation, recently completed an extensive design study of organic cooled reactor plants. These studies were concentrated on oxide-fueled, APM-clad, organic-moderated reactor plants in the intermediate (75 Mwe) and large (300 Mwe) size range. Reactor cores for both sizes were designed for operation under conditions of forced convection heat transfer and nucleate boiling in the core.

In addition to these design studies an oxide-fueled, organic-moderated reactor plant for use as a propulsion plant for a T-7 tanker, a large graphite-moderated organic cooled plant (285 Mwe) were designed at Atomics International and a $D_2O$-moderated, organic-cooled plant was designed by Canadian General Electric Co. The major reactor parameters for all of these plants are summarized in table 15.

### *b. Summary of 300 Mwe Organic Cooled Reactor Design*

The organic moderated and cooled reactor has a design capability of 934 Mw of heat and is cooled by Santowax R having a bulk temperature of 675° F. at the reactor outlet. The design load coolant flow is 50,500,000 lb/hr with a temperature at the reactor inlet of 550° F. (table 16, fig. 30 through 34).

TABLE 15

PERFORMANCE CHARACTERISTICS

| | |
|---|---|
| POWER PLANT CHARACTERISTICS: | |
| *Power Output:* | |
| Net, electrical | 20,000 kwe. |
| Gross, electrical | 22,000 kwe. |
| Gross, thermal | 73,000 kwt. |
| Thermal efficiency | 27.4%. |
| *Steam Conditions:* | |
| Steam pressure at turbine throttle. | 800 psia. |
| Steam temperature | 580° F. |
| Steam rate | 272,000 lb/hr. |
| Feedwater temperature at full load. | 375° F. |
| *Reactor Cooling:* | |
| Coolant | Santowax-R. |
| Coolant operating pressure | 135 psia. |
| Coolant inlet temperature | 552° F. |
| Coolant outlet temperature | 625° F. |
| Number of primary loops | 2. |
| *Reactor Characteristics:* | |
| $U^{235}$ loading | 200 kg. |
| $U^{235}$ enrichment | 1.7%. |
| Number of fuel elements | 97. |
| HEAT TRANSFER CHARACTERISTICS: | |
| Coolant | Santowax-R. |
| Number of loops | 2. |
| Total flow rate | 14,700 gpm (6.75 $\times 10^6$ lb/hr). |
| Total flow rate | 14,700 gpm (6.75$\times 10^6$ lb/hr). |
| Reactor inlet temperature | 552° F. |
| Reactor outlet temperature | 625° F. |
| Average coolant temperature rise in core (full power). | 73° F. |
| Coolant system design pressure | 300 psig. |
| Nominal operating pressure (inlet to core tank. | 135 psia. |
| Coolant velocity through fuel element (maximum). | 15.3 ft/sec. |
| Average heat flux in the core | 32,400 Btu/hr-ft$^2$. |
| Maximum heat flux in the core | 212,000 Btu/hr-ft$^2$. |
| Pressure drop through core | 49 psia. |
| Heat transfer coefficient | 1,298 Btu/hr-ft$^2$-°F. |
| Main coolant pump capacity (one in each loop). | 7,350 gpm (each). |
| Pressurizing pump flow rate (normal). | 200 gpm. |
| Purification flow rate (maximum). | 360 lb/hr. |
| Coolant makeup rate (full power). | 83 lb/hr. |
| Charging pumps capacity (2) | 20 gpm (total). |
| Volume of coolant in the system | 17,000 gal (total). |
| Volume of coolant in each main coolant loop. | 3,600 gal. |
| Power density | 400 kwt/ft$^3$. |

