Since being placed into operation, this small research reactor has been useful in experimentation other than that originally contemplated. Figure 17 shows the testing of an automatic servo system designed for operating a 2000-watt reactor.

This small reactor is well within the economic limits customarily spent for conventional equipment. Depending on the nature of experimental facilities, shielding, and building required, such a unit may cost from $75,000 to $100,000. Located as it is within an existing manufacturing plant it has proved beneficial not only in the experimental program for which it was designed but also as a practical tool for testing and developing new reactor components and may therefore, contribute to a wider use of nuclear reactors both by industry and educational institutions.

The Engineering Design of the North American Aviation Homogeneous Graphite Research Reactor

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THE BASES for the North American homogeneous graphite reactor design are: it may be operated in a highly populated area, such as a university campus; it is safe for unskilled personnel to perform experiments in and around the machine; and there are no hazardous effluents. In addition to being a general research tool, the reactor includes facilities for simultaneous service irradiations to produce isotopes that might provide a source of income for the operating institution. It is to operate at a power of 135 kw with 1×10^{12} neutrons/cm^2/sec available in the experimental facilities. Low construction cost consistent with the above requirements is of prime importance. This is kept to a minimum by using commercially available parts, equipment, and materials, wherever possible.

The basic design for the homogeneous graphite reactor was chosen from a study of six different configurations of both liquid and solid moderator designs. The homogeneous graphite configuration presented the most economical and practical solution for the design of an extremely safe reactor which has no radioactive effluents. The core is a homogeneous mixture of graphite and uranium contained in a sealed core tank. It is homogeneous only in the nuclear sense; that is, in the intimate association of the moderator and fuel, so that at all times they will have the same temperature. Since the moderator temperature determines the minimum velocity of the neutrons and the probability of fission is sharply dependent on neutron velocity, an increase in moderator temperature will decrease the reactivity of the reactor. This phenomenon is represented by a negative coefficient of reactivity. It gives the reactor inherent safety and stabilization. Thus, an accidental increase in reactivity, which always causes a rise in moderator temperature, will be arrested before damage can occur. As a precaution against an accidental increase of reactivity, no access is provided to the interior of the core tank except after first removing the core assembly from the reactor. It should only be necessary to remove the core for refueling, and the design provides sufficient fuel to operate the reactor for 3.5×10^6 kw hr. Operating at full power on an 8-hr day, refueling would be required about every 10 years. Another important feature of this configuration is the large quantity of neutrons available for experimental use. Many irradiations may be conducted simultaneously without materially reducing the number of available neutrons. Thus, certain long-time high absorption experiments may be conducted without interfering with other short-time experiments.

The design lends itself to simple components. Because of the large amount of room in and around the core, the control mechanism is simple and rugged commercial parts are used throughout. The shield, too, is a convenient size for the location of many experimental facilities that will not interfere with one another. The coolant system is conveniently located in a room below the reactor so that radiation from the coolant is not a problem.

The homogeneous reactor as proposed is an octagon, with outside dimensions of 20.5 ft across the flats by 13.5 ft high. The experimental facilities that pierce the shield are arranged on each of the eight faces and on the top. Also on the top are the control rod mechanisms which move the six rods extending vertically into the core. These mechanisms extend 10 ft above the reactor. Beneath the reactor, in a special room, is the cooling system equipment. The coolant, D_2O, is circulated in a closed system through the reactor and a heat exchanger. The core is in the center of the shield and is surrounded by a 2-ft thick graphite reflector. A control console may be located anywhere near the reactor.

The shield is 13.5 ft high and only 6 ft thick. These dimensions are achieved by using an iron ore-coleman-

