Design and Construction of Water Boiler Neutron Source

Ralph Chalker

Atomic Energy Research Department, North American Aviation, Inc., Downey, California

NORTH AMERICAN AVIATION has studied reactors of several types, which have different operative powers in the range 0.1 to 200,000 watts, for operation as research reactors. These types have included designs with homogeneous liquid fuel (water boilers), homogeneous solid fuel (the homogeneous graphite reactor) and heterogeneous solid fuel, water moderated and shielded (the "swimming pool" type reactor).

Recently a natural radioactive material being used as a source of neutrons in research and development work by North American Aviation for the Atomic Energy Commission became depleted. A careful analysis indicated and was later confirmed that a small water boiler reactor would be both a more powerful and more economical source of neutrons. Consequently, a low-powered water boiler neutron source (WBNS) was designed, constructed, and installed at the Company's Downey research and manufacturing facility.

Since this reactor is small, simple, safe, and economical and yet embodies the major components and manufacturing techniques typical of all reactors, a description of its design and construction is thought to be of interest.

In the complete installation prior to placing the final shield wall (Remley, Fig. 2, p. 22), the lower tank is 5 feet in diameter and 6 feet high and contains 2 feet of machined graphite reflector which surrounds a 1 foot spherical fuel and moderator core tank. Attached to the tank are a small mixing tank with valves and connecting piping, a large cylindrical accumulator tank and two neutron detecting ion chambers. The associated control and safety rod system and instrumentation panel are located behind the structure and are not visible. The upper tank is experimental equipment which utilizes the neutrons produced in the reactor. The designed power of the reactor is one watt with a maximum flux density of 4×10^6 neutrons per square centimeter per second.

Figure 1 shows the three major systems of this reactor: safety, fuel, and gas disposal. Higher-powered reactors require a fourth system consisting of cooling equipment for removing the heat generated by nuclear fission. The safety system includes two gravity-powered safety rods, and two control rods. The control rods are positioned according to instrumentation indications and recordings on the control panel. These instruments are in turn fed by signals from the neutron detecting devices located around the reactor tank. The fuel system includes a fuel mixing tank, valves, piping, and the reactor core tank.

A description of the major reactor components follows.

Core and Fuel Handling

The reactor core components are shown in Fig. 2. The fuel is contained in a 12-inch diameter stainless steel sphere made of two spun hemispheres each provided with a small upstanding flange at the joint surface. The design of the core tank is representative of the new problems encountered by the engineer developing nuclear reactor components. Corrosion considerations which may be accentuated by radiolysis indicate that special corrosion-resistant steels may be in order. Pressure and corrosion indicate thick walls. Nuclear considerations indicate either thin walls or use of material which does not offer a large cross section to neutron absorption. The answer may be a thin stainless steel capable of being heat treated to a high tensile strength. However, heat treatment causes scaling which is difficult to clean to the degree necessary in the system. The final compromise which included fabrication and economical requirements was the selection of 1/16-inch 347 stainless steel sheet welded without filler by heliarc. Cooling coils are shown to which a refrigeration system can be added at a later date should the reactor be run at higher powers. The long tube and extra tank is an added safety feature developed by North American Aviation which provide an auxiliary catch basin in the event of a flash run-away. The fuel is retained and slowly returned to the core after the conditions that caused the flash have been rectified. Not shown in the photograph is a tube 1⅛ inches in diameter that runs completely through the sphere. After all the components shown are welded in place, the tank is cleaned thoroughly to remove all foreign material. The flanges of the hemispheres are spot welded together to produce accurate alignment and then fused down in a heliarc butt weld. A final cleaning is then performed in the laboratory using hot nitric acid. The welded core tank is then pressure tested to 300 psi using conventional leak testing methods. To find minute leaks, a vacuum is pumped on the core tank assembly while attached to a mass spectrograph. Helium is then introduced on all welds and if a leak large enough to admit helium is present, the leak detector will indicate and the weld may be repaired. The volume of the core tank is then accurately determined as a function of height (see Fig. 3).

