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AQUEOUS HOMOGENEOUS REACTORS FOR PRODUCING CENTRAL STATION POWER

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Abstract

General technology of aqueous homogeneous reactors for central station application is presented. Problems of design and operation of circulating fuel reactors are considered in the discussion of the design of a 100-megawatt power station. (auth)

Introduction

For many years aqueous homogeneous reactors have been among the most promising "long range prospects" for producing economical central station power. Among the many attractive features which they derive from the use of aqueous fluid fuel systems are excellent fuel economy, adaptability to continuous fuel purification, excellent nuclear stability and simple mechanical design. Exploitation of the advantages has been difficult because of problems of corrosion, fuel chemistry, containment of radioactive fluids at high temperature and pressure, and maintenance of radioactive equipment.

Since 1950 the technology of the aqueous homogeneous systems has been under development at the Oak Ridge National Laboratory. The Homogeneous Reactor Experiment^(1,2) was operated successfully in 1953 to demonstrate the nuclear stability and, to some extent, the chemical and engineering feasibility of this type of reactor when operated at a high enough temperature for power applications. The Homogeneous Reactor Test⁽³⁾ is being constructed as a pilot plant for developing power reactor systems and will be completed in 1956. Recently a major equipment manufacturer and a large power company revealed plans for participating in the development of the technology with the objective of constructing a large homogeneous reactor power station to produce competitive power in 1962.

Reactor Types

A homogeneous reactor power station like a conventional power station can be subdivided into two plants, the steam generating plant and the electrical generating plant. The reactor and its auxiliaries replace the fossil fueled boiler and auxiliaries in the steam generating plant. Although there are differences in the turbines necessitated by differences in optimum steam conditions, the turbogenerator and transmission plant are essentially the same for both types of stations. Depending on the size and location of the reactor station a partial or complete fuel purification plant might be included as an integral part. Fuel processing is a separate, but very important, branch of the technology and will not be considered here.

Homogeneous reactor steam generating plants resemble large, high-pressure chemical plants. They consist of the reactor proper in which the nuclear chain

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reaction is sustained and heat is generated in the fuel, the piping, pumps and heat exchangers in which this heat is transferred to water to produce steam for operating the turbogenerators and equipment for charging and discharging fuel and for storing fuel and wastes.

Because fuel costs are of primary importance in central station applications, the reactors will be converters or breeders in which some of the excess neutrons which are emitted when the fissile material (U-233, U-235 and Pu-239) fissions will be absorbed in the relatively inexpensive fertile materials (Th-232 and U-238) to regenerate U-233 or Pu-239. Fuels for the reactors will be solutions or slurries of thorium, uranium and plutonium compounds in water. The water acts as a carrier for both fuel and heat and as a neutron moderator. Heavy water will be used in the fuel in preference to ordinary water. The increase in conversion ratio (and decrease in fuel cost) resulting from the reduced parasitic absorption of neutrons when deuterium is substituted for hydrogen more than compensates for the costs associated with the use of expensive heavy water. With water as the heat transfer medium in the reactors, the primary system must be designed to operate at pressures in excess of 1000 psia to attain temperatures of real interest for generating power.

The reactors are classified as "circulating fuel" or "boiling" depending on the method of removing heat. They are "one-region" or "two-region" according to the distribution of fissile and fertile materials. A circulating fuel reactor is one in which the fuel is circulated by natural or forced convection through the reactor vessel where the fluid temperature rises and then through external heat exchange equipment where the fluid is cooled. A boiling reactor is operated at the saturation temperature so that the heat produced in the fuel in the reactor vessel causes some of the water to be vaporized. Heat is extracted from the system by condensing the vapor in external heat exchangers; the condensate is returned to the fuel.

Typical one-region and two-region configurations are shown in Fig. 1. Fissile and fertile materials are mixed uniformly in a one-region reactor. They are separated into a core of predominantly fissile material and blanket of predominantly fertile material in a two-region machine. Fissile material produced in the blanket is separated and burned in the core.