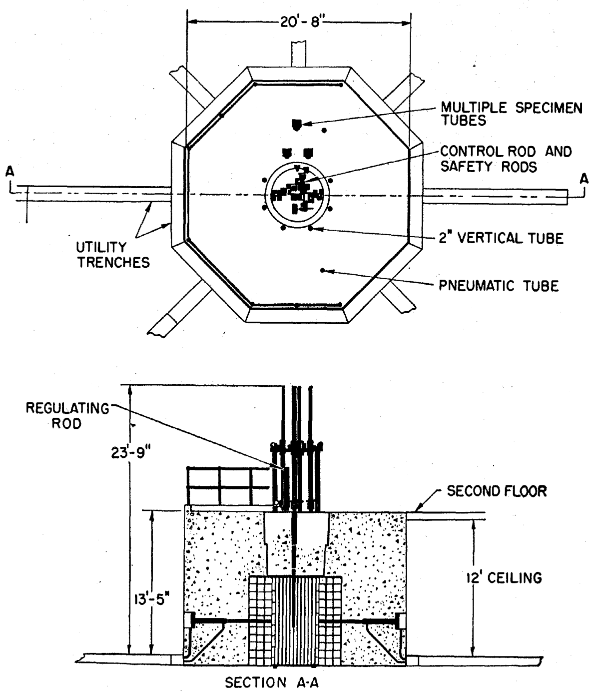

FIG. 1. General installation layout.

ite concrete for the shield. It has a specific gravity of 3.6 to 3.8, as compared to 2.3 for ordinary concrete. Thus, a substantial saving in the bulk of the shielding is realized. The small size of the shielding makes it possible to construct the forms as concentric, ½-in. thick steel tanks with the experimental tubes and reinforcing steel welded in place. Perhaps this can be done at the fabricator's shop. The annular space is filled with the dense concrete at the construction site. The steel outside face is convenient for attaching special equipment or brackets to the reactor face, while the inner steel form provides a permanent vapor-tight envelope for the reflector graphite.

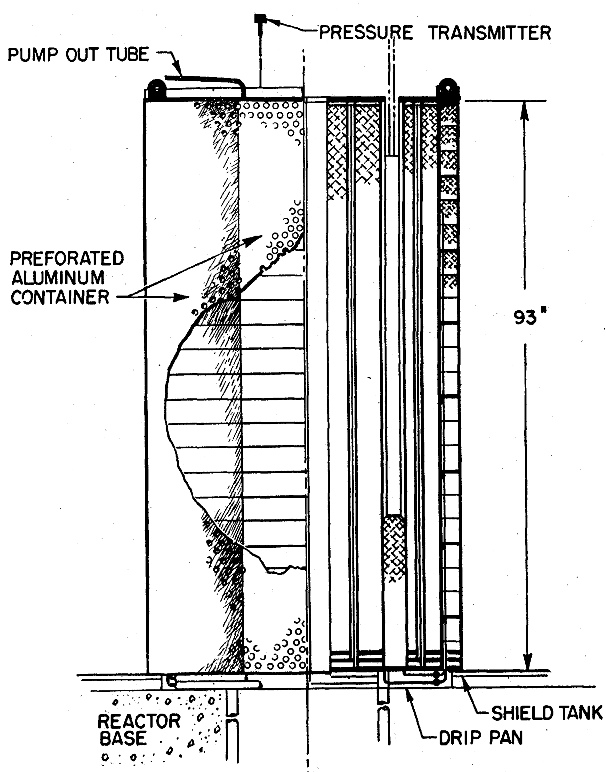

FIG. 2. Core assembly.

EXPERIMENTAL FACILITIES

Each of the eight faces of the reactor is 8.5 ft wide. This provides ample flat surface around a hole for assembling experimental apparatus and for providing a minimum of interference with the experiments that are being conducted in the adjacent faces. Each face has a radial utility trench that contains outlets for the electricity, water, and air below floor level. The trench connects with each experimental hole, so instrument lines may also run below the floor, thus preventing accidental damage to them by laboratory traffic. Four types of holes pierce the shield and reflector for inserting samples or equipment into the neutron flux: (1) the universal experimental hole, (2) the pneumatic tube, (3) the multiple specimen tube, and (4) the thermal column. These experimental holes are sealed from the atmosphere inside the reactor, thereby preventing radioactive air from emerging from the large void spaces in the reflector volume or the accidental drawing in or spilling of contaminants into the voids in the graphite reflector. There are 17 universal experimental holes, including four 3-in. diameter tangential holes, six 3.5-in. diameter radial holes, six 2-in. diameter vertical holes, and one 6-in. diameter radial hole.