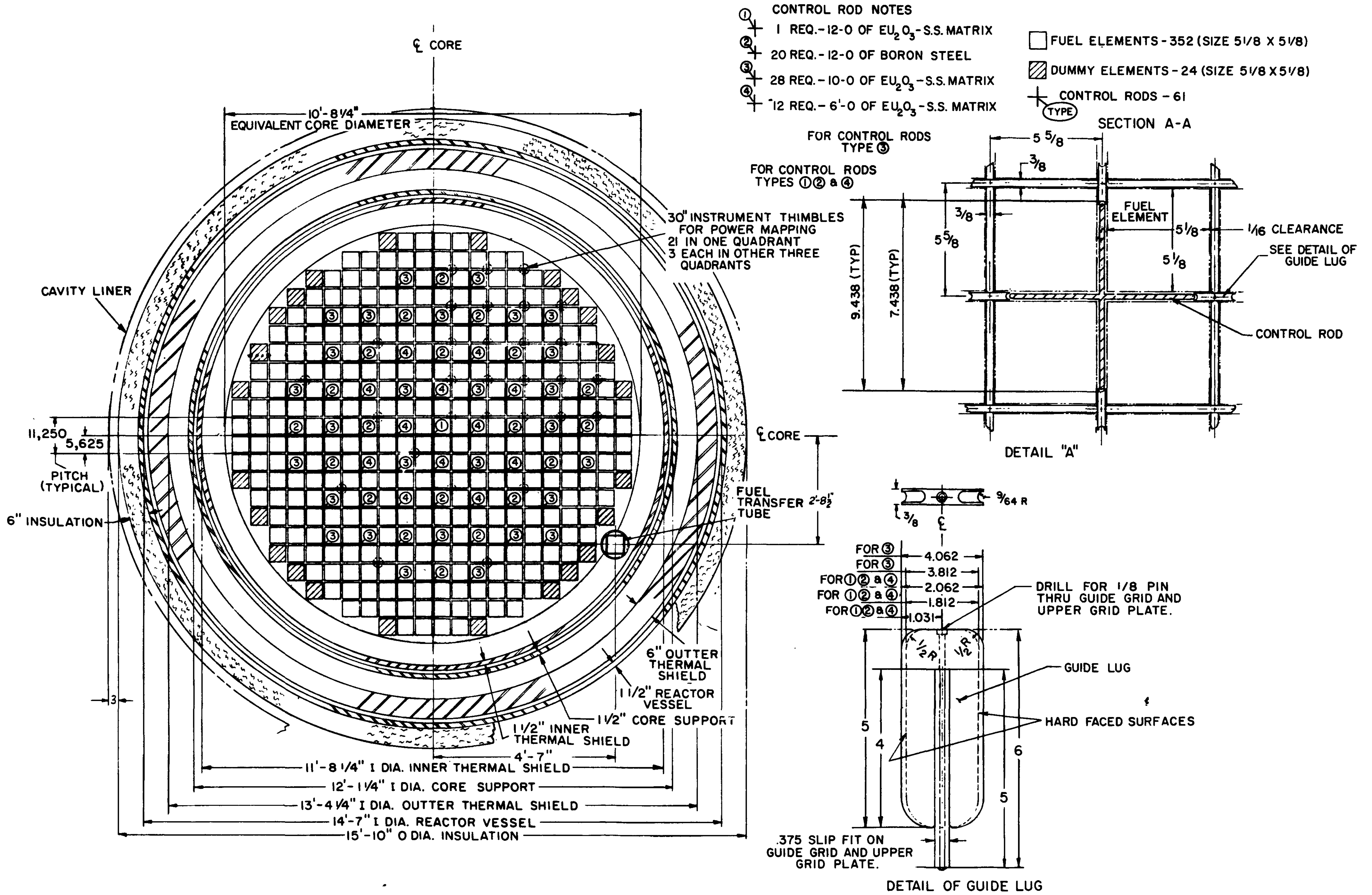


FIGURE 30.—*Reactor plan cross section (300-Mwe OCR).*

535322 O—60 (Face p. 62)

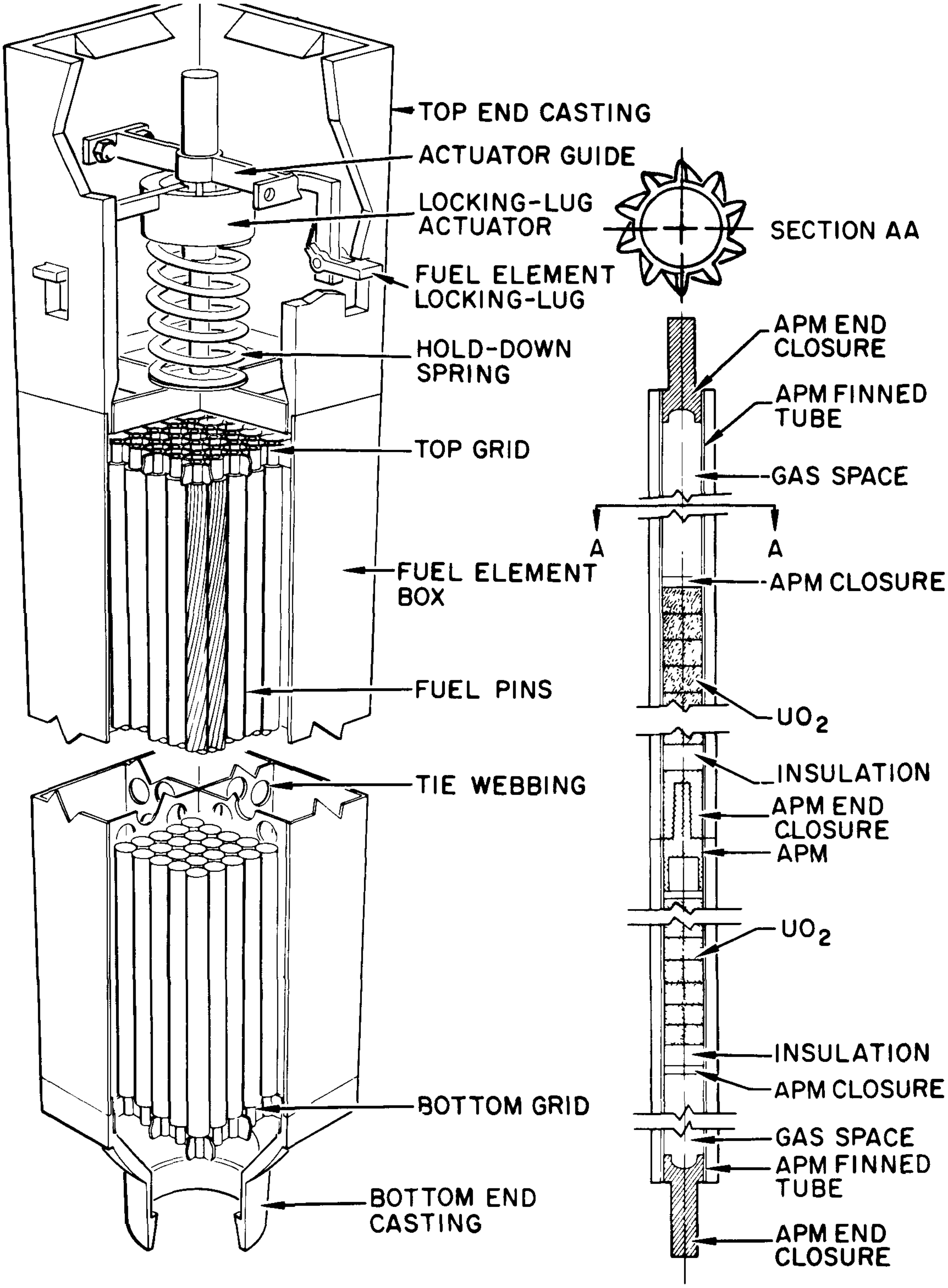


FIGURE 31.—*Fuel element (300-Mwe OCR)*

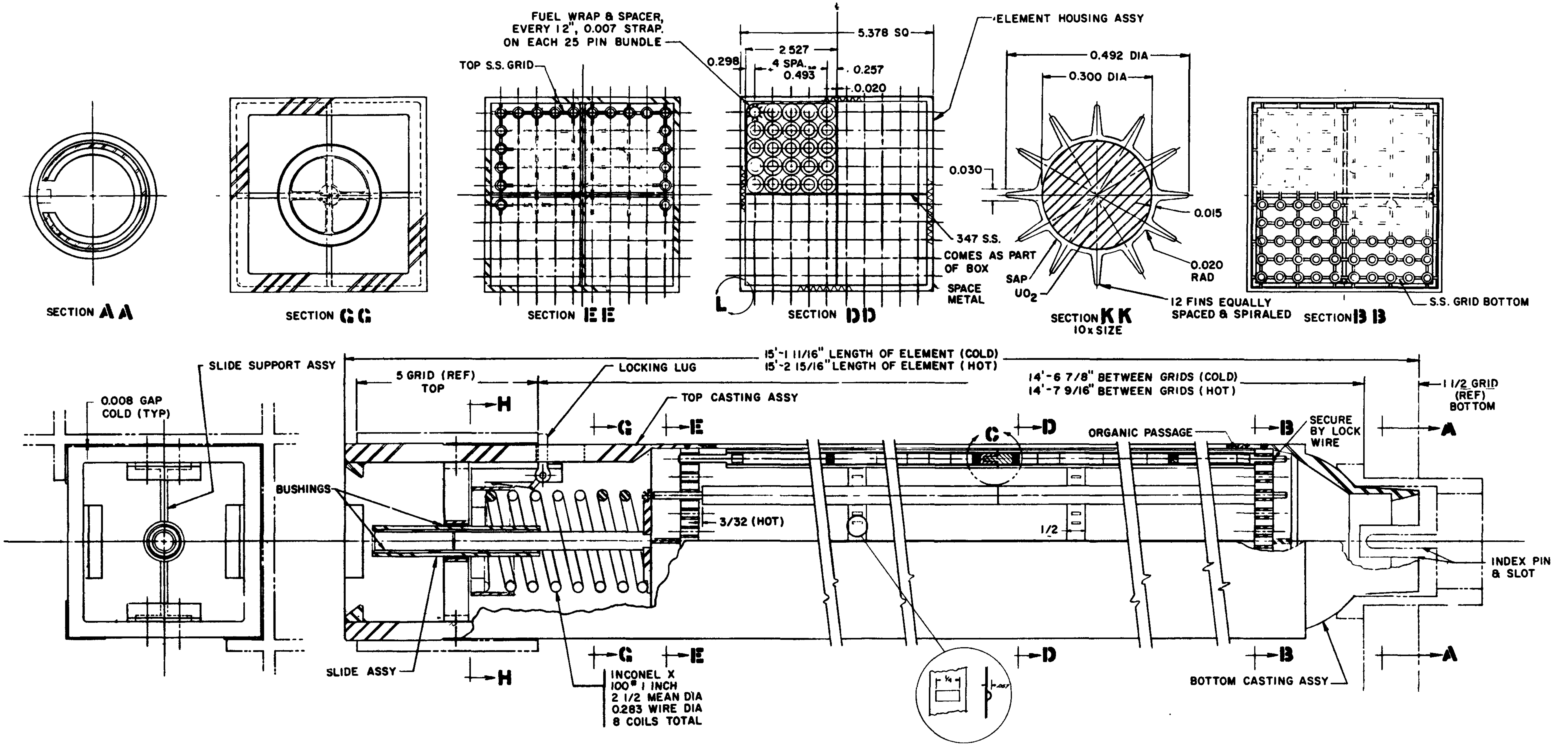