Most of the development of aqueous homogeneous systems has proceeded along the path of the circulating fuel reactors because they present fewer obvious nuclear stability and heat removal problems. The Homogeneous Reactor Experiment demonstrated that a circulating fuel reactor has excellent nuclear stability. The heat production rate appears to be governed only by the rate at which fuel can be pumped through the core and by a temperature rise which is dictated by the chemistry of the fuel and the economics of the heat removal and power generating equipment.

The relationship between heat generation rate and vapor fraction in the fluid fuel and the problems of controlling a reactor which contains large and rapidly fluctuating volumes of vapor were early uncertainties concerning boiling reactors. Experiments which are still in progress indicate that a large boiling reactor operating at high power output would contain a vapor fraction in the range of 0.25 to 0.35.⁽⁴⁾ Although this vapor fraction would have been disconcertingly large a few years ago, calculations support the present belief that boiling homogeneous reactors will be stable and easy to control. Reactor experiments are required for confirmation.

Feasibility studies for large reactor systems have revealed no potential decisive advantages for either the circulating fuel or the boiling reactor type. Boiling reactors operate at the saturation pressure, the lowest pressure consistent with a given maximum temperature. All of the heat can be extracted

at the maximum temperature so the thermodynamic efficiency of the power cycle can be the highest. Because the neutron leakage decreases with decreasing vapor fraction and increasing size, circulating fuel reactors, which normally contain only small amounts of vapor, can be smaller and have equal or better fuel utilization than boiling reactors which operate at the same power level.

Boiling reactors might require the least amount of equipment because they can be designed to operate without large fuel circulating pumps and without intermediate heat exchangers if steam from the reactors is expanded in the turbines. It is questionable whether the savings resulting from elimination of the heat exchangers would be as great as the added cost of fabrication, shielding and maintenance of turbines and auxiliaries which must be designed to prevent the loss of heavy water and which will contain the radioactive fission products present in the steam from boiling homogeneous reactors. Elimination of the fuel circulating pumps remains a major attraction until more reliable pumps are developed.

In developing the circulating fuel reactors emphasis has been placed on meeting the requirements of the two-region systems. With few exceptions, the information which has been obtained is equally applicable to one-region reactors.

Good neutron economy can be achieved in small two region reactors. The size of a reactor is governed by the core volume required to obtain a critical mass and to permit the removal of heat and the blanket thickness necessary to absorb the excess neutrons which leak from the core. Representative dimensions are 3 to 6 ft for the core diameter and 1.5 to 3 ft for the blanket thickness, making the overall diameter 6 to 12 ft. One-region reactors must be 12 to 20 ft in diameter to limit the neutron leakage and achieve high conversion ratios.

Two-region reactors are the more versatile because fuels which have different handling, processing or neutron absorption characteristics can be used in the core and blanket systems. Core and blanket fluids must be kept separate and the tank which separates the two media must be thin and made of a material like zirconium which absorbs few neutrons. Two-region reactors are more complicated to build and operate than one-region reactors.

While the smaller size and greater versatility have led to the emphasis on the development of two-region systems for the first experimental power reactors, the greater simplicity of the one-region reactors may prove more attractive for large power stations. The selection of a reactor for a particular power station will depend on the current state of the technology, the role of the reactor in the plans of the power company and the engineering judgement of the designers.

Reactor Fuels

The most promising compounds for central station reactor fuels presently appear to be uranyl sulfate and fluoride solutions and uranium oxide and thorium oxide slurries.^(5,6) Other uranium and thorium compounds which have been studied are unstable at high temperature or in the presence of nuclear radiations, their solutions are too corrosive to be contained by any but the noble metals or the associated elements absorb too many neutrons. Too few data have been published to permit an evaluation of plutonium fuel compounds.