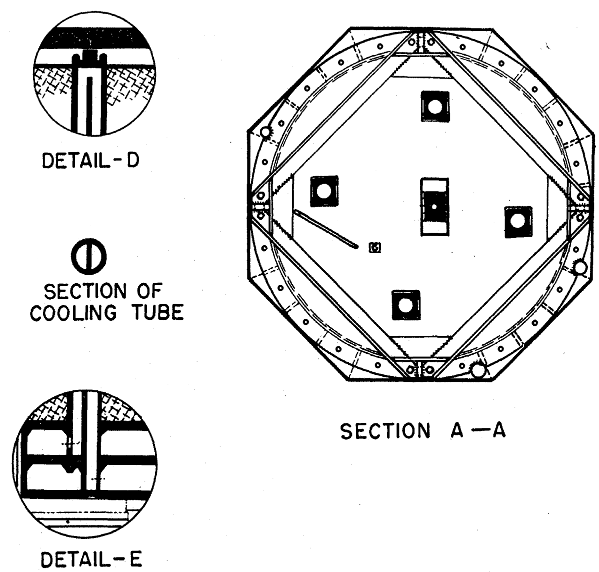

FIG. 3. Core tank details.

In general, larger holes are preferred, but restrictions are placed on their size for: (a) convenience in

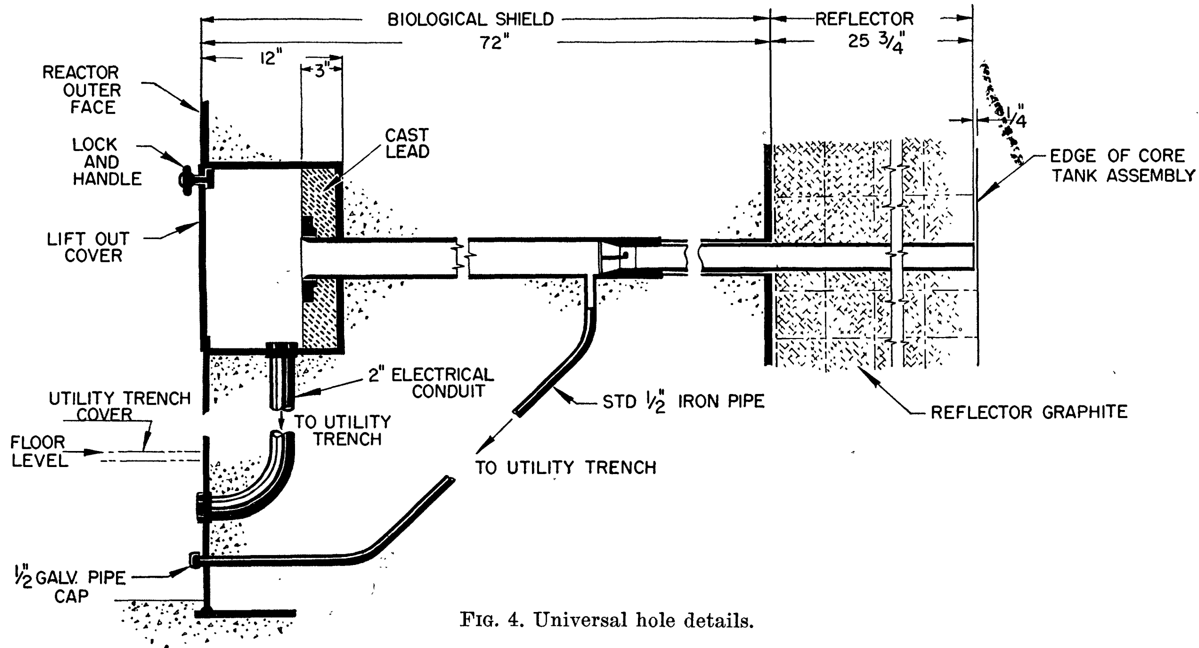

FIG. 4. Universal hole details.

handling and removing the shied plugs; (b) limiting the volume of high neutron absorbent material that may be placed into the hole because, if suddenly withdrawn, too large a volume would cause a runaway; and (c) limiting the amount of air in the tubes which may become radioactive and be displaced into the reactor room when the hole plugs are inserted. These three limitations indicate that, for this particular reactor configuration, hole of diameter 6 in. is the largest recommended.