FIGURE 32.—*Fuel element section and elevation (300-Mwe OCR).*

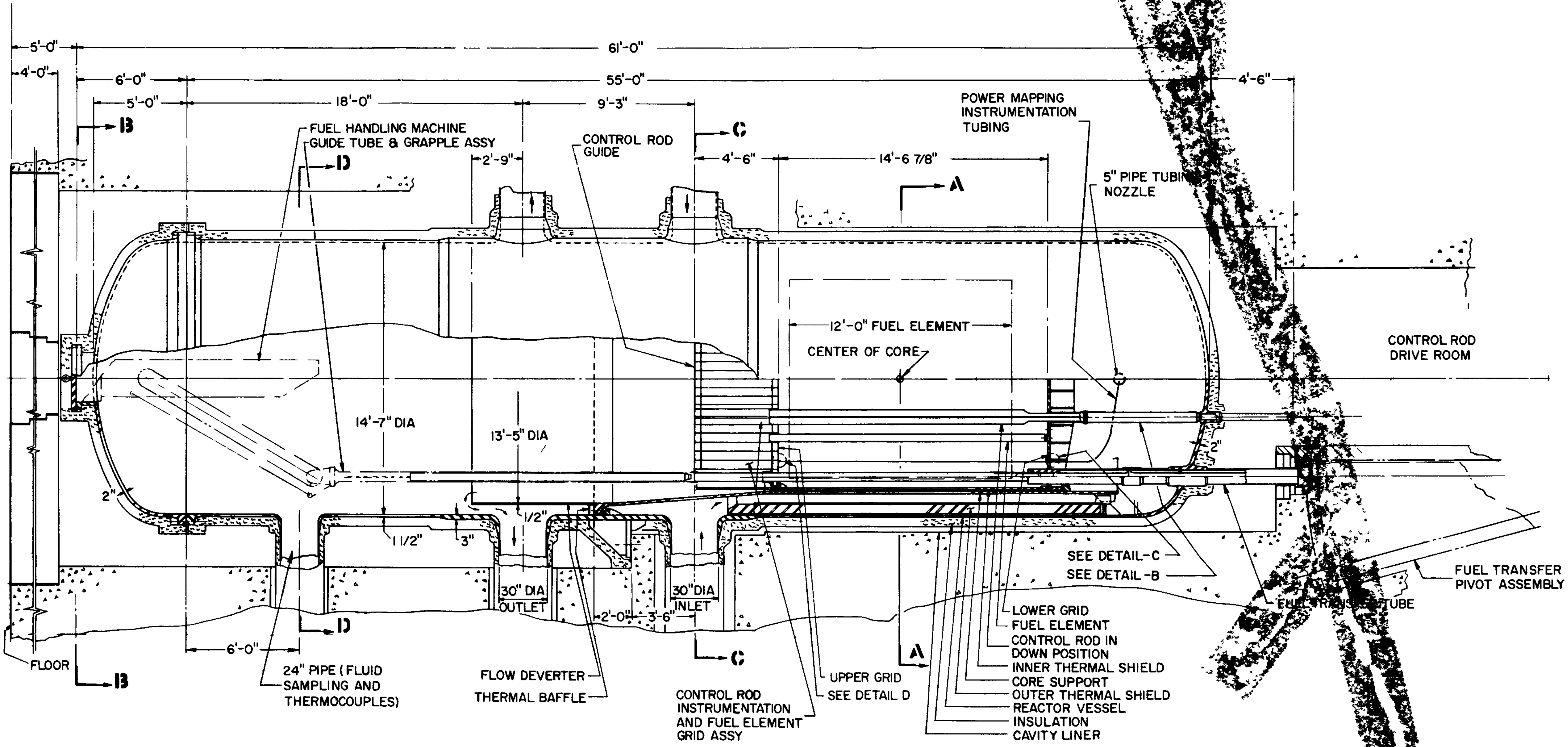


FIGURE 33.—*Reactor elevation cross section (300-Mwe OCR).*

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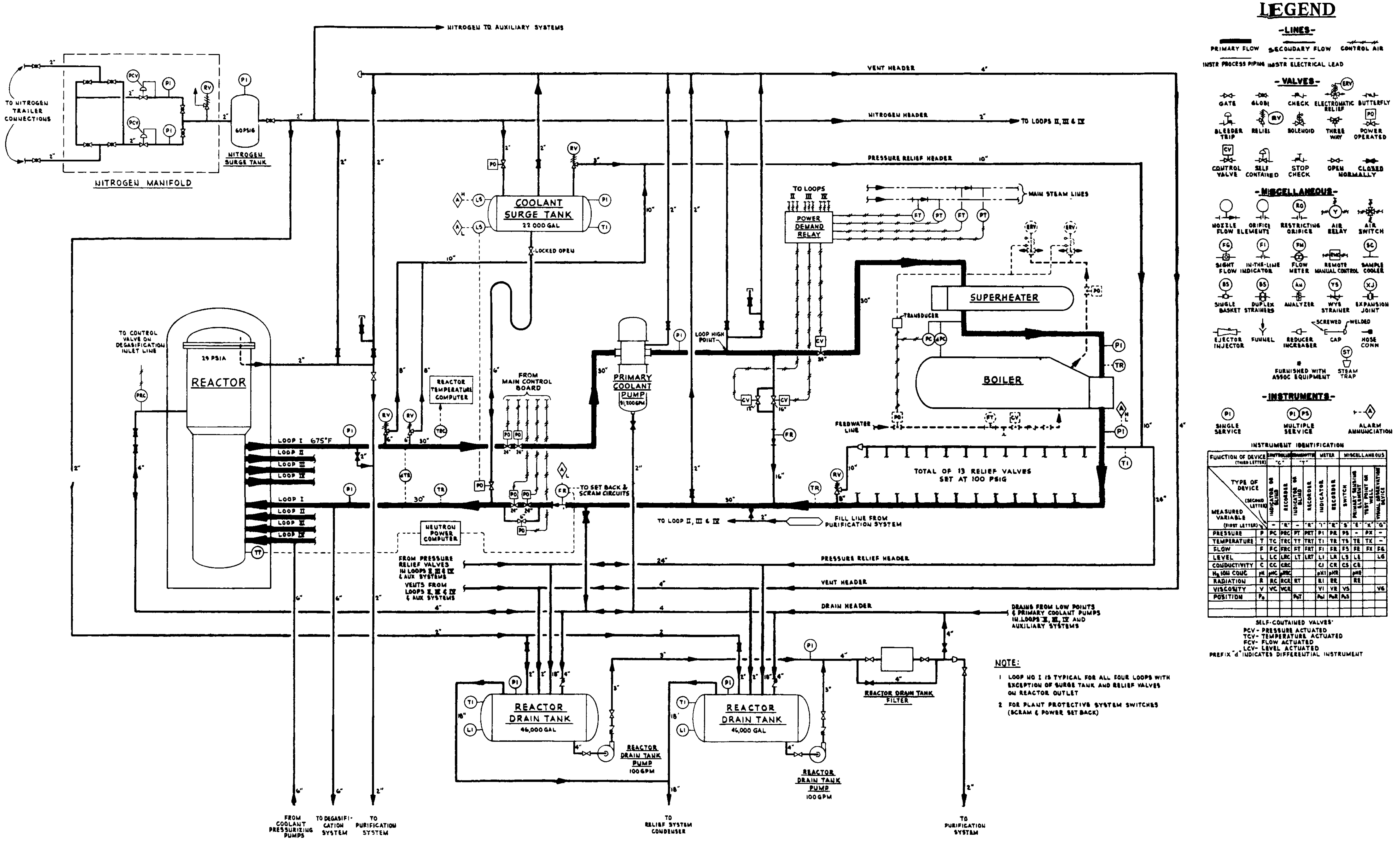