The concentrations of fissile and fertile material in the fuels which lead to the lowest net fuel costs appear to be the following:

One-region reactors:

100 to 500 g of thorium plus 5 to 50 g of uranium per liter of slurry.
100 to 500 g of uranium plus 2 to 20 g of plutonium per liter of solution or slurry.

Two-region reactors:

1 to 10 g of uranium per liter of solution or slurry in core.
500 to 1000 g of thorium plus 0 to 5 g of uranium per liter of slurry in blanket.
1 to 10 g of plutonium per liter of solution or slurry in core.
500 to 1000 g of uranium plus 0 to 5 g of plutonium per liter of solution or slurry in blanket.

Engineering experience is limited to temperatures below 570°F with the sulfate, fluoride and oxide fuels. Solutions are generally considered to be more satisfactory than slurries for reactor fuels because their homogeneity is essentially independent of the geometry of the container and the state of agitation of the fluid. However, at temperatures between 530° and 640°F uranyl sulfate (and fluoride) solutions separate into two liquid phases of different uranium content. The homogeneity of the fuel can be restored at the expense of increasing the corrosiveness and the parasitic absorption of neutrons by adding sulfuric acid to the fuel.

Type 347 stainless steel is a satisfactory material of construction for containing dilute uranyl sulfate solutions at 570°F if the fluid velocity is kept below 30 or 35 ft/sec. The critical velocity (or critical turbulence level) decreases with increasing concentration becoming less than 10 ft/sec for solutions of interest for one-region reactors. Titanium and zirconium are almost completely resistant to corrosion by all concentrations of uranyl sulfate, even at velocities above 80 ft/sec.

In the few tests which have been made in uranyl fluoride solutions the stainless steels and titanium have exhibited a corrosion behavior similar to that found with uranyl sulfate solutions. Zirconium is severely corroded even by dilute fluoride solutions.

The oxide slurries are mixtures of water with inert solids, so that in the absence of abrasion effects the corrosion observed is similar to corrosion in pure water. There is very little corrosion when uranium trioxide slurries are circulated through type 347 stainless steel equipment. There is no evidence of abrasion by the trioxide crystals which are softer than the stainless steel. Thorium oxide crystals are harder than stainless steel and that material is subject to severe attack by combined corrosion and abrasion by some thorium oxide slurries in circulating systems. Thorium oxide slurries of properly controlled composition can be circulated in stainless steel equipment at velocities as high as 30 ft/sec with only minor attack. Titanium and zirconium exhibit excellent resistance to attack by slurries.

Reactor Design

The general characteristics of homogeneous reactors and the similarities between one-region and two-region reactors are most evident in descriptions of reactor and station designs. Selected for this discussion is a station of 100 megawatts net electrical generating capability. Characteristics of the station and of two different reactors that can be used to supply the steam to the

turbogenerator are presented in Table I. Both reactors are circulating fuel,

Table I
DESIGN CHARACTERISTICS OF POWER BREEDER STATIONS

<u>Power Plant</u>			
Net electrical output, megawatts		100	
Gross electrical output, megawatts		106	
Net station efficiency, per cent		23	
Steam temperature, °F		435	
Steam pressure, lb/sq in absolute		365	
<u>Reactor Plant</u>			
	<u>Two-Region</u>		<u>One-Region</u>
	<u>Core</u>	<u>Blanket</u>	
Heat output, megawatts	360	80	440
Operating temperatures, °F			
Inlet	482	482	482
Outlet	572	572	572
Operating pressure, lb/sq in absolute	2000	2000	2000
Fuel circulation rate, gal/min	26000	6000	32000
Effective core diameter, ft	5.0		12
Blanket thickness, ft		2.25	
Reactor volume, cu ft	70	410	950
Volume of reactor and auxiliaries, cu ft	390	550	1470
Fuel	UO ₂ SO ₄ -D ₂ O	ThO ₂ -UO ₃ -D ₂ O	ThO ₂ -UO ₃ -D ₂ O
Fuel composition, g/kg D ₂ O			
U-233 + U-235 + Pa-233	2.8	4.7	6.8
Total U	8.5	3.4	21
Th-232		1100	300
Inventory, kg			
U-233 + U-235 + Pa-233	30	70	260
Th-232		15000	11000
D ₂ O	12000	17000	46000
Excess U-233 produced, g/day		60	6

breeder reactors based on the thorium-U-233 fuel cycle. The characteristics are essentially those which are found to result in minimum power costs for the specified power level in design studies based on the present technology and cost information. The power level was selected as representative of a first power plant. The effect of plant output on cost will be discussed.