To fill the core tank for operation, the concentrated solution of uranyl nitrate is carefully measured into a vinyl bottle by volume using the burette shown in Fig.

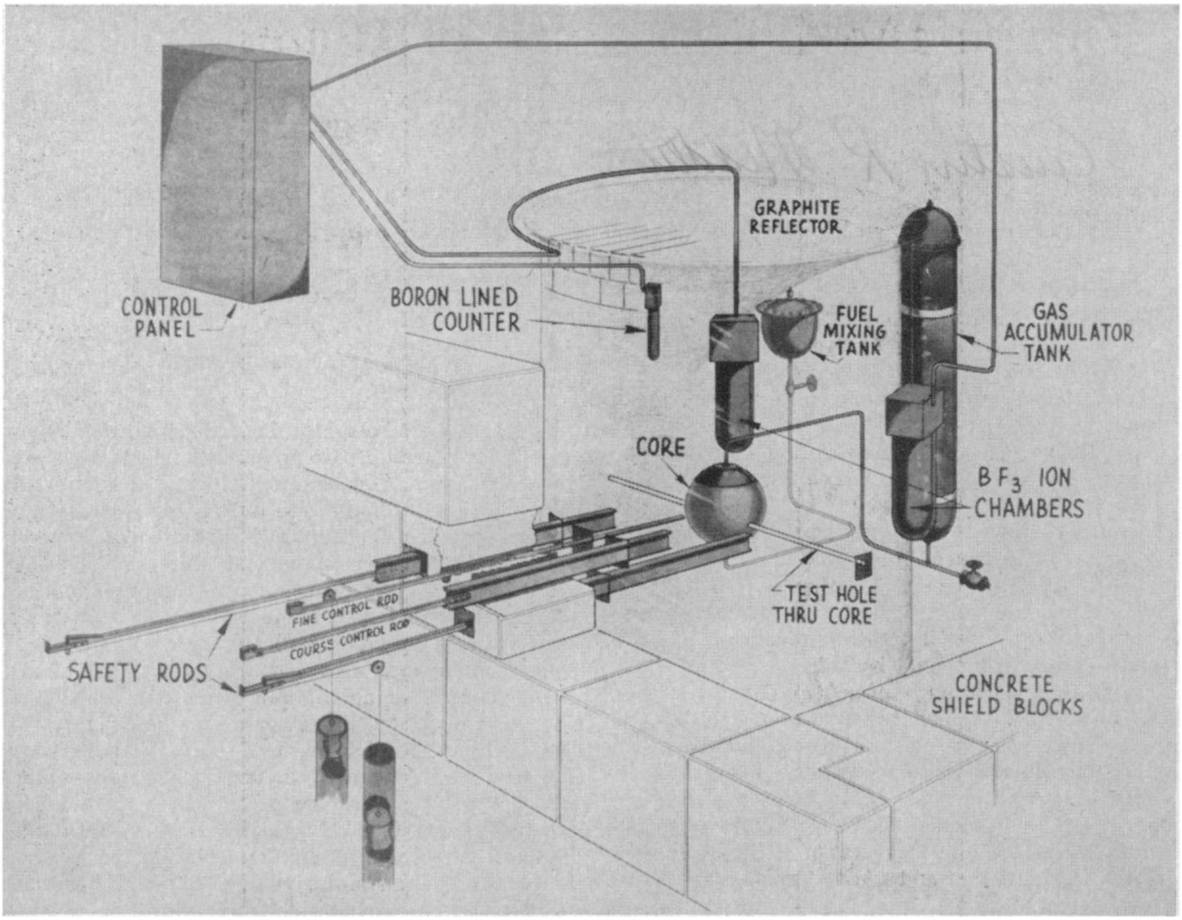

FIG. 1. Three major systems in reactor: (1) gravity-actuated safety rods and remotely controlled powered control rods, instrumentation, and neutron detection instruments; (2) fuel handling and mixing tank, valves, piping, and fuel core tank; (3) gas disposal system with accumulator, gages, and valving.