INSTRUMENT IDENTIFICATION

| FUNCTION OF DEVICE (THIRD LETTER) |  | CONTROLLER "C" |  | TRANSMITTER "T" |  | METER |  | MISCELLANEOUS |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
| TYPE OF DEVICE (SECOND LETTER) / MEASURED VARIABLE (FIRST LETTER) |  | INDICATOR OR BLIND | RECORDER | INDICATOR OR BLIND | RECORDER | INDICATOR | RECORDER | SWITCH | PRIMARY SENSING ELEMENT | TEST POINT OR WELL | VISUAL OBSERVATION DEVICE |
|  |  | - | "R" | - | "R" | "I" | "R" | "S" | "E" | "X" | "G" |
| PRESSURE | P | PC | PRC | PT | PRT | PI | PR | PS | - | PX | - |
| TEMPERATURE | T | TC | TRC | TT | TRT | TI | TR | TS | TE | TX | - |
| FLOW | F | FC | FRC | FT | FRT | FI | FR | FS | FE | FX | FG |
| LEVEL | L | LC | LRC | LT | LRT | LI | LR | LS | LE |  | LG |
| CONDUCTIVITY | C | CC | CRC |  |  | CI | CR | CS | CE |  |  |
| $H_2$ ION CONC | pH | pHC | pHRC |  |  | pHI | pHR |  | pHE |  |  |
| RADIATION | R | RC | RCR | RT |  | RI | RR |  | RE |  |  |
| VISCOSITY | V | VC | VCR |  |  | VI | VR | VS |  |  | VG |
| POSITION | Po |  |  | PoT |  | PoI | PoR | PoS |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |

SELF-CONTAINED VALVES:
PCV- PRESSURE ACTUATED
TCV- TEMPERATURE ACTUATED
FCV- FLOW ACTUATED
LCV- LEVEL ACTUATED
PREFIX "d" INDICATES DIFFERENTIAL INSTRUMENT

NOTE:

1 LOOP NO I IS TYPICAL FOR ALL FOUR LOOPS WITH EXCEPTION OF SURGE TANK AND RELIEF VALVES ON REACTOR OUTLET

2 FOR PLANT PROTECTIVE SYSTEM SWITCHES (SCRAM & POWER SET BACK)

FIGURE 34.—*Flow and instrumentation diagram (300-Mwe OCR).*

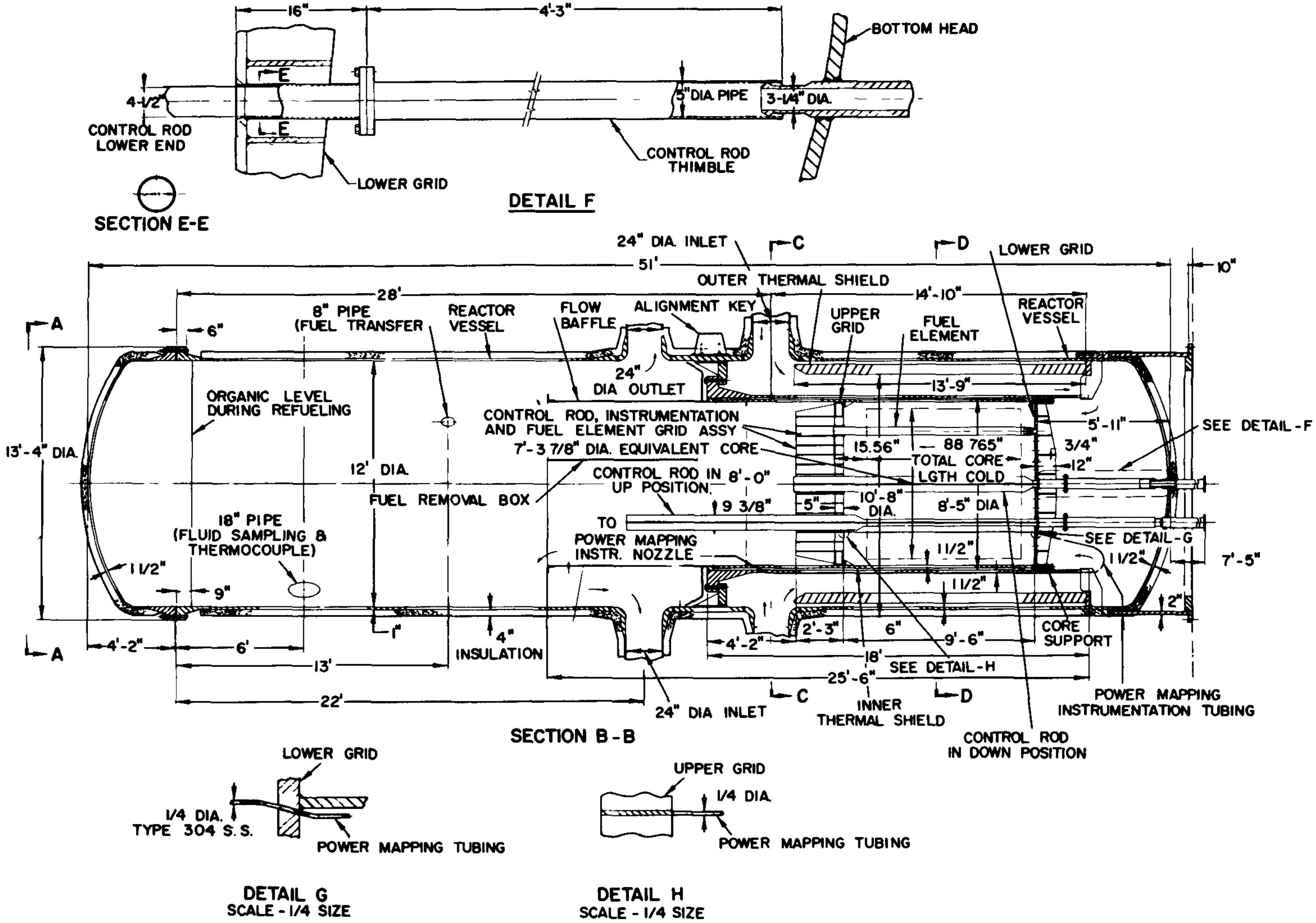

FIGURE 35.—*Reactor elevation cross section (75-Mwe OCR).*

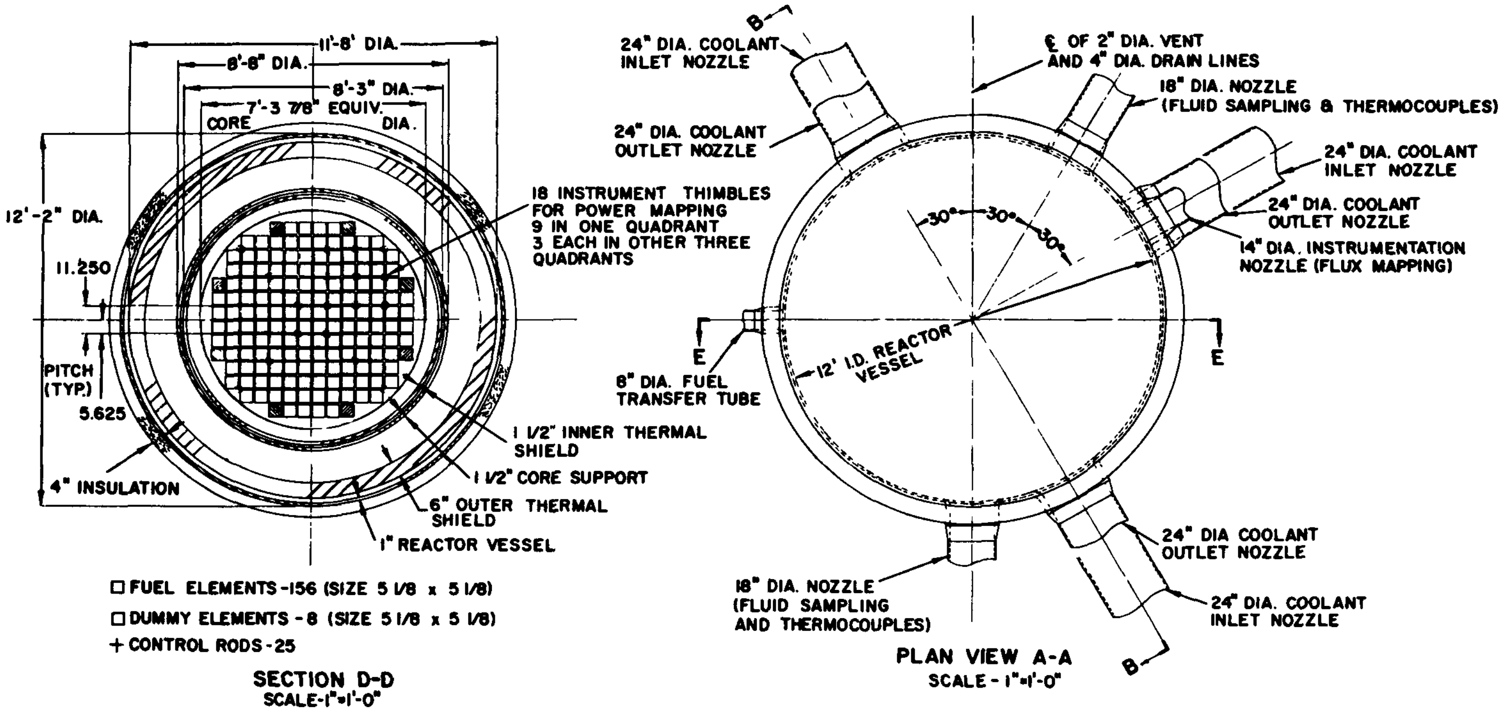

FIGURE 36.—*Reactor plan cross section (75-Mwe OCR).*

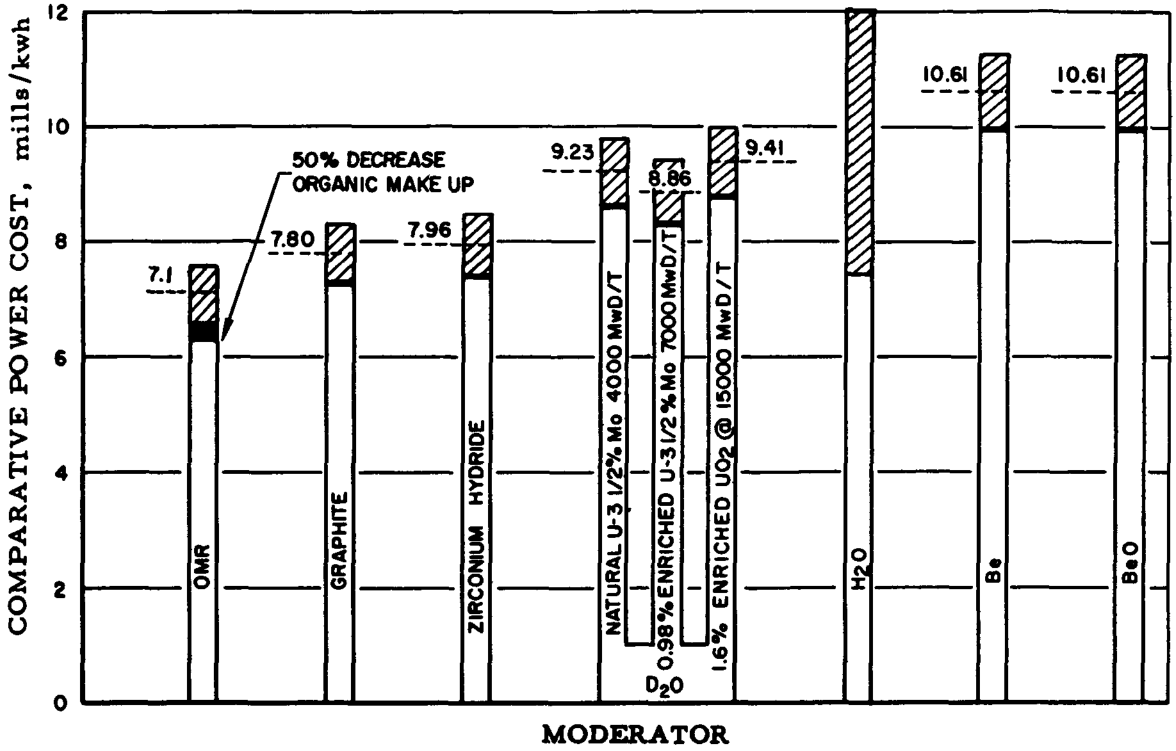

FIGURE 37.—*Comparative power costs for various moderators.*

TABLE 15—Continued

| | |
|---|---|
| HEAT TRANSFER CHARACTERISTICS—Continued | |
| Specific power | 6,200 kwt/MTU. |
| Peak to average power ratio | 6.55. |
| *Steam Generators:* | |
| Coolant flow to each steam generator. | $3.37 \times 10^6$ lb/hr. |
| Coolant temperature entering superheater. | 625° F. |
| Coolant temperature drop in superheater. | 5° F. |
| Coolant temperature entering boiler. | 620° F. |
| Coolant temperature drop in boiler. | 68° F. |
| Coolant temperature leaving boiler. | 552° F. |
| Feedwater temperature entering boiler. | 375° F. |
| Steam pressure at superheater outlet. | 800 psig. |
| Pressure drop through superheater. | 20 psi. |
| Steam temperature leaving superheater. | 580° F. |
| HEAT TRANSFER CHARACTERISTICS—Continued | |
| *Steam Generators*—Continued | |
| Steam flow leaving each generator. | 136,000 lb/hr. |
| Heat duty for the boiler, each unit. | $11.5 \times 10^6$ Btu/hr. |
| Heat duty for the superheater, each unit. | $7.57 \times 10^6$ Btu/hr. |
| FUEL ELEMENT CHARACTERISTICS: | |
| Type | Concentric tubes. |
| Number | 97. |
| Tubes per element | 2. |
| Cladding material and thickness. | 0.035 in. finned aluminum. |
| Element outside diameter | 5.25 in. |
| Element inside diameter | 3.10 in. |
| Thickness of fuel tube | 0.208 in. |
| Fuel can material and thickness. | 0.030-in. stainless steel. |
| Fuel alloy | 3.5 wt % Mo-U alloy +0.5 wt % Si. |
| Fuel inventory | 11.8 MTU. |
| Active length of fuel element | 78 in. |