Standard steel pipe is used for construction of the experimental holes in the shield. A thin removable aluminum thimble or tube is inserted through the reflector portion of the hole. It is sealed to the steel pipe by a gasket and nut. Aluminum is used to minimize the amount of neutron shadowing of the experiment placed inside the hole. The outer open ends of the holes terminate in a box or recess 16 in. square and 9 in. deep. Instrument leads or additional shielding may be installed in this recess. The holes may be sealed by placing a face plate over the open end, inside the recess. The hole may then be evacuated or purged through the ½-in. diameter drain and purge line. In addition, a 2-in. electrical conduit provides communication between the recess and the utility trench for instrument and power leads.

When a hole is not in use, it is plugged with a set of graphite plugs in the reflector section and steel plugs in the shield section to reduce the emitted radiation to below tolerance levels. Each plug weighs less than 30 lb for easy handling. The plugs may be easily withdrawn with a special tool which is positively engaged on contact.

Universal holes are useful for irradiating samples either in static or dynamic systems. Items such as the piston rings or wearing parts on machinery may be irradiated for subsequent wear testing. Also, beam experiments, such as determining the time of flight of neutrons or testing shielding materials, may be performed.

The pneumatic tube that has access at the top of the reactor is a specialized form of a universal hole. The main feature is the reduced shielding required to introduce and remove samples while the reactor is in operation. This tube is constructed of aluminum and is a commercial pneumatic system size. Thus, all the equipment and technics used in commercial installations may be used without change. A 2-in. diameter tube is shown, but a wide variety of sizes and shapes are available. This equipment is especially useful for the determination of the half-life of extremely short-life isotopes and for other controlled exposure experiments.

The thermal column, as shown, occupies one entire face of the reactor. Depending on the requirements of the research program, a thermal column initially may be made to cover more than one face, may be made smaller, or may be omitted. The size shown is 40 ft^2. The lead barrier between the reflector and the thermal column graphite shields the gamma rays produced in the core and allows only the neutrons to enter. Thus the emerging beam is composed of neutrons and gamma rays produced in the thermal column by the capture of neutrons in the graphite. A lead and cadmium door of 9-in. thickness is provided for shielding when the thermal columns is not in use. This door weighs 23,000lb. It is horizontally divided in the center and counterbalanced to move apart vertically. It is actuated by a pneumatic cylinder.

Some longitudinal bars placed in the graphite stack may be removed to make a very high-intensity short-range beam through one of the smaller doors in the large counterbalanced door. This beam would be useful for medical therapeutic work.

The general arrangement of the thermal column

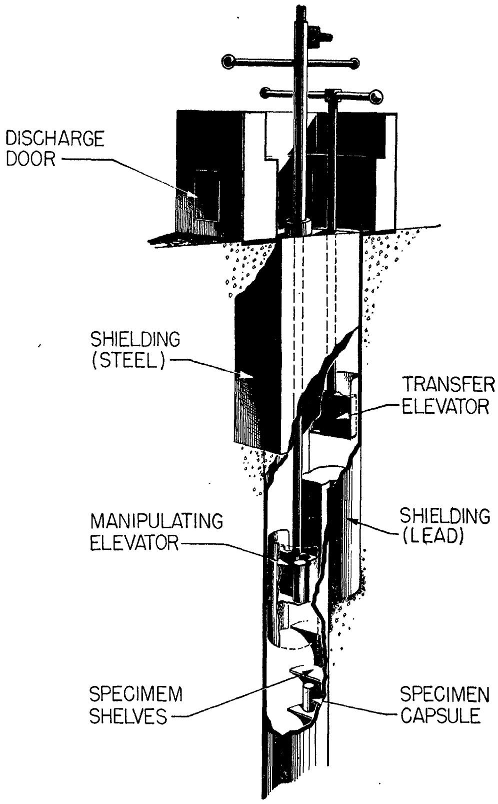

FIG. 5. Multiple specimen hole details.

makes it useful for exposing either a large number of test animals together or large areas of a material.

On the top face of the reactor are three multiple specimen tubes. Each consists of a vertical 5-in. diameter tube with small shelves placed at 3-in. intervals, and each terminates in a shielded transfer box. The transfer box eliminates the use of shield plugs and makes easier the transfer of the samples into a shielded casket. Standard 2¼-in. diameter by 2½-in. high, 25-cc sample capsules are provided which may be placed in the reactor and removed without disturbing any other capsule. A capsule is introduced in two steps. First, it is lowered to the offset in the transfer box; then, by rotating the paddles on each of the elevators in turn, it is transferred to the main elevator. The elevator is lowered to the selected shelf and again, by rotating the paddle, the capsule is transferred to the shelf. To remove a capsule, the procedure is reversed, and the capsule is finally discharged into a shielded casket.