4. The amount is then checked by weight. Figure 5 shows the fuel being poured from the vinyl bottle into the mixing tank which is made of stainless steel highly polished for cleanliness and fitted with a sealed cover which allows the container to be either pressurized or evacuated. The mixing tank is connected by a plug valve to the tubing leading to the core sphere.

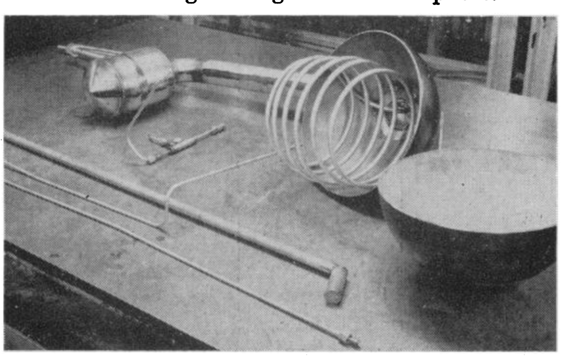

FIG. 2. Components of reactor core tank. Two spun stainless steel hemispheres, cooling coils, emergency overflow tank, and slow return pump.

The fuel handling system is shown in Fig. 6. A loading sequence includes: (1) filling the core tank with the total calculated amount of distilled water; (2) adding the first aliquot of fuel which is one-half that calculated for the critical mass; (3) bubbling the gas through the solution thus mixing the fuel and

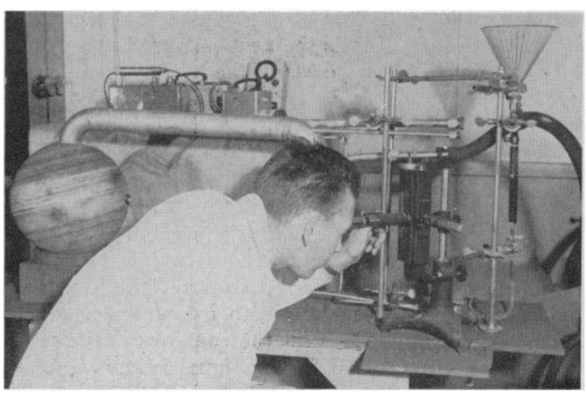

FIG. 3. Accurate calibration of volume of sphere as function of height.

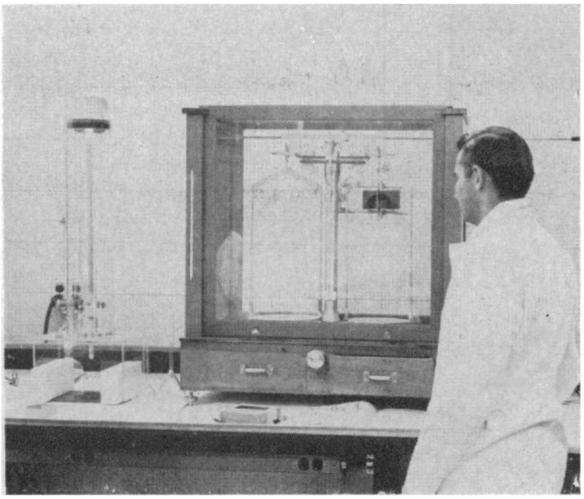

Fig. 4. Apparatus for measuring solution of uranyl nitrate by both volume and weight.

distilled water; (4) raising a portion of the solution into the mixing tank by pressure or vacuum; (5) adding the next measured aliquot which is again one-half the remaining amount to reach the required critical mass; (6) repeating steps 2 through 5 until the reactor is loaded.