Reactor Plant

The reactor plant can be subdivided into three systems or groups of equipment according to function.⁽⁷⁾ They are the high-pressure circulating system, the recombiner system and the low-pressure storage and waste disposal system. The high-pressure circulating system contains the primary reactor equipment in which the fuel is burned and steam is generated to drive the turbogenerator.

Recombiners are required to unite the deuterium and oxygen gases that are produced by collisions between fission fragments and heavy water molecules in the fuel. The low-pressure system contains the fuel feed pumps and fuel removal equipment and facilities for storing fuel and the radioactive gases and other reactor wastes.

High-Pressure Circulating System

A flow diagram for the high-pressure circulating system for the two-region reactor is presented in Fig. 2. Separate equipment is provided for handling the core and blanket fluids. Although only one pump loop is shown for the core fluid the actual number of circuits in the reactor will depend on the availability and reliability of equipment.

The flow diagram for the one-region reactor would be similar to that of the core circuit shown in Fig. 2. A total of 32,000 gal/min of fluid would be circulated through two or more pump and heat exchanger loops. The total gas production would approach 165 lb/min of deuterium and oxygen.

Reactor Vessels

The general features of one-region and two-region reactor vessels are illustrated in Figs. 3 and 4. Important factors which must be considered in designing the vessels include the flow distribution, vessel cooling requirements, mechanical strength requirements and materials specifications.

Proper distribution of flow is important because the effect that a unit volume of fluid has on the reactivity of a homogeneous reactor depends on the temperature, fuel concentration, vapor fraction and location of that fluid in the core. Changes in the distribution of temperature and gas bubbles could cause the reactor power to fluctuate in a manner that would make control difficult. Two methods of obtaining a satisfactory flow distribution are shown in the figures.

Fuel enters the one-region reactor at the bottom of the vessel and flows out at the top. Perforated plates in the inlet provide a smooth expansion of the flow. There is essentially no separation at the wall and no recirculation of fluid in large eddies. Estimates based on the measured flow distribution and the calculated neutron flux distribution indicate that the temperature and concentration of gas bubbles would be nearly constant in horizontal planes.

In the two-region reactor core the fluid is introduced as a jet which passes through the center of the core, reverses direction and flows out through an annulus around the inlet. There is a very high degree of mixing. The average temperature and gas concentration outside of the central jet would approach the temperature and gas concentration in the exit stream.

Either type of flow could be used for both types of reactor. The "concentric inlet and outlet" design has an advantage in mechanical simplicity, especially in two-region reactors where the core tank material would have a coefficient of thermal expansion different from that of the pressure vessel material. The "straight-through" design has slightly better nuclear characteristics because the average temperature and volume fraction of gas bubbles are less for a specified power and maximum temperature.

The pressure vessels probably would be fabricated of carbon steel clad with stainless steel. In the absence of thermal effects the thickness would be 4 in and 5 in, respectively, for the two-region and the one-region reactors. In a simple vessel large thermal stress would result from the temperature differences established in removing heat produced by the absorption of

neutrons and photons in the metal. Thermal shields, thick metal plates that absorb most of the radiations before they reach the wall, are provided to reduce the heat production so the combined pressure stresses and thermal stresses can be kept within acceptable limits.

The core tank for the two-region reactor would be made of 1/2-in-thick zircaloy plate.