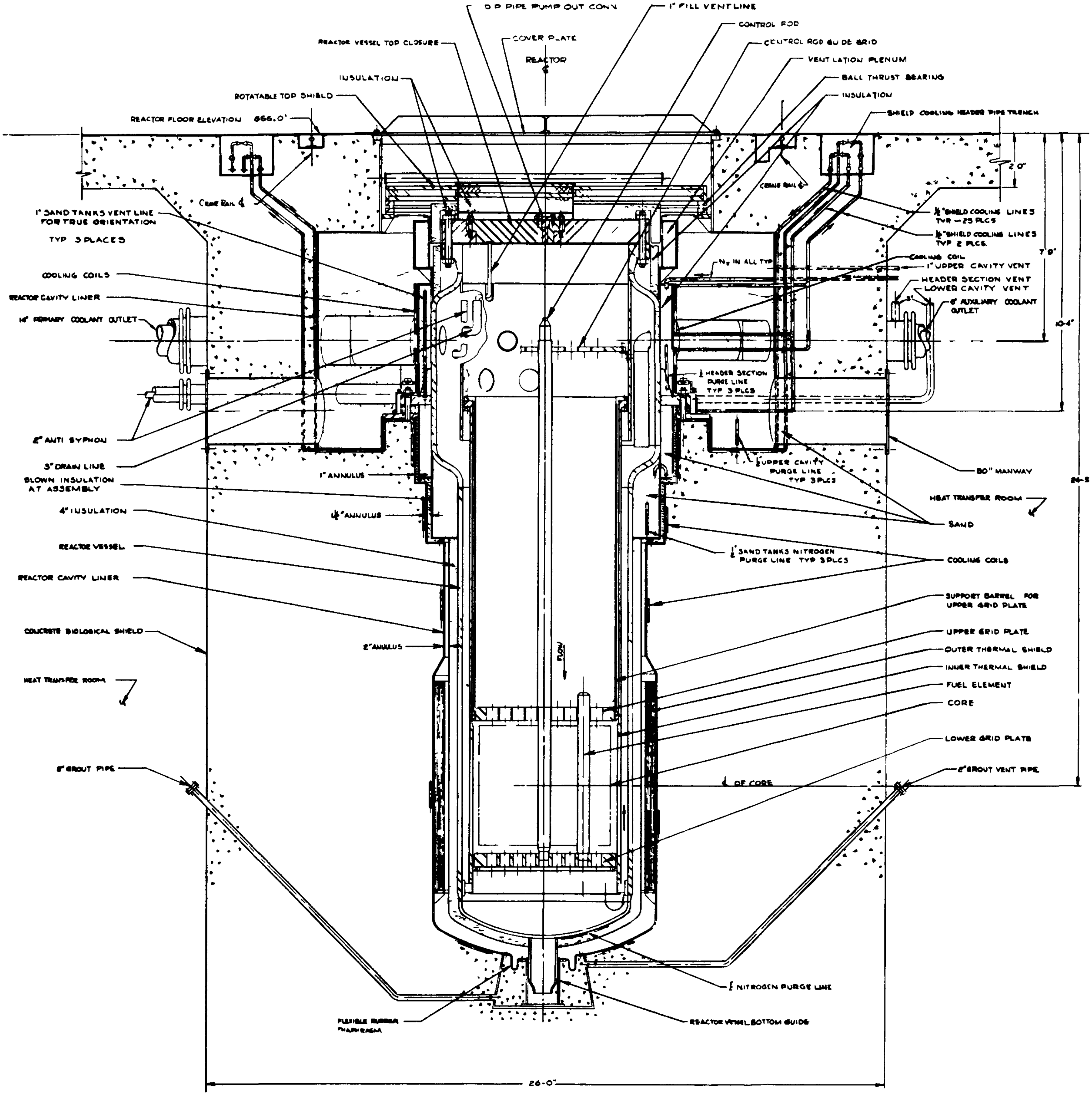

FIGURE 38.—*Reactor vessel; elevation cross section (Piqua OMR).*

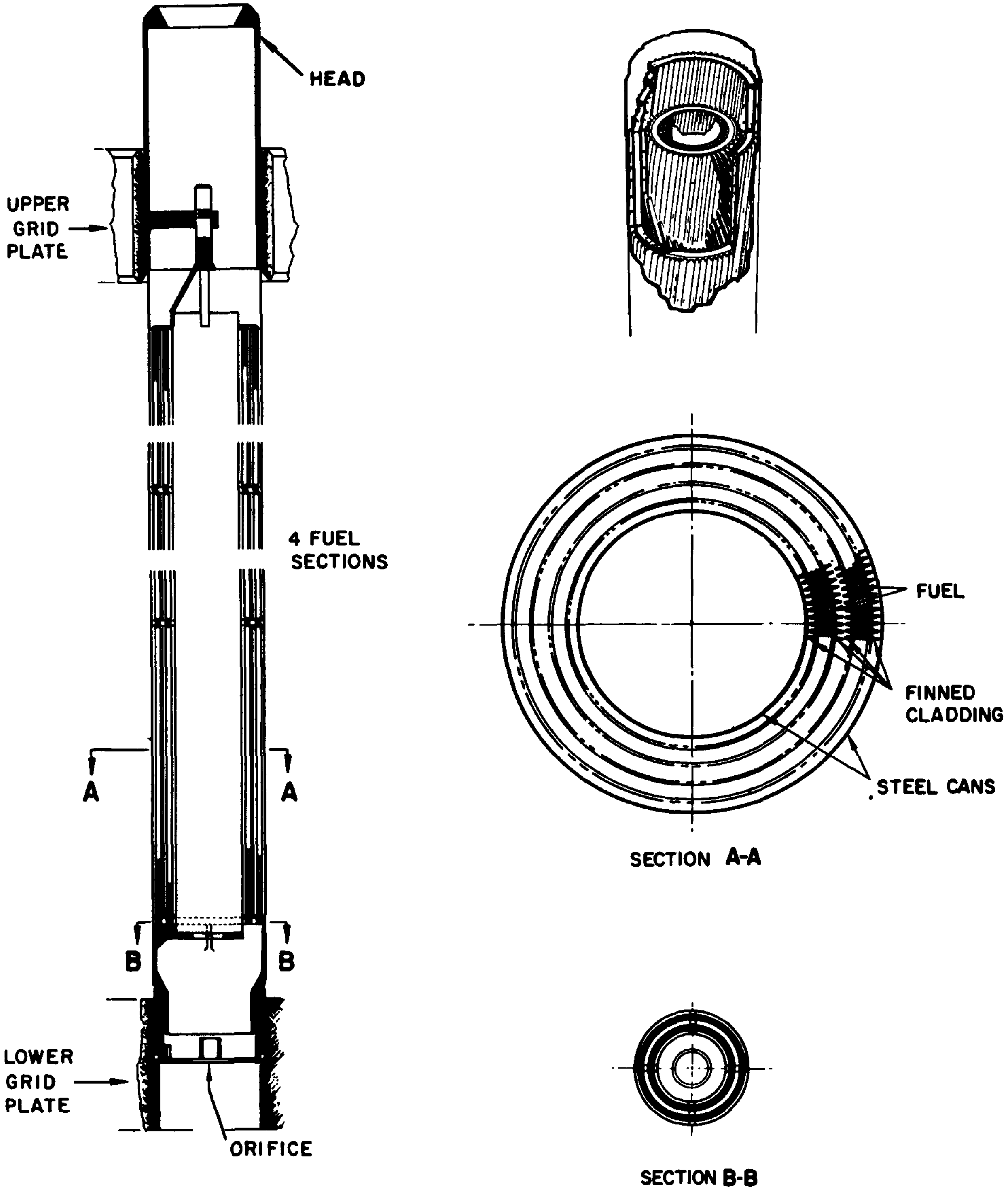

FIGURE 39.—*Fuel element (Piqua OMR).*