During operation of the reactor fission gases are given off as well as hydrogen and oxygen. Since a favorable mixture of H and O might be produced to cause an explosion, the entire system is designed to withstand 300 psi and explosion traps are provided at critical areas. To contain the fission gases at low power operation, calculations had shown that temporary storage and periodic disposal of the accumulated gases would be sufficient. Thus a stainless steel container connected to the top of the core tank was provided (Fig. 6). Inside the container is a Neoprene bag which when pressurized, completely fills the tank expelling all contents as it expands. The pressure connection to the bag passes directly through a packing gland in the top end of the container. Thus, as fission gases are collected in the container, the Neoprene bag is compressed and the rise in pressure indicated on the gage. When sufficient gas has accumulated, the bag is pressurized and the fission gases forced into the disposal tank which can be removed from the system.

For higher-powered reactor operation, the gas generation increases to the point where this system becomes impractical. North American Aviation has recently developed a closed cycle gas handling system which recombines hydrogen and oxygen and processes the fission gases to allow practical disposal of gases at powers up to 50,000 watts.

Reflector

Graphite for the reflector was obtained in rough extrusions about 4½ inches high, 12 inches wide, and 4 feet long. The extrusions were machined on four sides and one end to accurate uniform dimensions

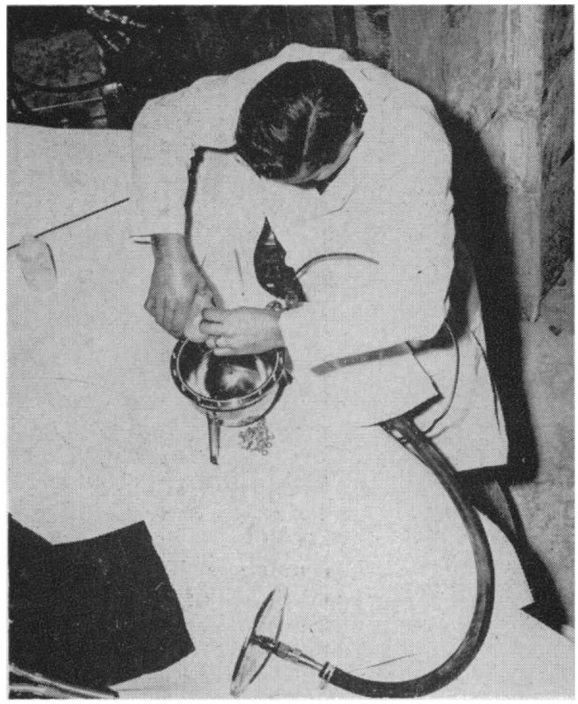

Fig. 5. Pouring measured aliquot of fuel into mixing tank to be mixed with distilled water moderator.

(Fig. 7). The blocks were then selectively assembled so that the layers of graphite were composed of blocks having the same thickness. By this method uniform load distribution was assured. Special care was given to shaping those blocks which were adjacent to the sphere to leave a minimum of air space (Fig. 8). Each layer of blocks was laid with joints in adjacent layers ninety degrees apart (Fig. 9). The principal experimental facility for this reactor is a tank which is placed directly on top of the graphite. The top surface was therefore carefully levelled and kept scrupulously clean by the use of a sealed cover both during

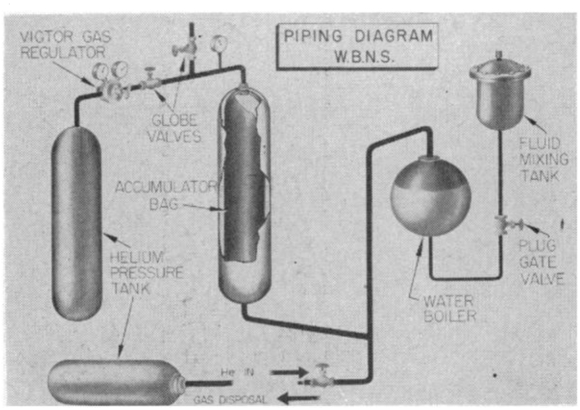

Fig. 6. Schematic diagram of fuel handling and gas disposal system. Fission gases enter stainless steel accumulator tank, compressing Neoprene bag. Gas is disposed of by pressurizing bag forcing gases into disposal tank.