It appears that both reactor vessels can be constructed and at about equal cost. Additional data concerning the embrittlement of carbon steel by neutron bombardment must be obtained before the reliability of carbon steels can be assured. Stainless steels are not embrittled by radiation; however, the fabrication and thermal stress problems seem to be more difficult and the cost would be greater. Although zirconium is a new material of construction, fabrication of the 5-ft-diameter core tank should present few problems that were not solved in making the 32-in-diameter core tank for the Homogeneous Reactor Test. The reliability of zirconium alloys as structural materials in aqueous fuels in the reactor environment remains to be demonstrated.

Gas Separator

In the absence of catalysts added to the fuel, a stoichiometric mixture of deuterium and oxygen saturated with water vapor will be produced in the reactor at a rate of about 160 cu ft/min at 572°F and 2000 lb/sq in. A device for removing these gases is the axial flow gas separator shown in Fig. 5. Vanes at the inlet impart a swirling motion to the fluid. The resulting centrifugal forces separate the liquid and gas causing the gas to collect in a void along the axis. The void is stabilized on hubs at the two ends and gas and entrainment are withdrawn through a pipe which is attached to an opening in one of the hubs. Vanes are provided at the discharge of the separator to recover some of the rotational energy. A separator designed to remove the gas from the full 26,000 gal/min flow from the core of a two-region reactor would be 24 in. diameter inside and 15 ft long between hubs. The entrainment would be less than 100 gal/min.

Heat Exchangers

A typical design for a natural recirculation steam generator to extract the entire 360 megawatts of heat from the core solution of the two-region reactor is shown in Fig. 6. Solution is pumped through 7800, 3/8-in. outside diameter stainless steel tubes at a velocity near 18 ft/sec. Each tube has an effective length of 24 ft and wall thickness of 0.048 in. The tubes are welded into 5-ft-diameter by 8-in-thick tube sheets made of stainless steel or carbon steel clad with stainless steel. Steam is generated in water outside of the tubes and separated in an elevated drum at a rate of 22,000 lb/min at 435°F and 365 lb/sq in absolute.

The slurry fuels are expected to have poorer heat transfer coefficients and to require proportionately larger exchangers for the same capacity.

Single, large heat exchangers apparently can be fabricated and for an initial cost which would be less than the cost of several smaller units of equal total capacity. Whether it is more economical to use one large exchanger depends on its reliability. The difficulty of ensuring perfect tube joints and the cost increase, but the amount of surface required and the fuel inventory decrease with decreasing tube diameter in an exchanger of fixed capacity. An optimum tube diameter of 3/8 in was found in a study of the effect of tube size on inventory and fabrication costs.

Although a shell and tube, double drum exchanger is described above, the exchangers used in a reactor must be selected from a number of different competitive possibilities. The type specified will be that which best meets the requirements of reliability, ease of maintenance, minimum inventory of fuel and low cost.

Fuel Circulating Pumps

Obtaining satisfactory fuel circulating pumps for the reactors is a major problem. The pumps must be completely leak-tight. They must operate for long periods without maintenance. The internals must be easy to remove when replacement or repair becomes necessary.

Modifications of the large canned rotor pumps which are being developed for the pressurized water, heterogeneous reactors should ultimately meet the requirements. They are designed to circulate water at rates near 17,000 gal/min against 280 ft of head at 2000 lb/sq in and 600°F. There is little doubt that pumps of greater volumetric capacity can be built. The reliability and ease of maintenance of the pumps remains to be demonstrated.

Stainless steels are satisfactory materials of construction for most of the pump parts. Titanium should be used for impellers and for other parts where the fluid velocity is high. The bearings can be hydrostatic bearings or Stellite-Graphitar thrust and journal bearings. Injection of condensate into the rotor cavity probably is required to keep the fuels out of the bearings and to minimize the radiation reaching the electrical insulation.