The multiple specimen tube is a single-use device designed for the production of commercially usable radio isotopes or for long-time experimental exposures.

The experimental facilities were selected to give access to a variety of simultaneous experiments. The arrangement was chosen to provide the greatest amount of general purpose use. Other arrangements may be selected according to the needs of the operating organization.

COPE AND CORE TANK

The safety of the reactor is inherent in the design of the core assembly. The homogeneous core, which is homogeneous only in the nuclear sense, has a negative coefficient of reactivity of the order of -3×10^{-4} per °C. Under runaway conditions the coefficient is a bit lower but still is sufficient to arrest the reaction and to keep the aluminum parts from melting. By using only solid materials (graphite and uranium) in the core, the problem of containing all the fission and decomposition products was resolved simply by evacuating and sealing the core tank for the life of the core. Thus no radioactive effluents may escape and the need for a stack or hold-up equipment is eliminated.

That part of the core which contains the fuel is a right circular cylinder 45.5 in. in diameter and 42 in. high. The core tank, which contains the core and the portion of the reflector graphite immediately above and below it, is 46 in. in diameter and 93 in. high. The reflector was included inside the core tank to make removal of the assembly easier and to provide expansion space for the fission and decomposition products. The design of the core tank was complicated somewhat by including the reflector, but the simplification in gas handling and in the installation and removal procedure made it worth while.

The core tank design was interesting in that the tank, 46 in. in diameter and 93 in. high, was to be made of aluminum, evacuated to 2 cm of Hg with a helium atmosphere, made with as little metal in it as possible, and to have 70 re-entrant cooling tubes 1¼ in. in diameter passing, in an 8-in. rectangular lattice pattern, from the bottom through the core. The estimated temperature of the tank wall was 400° F.

The external pressure gave us the most concern. It was necessary to prevent a positive pressure from developing in the tank during its lifetime. This was specified so that, if a leak occurred, gas would leak in and trip a pressure monitor; whereas, if the tank were pressurized, gas would leak out and contaminate the room.

To develop strength with low neutron cross section, 52-SO aluminum was chosen for all the structural members. The tank wall was stressed for 2000 psi at 400° F. For these conditions, the wall was made ¼ in. thick, with stiffeners having a moment of inertia of 0.3 in.^{4} placed at 12-in. intervals. A long thin section, ⅛ by 3 in., was selected for the external ribs. They were prevented from buckling by filling the space between each rib with graphite bars, which also made the transition from the round core tank to the octagonal reflector stack. The bars are held to the tank by a perforated aluminum girdle.

The creep rate of 52-SO aluminum at 400° F and 2500 psi is about 5×10^{-7} in./in. hr. This is excessive. Therefore, cooling coils were placed around the tank walls to reduce the temperature to 200° F. At this temperature the creep rate is not significant below a stress of 12,000 psi. These cooling tubes are manifolded and fed separately from the main coolant flow. Thus, a failure in the tank wall coolant system would not be cause for immediate shutdown of the reactor, as the system can be independently turned off and the tank is adequate except for creep at the higher temperature.

The main coolant flow is manifolded from two plenum chambers in the bottom of the core tank. The 70 coolant channels are divided longitudinally in the middle, and the coolant flows up one side and down the other. The corrosion allowances were based on the assumption that turbulent flow gave lower corrosion rates. Therefore, the tubes were figured for a Reynolds number of 6500 and were made 1/8 in. thick. The plenum chamber has a very low Reynolds number, and the walls are 3/8 in. thick. Erosion at these velocities has been neglected. The tubes extend to the top of the tank to support the atmospheric load.

Five thimbles run vertically through the tank to permit entry of the control and safety rods. The rods are placed inside the core to prevent their shadowing the experimental facilities, as they would if placed outside the core. Located in the center thimble is also a separate 4-in. square element. Normally this element is filled with graphite, but if it becomes desirable to increase the fuel loading in the core, this element may be replaced with a fuel loaded element which can be connected to the D_2O cooling system. One might think of this as a means of rejuvenating a partially depleted core.