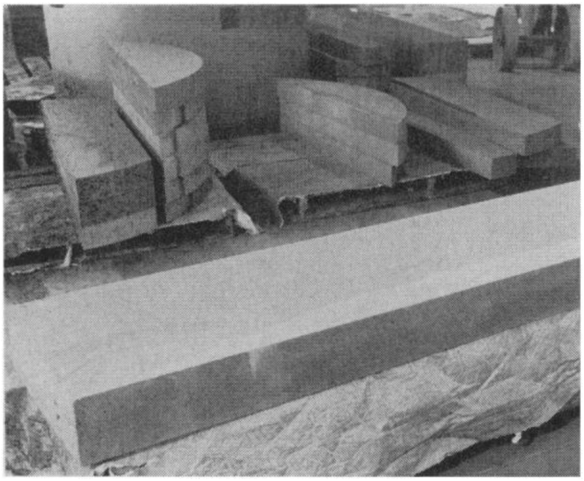

FIG. 7. Extruded reflector graphite to be machined to fit contour of steel tank and reactor core sphere.

the transfer to the laboratory and final assembly.

The tank in which the graphite and core were assembled was made in a structural steel shop and presented no special problems (Fig. 10). The tank bottom was made especially thick to minimize deflection under the graphite load. Openings were provided on the sides to match the locations of control rods and special stringers in the reflector graphite. A strong flange was provided at the top to anchor the experiment tank against movement due to horizontal forces. The graphite tank was mounted on a structural steel base which was furnished with lifting lugs capable of handling the total load of graphite and tank without damage. Leveling screws were incorporated into the base to permit accurate leveling of the assembly on its concrete foundation before anchorage and grouting. Research facilities were provided by removable stringers of graphite and an access hole through the reflector to the exposure hole, permitting maximum irradiation of experimental pieces at the center of the core. The removable stringers are shielded by special removable close tolerance plugs made of wood tipped with lead and cadmium (Fig. 11).

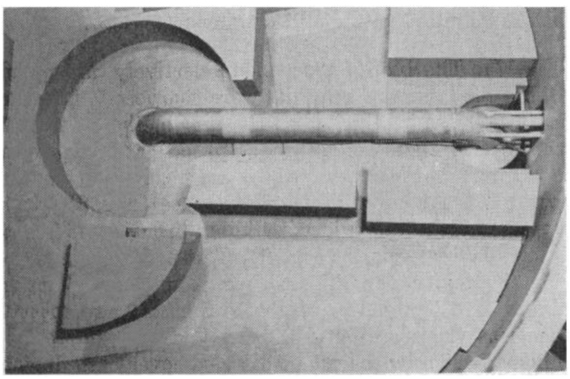

FIG. 8. Machined graphite accurately stacked to fit reactor core components with minimum air gap.

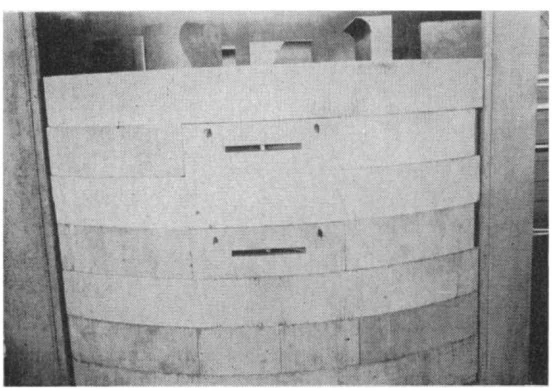

FIG. 9. Layers of reflector graphite stacked with alternate layers at right angles to each other.