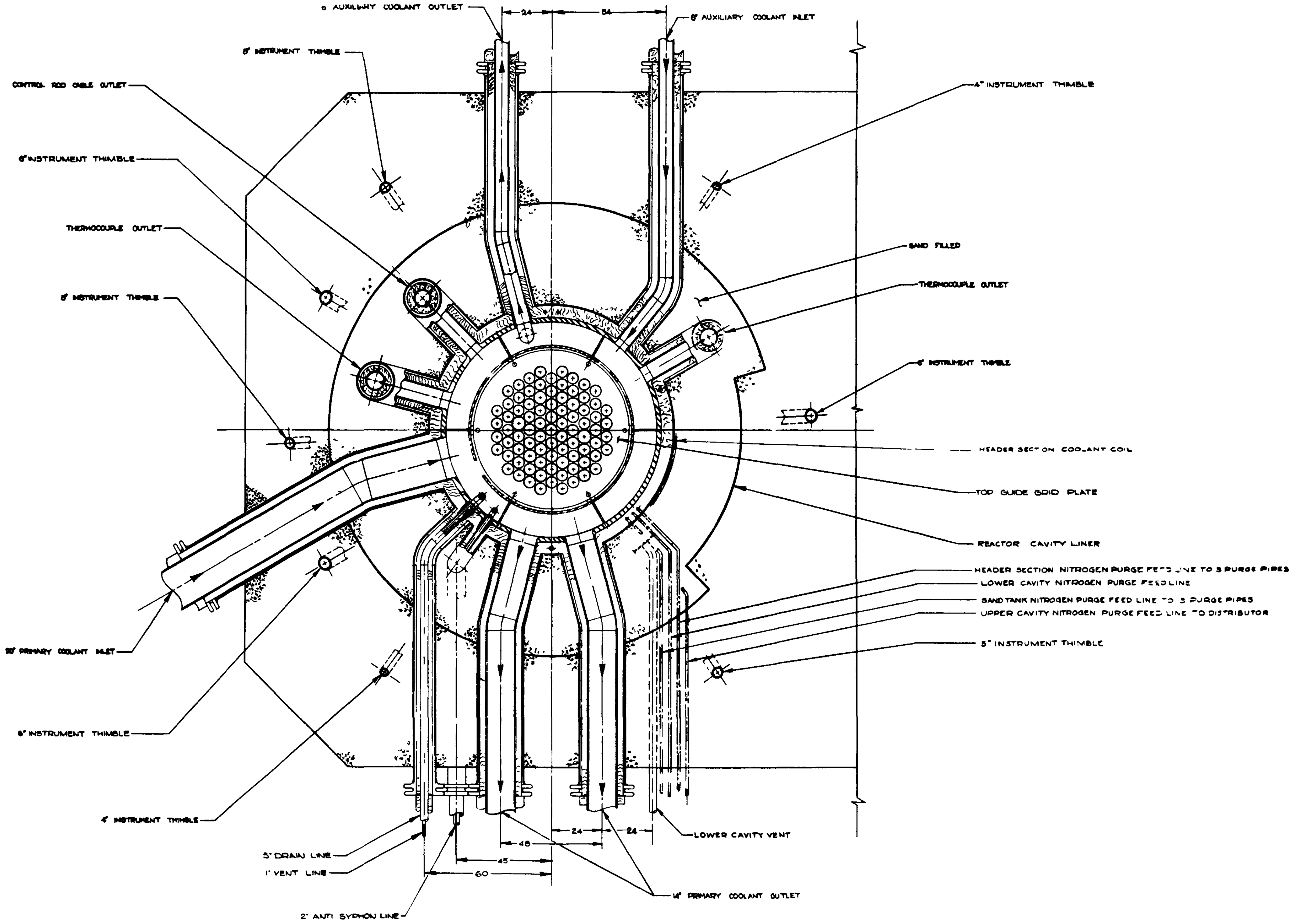

FIGURE 40.—*Reactor vessel; plan cross section (Piqua OMR).*

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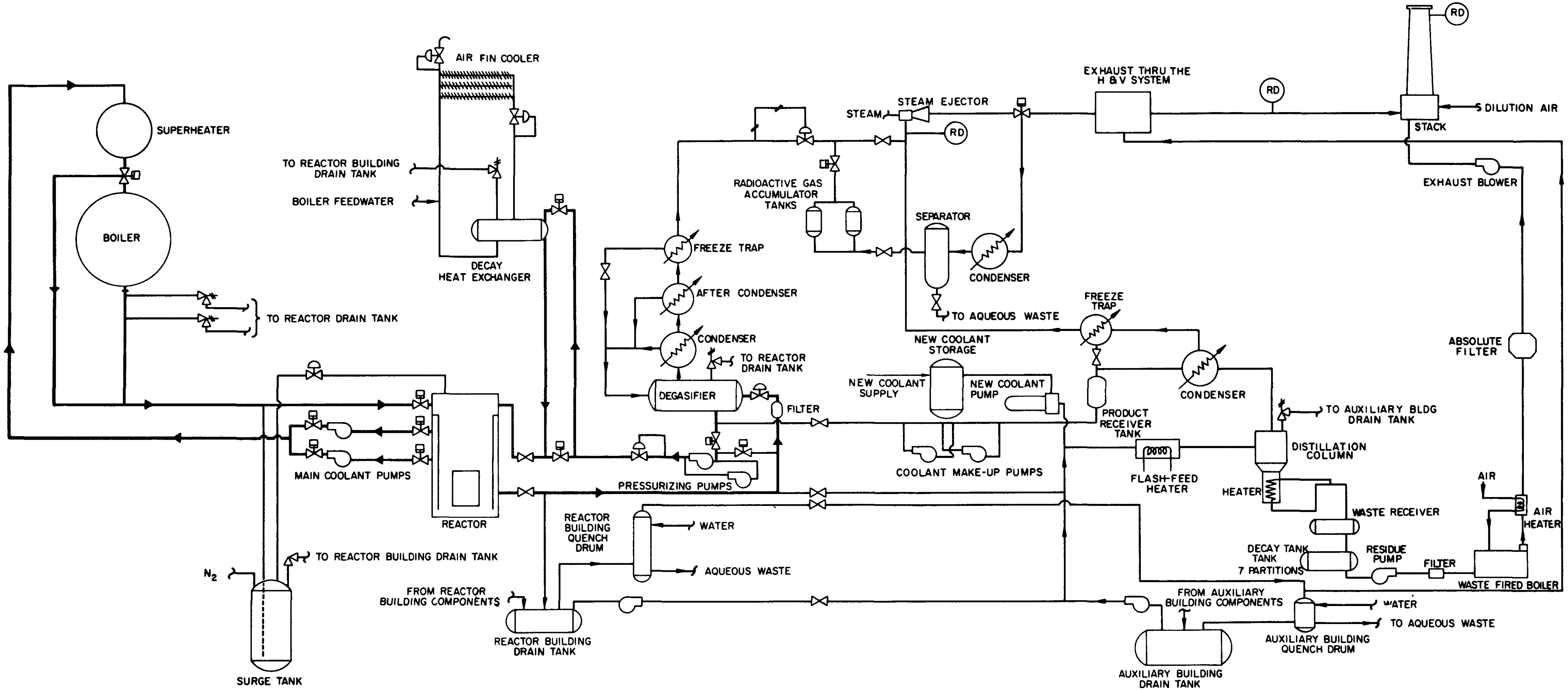