Core Removal

The core assembly is removed from the reactor by the following procedure. The control-shim rods are dropped from their magnets into the core. All the control and safety rod machinery is removed, and the top concrete shield plug is removed. The reflector graphite provides enough shielding so that radiation is not extra hazardous during this operation. A lead casket is moved over the opening; and, after having first cut off the four coolant feed lines flush with the bottom of the core tank, the core is raised into the casket by its permanently attached lifting sling. The casket and core are lifted together onto the casket bottom, which is secured, and the assembly is ready for transportation to a disposal site. The new core may be installed without the casket. The core exchange should take about two weeks.

Cooling System

The cooling system is a two-fluid circuit connected by a single-pass, one-tube, hairpin heat exchanger. D_2O is in the primary or reactor side, and ordinary water is in the secondary or heat-dump side. The pri-

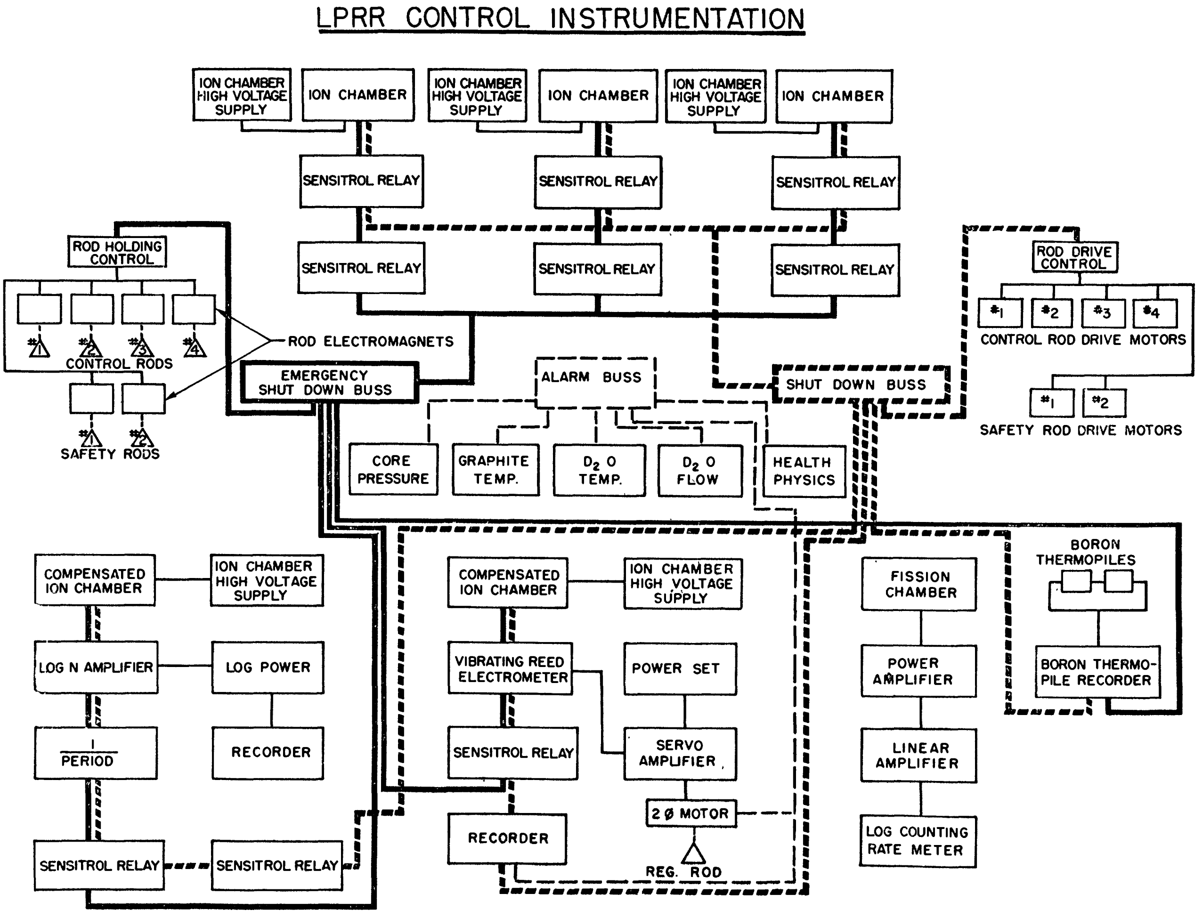

Fig. 6. Control circuit block diagram.