Pressurizers

The high-pressure system of a circulating fuel reactor is kept at a pressure greater than the vapor pressure of the circulating fluid to control the volume of gas in the reactor and to prevent cavitation in the pumps. This is ordinarily done by boiling fuel or condensate in vessels which are attached to the main circulating loop piping. The temperature of the boiling liquid is controlled to provide the specified pressure. Non-condensable gases are bled from the vessels before explosive mixtures are formed. Depending on the design, the pressurizer heat load can vary between 100 and 1000 kw.

The heat load can be reduced by pressurizing with a non-condensable gas. Provision must be made for recombining deuterium and oxygen that collect in the pressurizers to prevent the accumulation of explosive mixtures. Disposal of the gas when the reactor contents are discharged presents some problems.

The pressurizers also act as surge changers to accommodate the volume changes that occur as the fluid temperature and density change to compensate for sudden variations in reactivity. The volume of the vapor space, the distance from reactor core to pressurizer and the size of the connecting piping must be specified to limit the pressure rise that is required to transfer fluid from core to pressurizer.

Piping and Valves

Piping for the high-pressure systems will be type 347 stainless steel in sizes as large as 20 in. diameter and designed for service at 2000 lb/sq in. at 600°F. Because leak-tightness is essential, providing joints in the piping to permit the replacement of heat exchangers and other items of equipment presents many problems. Until machines are completely developed to make satisfactory welds when installed and operated remotely, reliance must be

placed on flanged joints. Ring joint flanges have been used successfully in pipe sizes up to 24 in. diameter in the experimental homogeneous reactors or in test facilities.

In a station where a reactor is provided to supply the steam for each turbogenerator, the use of large valves which must seal against a pressure of 2000 lb/sq in. can be avoided. The largest valves can be 6-in. valves which control the discharge of the reactor contents to the storage tanks. Larger valves may be required to permit the isolation and repair of defective equipment in very large generating stations where a single reactor supplies the heat for many turbogenerators.

Recombiner Systems

Whether the generation of deuterium and oxygen is an advantage or a major disadvantage is not yet clear. As much as 5 per cent of the energy released in the reactor can be recovered as heat of combustion of the saturated gases and condensation of the vapors. If the gases are burned at the maximum reactor pressure all of this heat is available at a temperature greater than the maximum fuel temperature. By using the energy to superheat the steam before it enters the turbogenerators, which would otherwise use saturated steam, the cost of the turbogenerator plant can be reduced and the thermal efficiency of the station can be increased.

In addition to providing a high-temperature source of heat, the decomposition gas is a carrier for the fission product gases which are produced in relatively small amounts. Removal of these gases, xenon-135 in particular, results in a decrease in the parasitic absorption of neutrons and greater ease of control of the reactor. Another equally effective means of removing the xenon-135 might be difficult to find.

The hazards associated with explosions of deuterium-oxygen mixtures constitute the major disadvantage. Although high-pressure recombiner systems which appear to be safe can be designed, it is not yet possible to insure against damaging explosions and the release of radioactive fluids under some abnormal conditions.

Two types of recombiner system have been operated, at least on an experimental basis. One employs a combustion chamber in which the gases are burned in a flame. Because the gases must be combustible and the probability of an explosion occurring is high, this system has been used only at low pressure as in the Homogeneous Reactor Experiment. Most of the heat is wasted and it is necessary to let down large volumes of gas and entrained fuel from high-pressure to low pressure and to return large volumes of fuel and condensate to the high-pressure system.

A more attractive scheme for large reactors employs a platinum catalyst for recombining the gases. The mixture of deuterium, oxygen and heavy water vapor which is separated from the fuel in the gas separator of the high-pressure circulating system and which would ordinarily be combustible is passed into an entrainment separator where it is diluted well below the explosive limit by a recirculated mixture of heavy water vapor and helium, oxygen or some other gas. The non-combustible mixture is passed through a bed of platinized alumina pellets or platinum gauze where the deuterium and oxygen unite and heat the gas to 800 to 1100°F. The gases are cooled and recirculated by a blower or by thermal convection and the excess condensate is returned to the fuel circulating system. A maximum amount of heat is recovered at high temperature and only small amounts of gas and liquid must be let down to low pressure. Although the probability of destructive explosions occurring is small it has not been eliminated.