FIGURE 41.—*Main coolant system; composite diagram (Piqua OMR).*

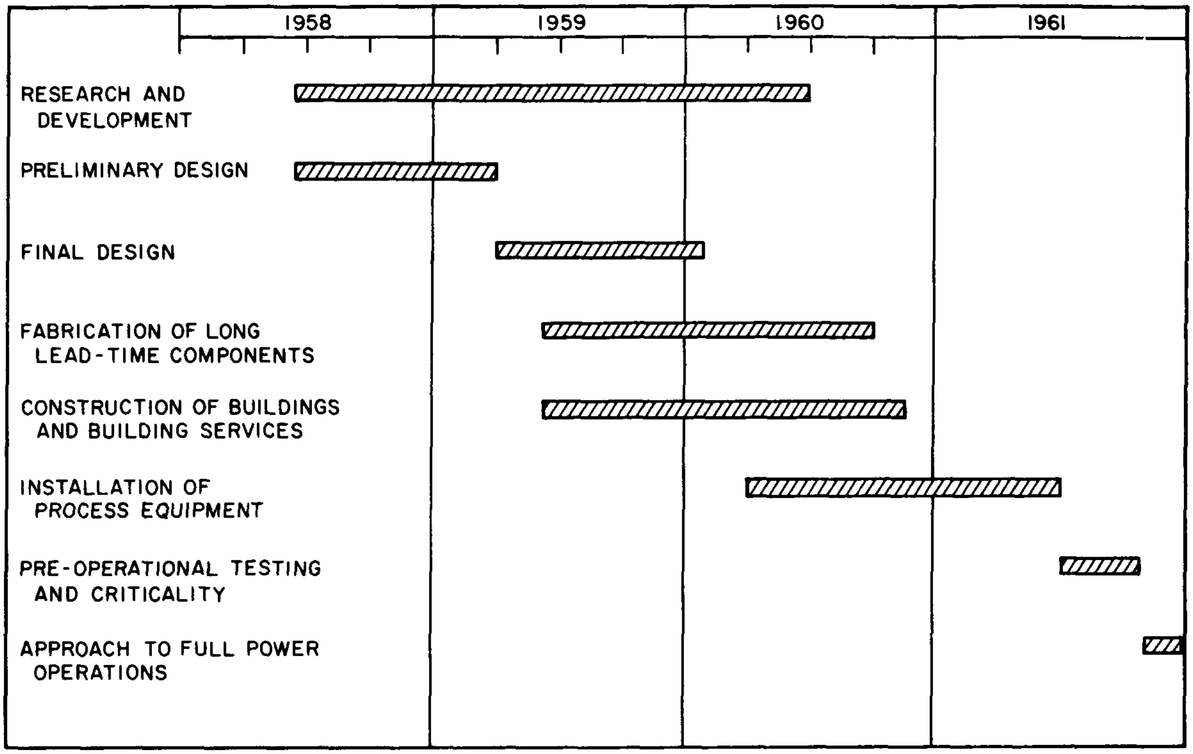

FIGURE 42.—*Design and construction schedule (Piqua OMR).*

TABLE 15—Continued

| | |
|---|---|
| FUEL ELEMENT CHARACTERISTICS—Continued | |
| Total length of fuel element | 104 in. |
| Temperature coefficient of reactivity (total at 550° F.). | $-5.7\times10^{-5}$/° F. |
| Excess reactivity (total, hot clean). | 7.0 %. |

TABLE 16

TURBINE PLANT SUMMARY DATA (300-Mwe OMCR)

| | |
|---|---|
| Nameplate rating (Mwe) at 3½ in. Hg abs. exhaust pressure | 300 |
| Gross electrical power (Mwe) at 1.5 in. Hg. abs. exhaust pressure | 314 |
| Net electrical power (Mwe) at 1.5 in. Hg abs. exhaust pressure | 301 |
| Gross cycle heat rate (Btu/kwh) at 1.5 in. Hg abs. exhaust pressure | 10,146 |

TABLE 16—Continued

TURBINE PLANT SUMMARY DATA (300-Mwe OMCR)—Continued

| | |
|---|---|
| TURBINE-GENERATOR: | |
| Type | Tandem-compound double-flow exhaust, 1,800 rpm. |
| Nameplate rating | 300 Mw at 3.5 in. Hg abs. and 3% makeup. |
| Guaranteed throttle flow. | $3.36\times10^{6}$ lb/hr. |
| Throttle steam conditions. | 600 psig, 650 FTT. |
| Number of feedwater extraction points. | 5. |
| Final feedwater temperature. | 394.4. |
| Condenser | Single pass, two water box, 1.5 in. Hg abs. at 57° F. inlet water and 203,000 gpm flow. |
| Generator | 384,000 kva, 0.85 pf, 13,800 kv. $H_2$ cooled at 45 psig. |
| Exciter | Motor driven 1,800 rpm, 1,800 kw, 375 v. |

TABLE 16—Continued

TURBINE PLANT SUMMARY DATA (300-Mwe OMCR)—Continued

**REACTOR, STEAM PLANT—SUMMARY DATA:**

| | |
|---|---|
| Type | Organic moderated and cooled. |
| Full load rating | 934 Mwt. |
| Coolant | Santowax R—30% high boiler. |
| Coolant temp | 550° F. inlet, 675° F. outlet. |
| Coolant flow | $50.5\times10^6$ lb/hr. |
| Number of primary loops. | 3. |
| Fuel | 0.30 in. diam. × 0.60 in. $UO_2$ pellets in APM-clad extended surface rods. |
| Number of fuel elements. | 310. |
| Control rods | 57 cruciform—$Eu_2O_3$ and $B^{10}$ clad in stainless steel. |
| Initial enrichment | 2.1%. |
| Initial reactivity | 15.2%. |
| Conversion ratio | 0.69. |
| Burnup, average | 15,000 Mwdt/metric ton. |
| Core size (active) | 10.33 ft diam. × 12 ft high. |
| Peak average power ratio, initial. | 2.55. |
| Peak average power ratio, final. | 3.77. |
| Specific power, average. | 20 kw/kg. |
| Maximum $UO_2$ temperature. | 4,000° F. |
| Maximum clad surface temperature. | 850° F. |
| Maximum heat flux, initial. | 93,300 Btu/hr-$ft^2$. |
| Maximum heat flux, final. | 133,000 Btu/hr-$ft^2$. |
| Steam generators and superheaters. | U-tube heat exchangers. |
| Rating (lb/hr) | 3,365,000 (delivered at 600 psig, 650° F. at the turbine throttle). |
| Core inventory | 46,500 kg U. |

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