FLUX RANGES OF THE CONTROL INSTRUMENTS

Power Level	Thermal Flux at (Center of Reactor) $n/cm^2/sec$	Neutron Flux at Instruments $n/cm^2/sec$	LEVEL INDICATING INSTRUMENTS: Compensated Ion Chamber and Vibrating Reed Electrometer	LEVEL INDICATING INSTRUMENTS: Fission Chamber & Count Rate Meter	SAFETY INSTRUMENTS: Parallel Plate Ion Chambers Sensitrol Relays	SAFETY INSTRUMENTS: Boron Thermopile and Recorder
200 KW	10^{12}	10^{10}	↑		↑	↑
20 KW	10^{11}	10^{9}	|		|	|
2 KW	10^{10}	10^{8}	|		↓	|
200 Watts	10^{9}	10^{7}	|	Withdrawn		↓
20 Watts	10^{8}	10^{6}	|	from Reactor		
2 Watts	10^{7}	10^{5}	|	↑		
0.2 Watts	10^{6}	10^{4}	↓	|		
0.05 Watts	2.5×10^{5}	2.5×10^{3}		↓		
0.02* Watts	10^{5}	10^{2} to 10^{3}				

* Lowest Power level with 1 gram Ra Be neutron source in reactor at initial start up.

FIG. 7. Range of control instruments.

mary circuit is 100 per cent 2S aluminum to minimize corrosion, and the secondary circuit is galvanized iron pipe. Most of the equipment in the cooling system, which consists of the D_2O pump and sump tank, exchange columns, heat exchangers, H_2O pump, and miscellaneous valves, are located in a small tunnel below the reactor. A cooling tower is located outside the building.

There are 65 gallons of D_2O in the system. This is circulated at 50 gal/min through the reactor and heat exchangers. To keep the D_2O at high purity for the purpose of reducing corrosion rate, 1 gal/min is bypassed through the resin exchange columns. The sump-type pump is totally enclosed in the sump to avoid rotary seals for the helium atmosphere maintained over the D_2O. All effort is made to prevent contamination of D_2O by H_2O which, if the atmosphere were not maintained, could be absorbed from the air. A blow-by valve connects the reactor to the sump tank so that, if the core overheats, the reactor will dump before a pressure buildup can damage coolant system or core.

The D_2O enters the core at 140° F and leaves at 158° F. The wetted area in each of the 70 tubes is 117 in.^{2}, or 8200 in.^{2} total. The heat exchange then is 9702 btu/ft^2 hr and is limited by the poor thermal conductivity of the graphite uranium mixture.

Control Rods

The control rod mechanisms, which are simple rack and pinion devices, are located on top of the reactor and are enclosed in vapor-tight containers to avoid direct communication between the room and the air in the reflector volume. The drive in all cases is a 1/20 hp, 3-phase, gear reduction motor. By selection of appropriate gears, the control rod speeds may be 4 to 75 in./min. A manually adjusted stop on the control rods limits the amount they may be withdrawn and serves as a shim adjustment; hence the name, control-shim rod. All the rods are held to the rack by electromagnets, which in case of emergency are de-energized and allow the rods to fall freely. They are arrested by an automotive type shock absorber.

The control-shim rods are stainless steel tubes filled with boron carbide. They are 2 in. in diameter, 42 in. long, and weigh approximately 40 lb each. Each rod controls 1.2 percent reactivity, or approximately 0.03 percent per inch. Cooling is by radiation to the cooled thimbles of the core tank. The safety rods are similar except that they are rectangular, 2 by 3.5 in., and have a graphite extension on the bottom which fills the hole when they are withdrawn. Each of these controls 5.0 percent of the reactivity, or approximately 0.12 percent per inch.

An automatic regulator rod may be provided if desired. It consists of counterbalanced rod assembly driven by a Brown Instrument 2-phase motor.

Instrumentation

The instrumentation for the control system has been designed to control the reactor under normal and emergency conditions. Since the total amount of excess reactivity for experimental purposes is limited to 2 percent, a simple instrument system is adequate. A fission chamber is used to bring the reactor from shutdown to a flux level of about 10^{-6} of full power. A compensated ion chamber is then used to monitor the level up to full power. In addition, a log amplifier will indicate the period from 10^{-10} full power up to full power. Simple relays are used wherever possible, and in the ion chamber instrument and relay circuit a response time of 300-millisec is expected. This speed is adequate, since a change in reactivity of 0.7 percent corresponds to a period of about 1 sec.