Fortunately, the feasibility of aqueous homogeneous reactors does not depend entirely on the development of methods for safe handling of the large quantities of deuterium and oxygen which can be produced during operation at high power. In the case of uranyl sulfate fuels it has been possible to suppress the production of gas at high temperature by adding small amounts of copper sulfate to recombine the gases in solution in the fuel. Possibly the savings resulting from the elimination of recombiner equipment and the added safety of operating without producing large quantities of gas when homogeneous catalysts are added to the fuel would more than compensate for the lower limit on thermal efficiency.

Low-Pressure Storage and Waste Disposal System

The reactor plant contains facilities for storing fuel while the reactor is being serviced, for charging fuel into the reactor, for withdrawing material to be sent to the processing plant and for disposing of the gaseous fission products. The storage tanks are sized or partitioned so that a nuclear chain reaction cannot be sustained when they are filled with fuel. An evaporator, a condenser and condensate storage tanks are provided so the concentration can be adjusted in fuel which is sent to the reactor and to the processing plant. Although the fissioning stops when the fuel is discharged from the reactor the energy emitted by radioactive decay of fission products results in the production of important amounts of heat and radiolytic gas in the storage tanks. A recombiner and condenser, probably the evaporator condenser, are included for recombining the gases and removing the heat.

High-pressure feed pumps are required for supplying fuel to the reactor. Positive displacement, diaphragm-type pumps were used for the Homogeneous Reactor Experiment and are specified for the Homogeneous Reactor Test. Similar pumps should be satisfactory for the large reactors if the capacity can be kept below 10 gal/min by recombining the radiolytic gases at high pressure.

Fission product gases from the reactor must be disposed of without creating a biological hazard. It is proposed that this be done for the first power reactors by passing the gases through cold traps or dryers to remove the heavy water vapor and then into water-cooled adsorption beds where all except the 10-yr krypton-85 would decay. The krypton-85 would be diluted with air and discharged through a tall stack at a rate of 1 to 1.5 curies per day per megawatt of reactor heat output.

Reactor Operation and Control

Aqueous homogeneous reactors rely completely on the temperature coefficient of reactivity for nuclear control. Reactor temperatures are adjusted by varying the fuel concentration and the power level is regulated by controlling the rate at which steam is withdrawn from the main heat exchangers. Mechanical control rods generally associated with nuclear reactors are unnecessary.

Because there is a large volume of fuel in a large power reactor, several hours would elapse in changing the fuel concentration by an amount required to heat or cool the reactor through the temperature range from 200° to 600°F. The reactors can be refueled continuously and are intended to be operated continuously at the design temperature and at design or reduced power levels for periods of time which are governed by the life of the equipment. In the event

of an emergency such as the development of a leak in the high-pressure equipment, the fuel can be dumped to the storage tanks in a few minutes.

Reactor Plant Assembly

An aqueous homogeneous reactor and auxiliary equipment assembly is shown as part of the power station in Fig. 7. Reactor equipment is housed in a tank which is 60 ft in diameter by 120 ft high. The tank contains much of the shielding and is designed to prevent the escape of radioactivity if leaks develop in the fuel systems. There is access to pumps, valves and other critical components through openings in the dome and in the shielding. A pool is provided adjacent to the reactor for storing contaminated equipment. The economic feasibility of the reactors may depend ultimately on the development of tools and methods for servicing the reactor and its highly radioactive components.

Turbogenerator and Transmission Plants

The turbogenerator and transmission plants for the homogeneous reactor power station and for the conventional station differ only in the turbine. Modern turbines use steam at temperatures and pressures in excess of 1050°F and 1000 lb/sq in. Temperature limitations imposed by the reactor require that the turbines for the reactor station use saturated steam at 435°F and 365 lb/sq in. Apparently turbogenerators having outputs well above 100 megawatts and employing special blading or external moisture separators can be designed for this service. The gross efficiency of the plant would be near 27 per cent. Station electrical loads and heat losses would reduce the net station efficiency to about 22 per cent.

Problem of Competitive Power

Many cost and feasibility studies have shown that if certain assumptions concerning the reliability, the operability and the costs of reactor equipment are valid, the homogeneous reactor stations should be capable of competing with the most modern fossil fueled stations. The first 100-megawatt stations are expected to cost \$200 to \$250 per kilowatt of capability as compared with \$150 per kilowatt for a comparable conventional station. Estimated fuel costs which include the feed, chemical processing and inventory and loss charges on the uranium, thorium and heavy water can be less than 1.5 mills/kwh if common processing facilities are shared by several reactors.

Differences in cost of power from one-region and two-region reactor stations are related almost entirely to the inventory and processing charges. The reactors are so similar that there is no obvious difference in total station cost. Investments in reactor inventories for 100-megawatt power stations are shown in Table II. Assuming a yearly fixed charge of 10 per cent on investment in inventory and a plant factor of 0.8, the inventory charges for the two-region reactor would be the lower by an amount equivalent to 0.3 to 0.6 mills/kwh. This difference decreases with increasing reactor and station power.

The value of the excess U-233 produced is an additional attraction of the two-region reactor. Sale of the material might not provide an important source of revenue but retention of the excess U-233 would make it possible for the station operators to provide fuel for new reactors with a doubling time of about 6 years. Production of a substantial excess of U-233 in a one-region

reactor requires that the reactor vessel and the inventory of fuel be uneconomically large.

The economic feasibility of homogeneous reactors does not appear to depend greatly on the fuel cycle employed. Although the more economical thorium-uranium cycle has been emphasized here, reactors operating on the uranium-plutonium cycle are estimated to have fuel costs which are only 0.5 to 1 mill/kwh greater. The additional cost is incurred because the reactors produce 10 to 20 per cent less fissile material than they burn and the deficit must be made up by the purchase of plutonium, produced in fast breeder reactors, or U-235 in natural or slightly enriched uranium.

Analyses of the economics and feasibility of homogeneous reactors have in effect been estimates of the potential of the reactors in the absence of radiation effects. Whether this potential can be exploited and whether one type of reactor is superior to another will depend on the effects that the intense radiations have on materials and fuels, on the reliability of equipment and the additional expense involved in maintenance of highly radioactive equipment and on the expense of ensuring complete containment of the radioactive fuels at all times. Answers to many of the problems of physics, chemistry and materials are being obtained in laboratory and reactor experiments today. Final answers to the major engineering and economics problems await the construction and operation of the first large reactor station.

Table II

INVESTMENT IN REACTOR INVENTORIES FOR 100-MEGAWATT STATIONS

	<u>Two-Region Reactor</u>	<u>One-Region Reactor</u>
U-233, U-235 and Pa-233, millions of dollars		
at \$15/g	1.5	3.9
at \$30/g	3.0	7.8
Th-232, millions of dollars		
at \$25/kg	0.4	0.3
D ₂ O, millions of dollars		
at \$28/lb	1.8	2.9
Total, millions of dollars	3.7 to 5.2	6.1 to 11.0

Cost of U-233 is assumed to be equal to that in current use for U-235.

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ONE REGION CONFIGURATION

TWO REGION CONFIGURATION

Fig. 1. Reactor Configurations.

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Fig. 2. Flow Diagram for High Pressure Circulating System

Fig. 3. One-Region Reactor Vessel with "Straight-Through" Flow.

Fig. 4. Two-Region Reactor with "Concentric Inlet and Outlet" Core

Fig 5 Axial Flow Gas Separator

Fig 6 Natural Recirculation Heat Exchanger

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Homogeneous Reactor Power Station.
FIG. 7.

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