Three ion chambers, two compensated ion chambers, and one fission chamber comprise the sensing instruments for controlling the reactor. Two boron thermopiles act as an emergency alarm and shutdown device.

These are connected to form an emergency shutdown buss and a normal shutdown buss. A separate alarm buss monitors the core tank pressure, graphite temperature, D_2O temperatures, and D_2O flow. Erratic behavior of these will not shut down the reactor but will sound an alarm. Remote rod-position indicators, rod-holding magnet current, and various other minor instrumentation are not tied into any one of the three main buss systems.

PRESENT STATUS

This reactor has been designed up to the point of making detail drawings of the various components. The technique of mixing graphite and uranium for the core has been worked out in full scale and was tested by a small scale experiment in another reactor. Other components are combinations of commercial parts in straightforward design. It is estimated that the cost of this reactor would be approximately $500,000, the exact amount depending on the extent of experimental facilities to be associated with it. The reactor described has the benefit of a very conservative design, and every effort has been made toward simplicity. It is a unit that will meet the requirements of safety while operated by unskilled personnel such as students in universities or technicians in a research institute.

Operation of the North American Aviation Water Boiler Neutron Source[1,2]

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A LOWPOWER HOMOGENEOUS REACTOR of the water-boiler type (*1*) has been in operation at the Atomic Energy Research Department of North American Aviation since April, 1952. This reactor, called the Water Boiler Neutron Source, or WBNS, was designed primarily as a source of neutrons for experimental purposes. The reactor is operated at power levels up to 1 watt, and at this level it supplies a maximum thermal flux of approximately 4×10^7 neutrons/cm^2 sec at the center of a test hole through the spherical core, along with somewhat lesser values of flux in exposure facilities in the graphite reflector.

The WBNS is well suited for neutron absorption cross-section measurements by the danger coefficient technique because of its low nuclear cross section which results in a high sensitivity. It is an economical type of reactor on which personnel training, instrument and material testing, along with other reactor engineering studies, can be conducted. It will furnish sufficient neutron flux for a great many types of neutron irradiations for studies in nuclear physics, radiochemistry, and biophysics. The water-boiler-type reactor also combines strong inherent safety features with the above characteristics. These result from the very large negative temperature coefficient and negative power coefficient of reactivity. These negative coefficients are sufficient to shut down the reactor in the event of accidental releases of large amounts of reactivity. This shut down will occur with a relatively small release of energy.

DESCRIPTION OF THE WBNS

The WBNS is a light-water moderated graphite reflected solution-type reactor. The core consists of a solution of highly enriched uranyl nitrate in a 1-ft diameter stainless steel sphere. The sphere has been constructed from two hemispherical spinnings of Type 347 stainless steel sheet, 1/16 in. thick, and has a volume of 14.38 liters. A central exposure facility in the core has been formed by inserting a tube, 1⅛ in. ID, through the sphere with its center line 3 in. below the horizontal diameter of the sphere. This sphere is encased in a cylinder of pile grade graphite, 5 ft in diameter by 6 ft high, which serves as a reflector and vertical thermal column. The entire cylinder is surrounded by a concrete block radiation shield 2 ft thick. A sectional assembly of the reactor is shown in Fig. 1. Figure 2 is a photograph of the installation with an experimental tank on top of the vertical thermal column.

The graphite reflector was formed by stacking graphite bars, 4⅛ × 4⅛ in. in cross section, horizontally inside a steel tank with the bars in alternate layers placed orthogonal to each other. Eight of these graphite bars, or "stringers," near the sphere, as shown in Fig. 1, can be removed to form radiation exposure facilities. Parallel to the removable stringers is the central exposure facility which passes through the graphite and through the stainless steel sphere and permits access with small samples to the region of highest flux.

The reactivity control is maintained with two safety

[1] Based on a paper presented at the 1953 Conference on Nuclear Engineering at the University of California, Berkeley, Sept. 9–11, 1953.

[2] Based upon studies conducted for the Atomic Energy Commission under Contract AT-11-1-GEN-8.