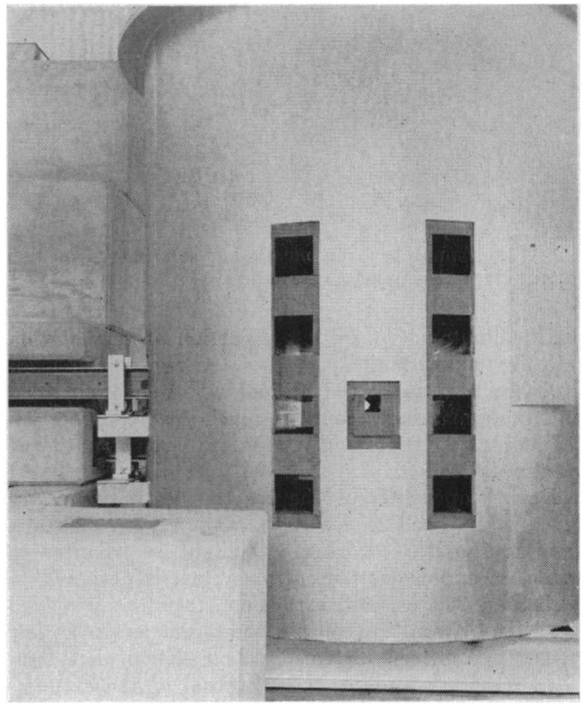

FIG. 10. Experimental facilities include eight removable 4-by-4 inch stringers and 1⅛-inch diameter exposure tube extending through the center of the core and surrounding reflector.

CONTROL

In the control rod system, illustrated in the Remley papers, Fig. 3, p. 23, the two safety rods are held in the "out" position by a trigger mechanism which can be tripped by hand or electrically by remote control at the control panel. Metal counterweights acting under the force of gravity pull the rods to the "in" position to shut down the reactor. When the rods are within 6 inches of their total travel, the counterweights are arrested and wedges on the control rods contact spring-backed brake shoes to absorb the momentum of the rods and stop them before they contact the graph-

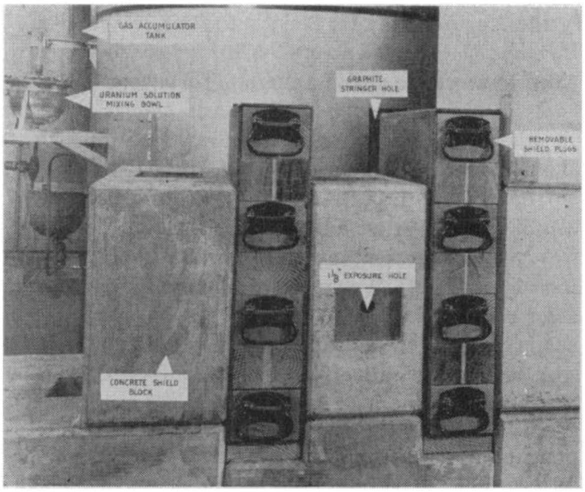

FIG. 11. Removable close tolerance shield plugs for experimental facilities made of wood with lead and cadium tips.

ite in the reflector. The coarse and fine control rods are motor-operated remotely from the instrument panel. A selsyn system is used to operate an indicator located on the panel which shows the position of the rods at all times with reference to the center of the core.

INSTRUMENTATION

The instrument panel, which is illustrated in the Remley paper, Fig. 4, p. 23, was designed to provide the necessary instrumentation of the sensing devices and control and safety rods required by the specifications set up by the nuclear designers. The block diagram for these arrangements in shown in Fig. 12.

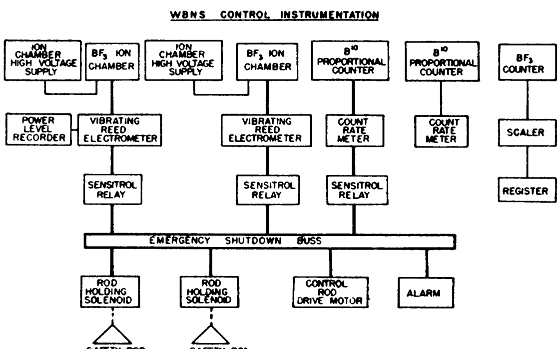

FIG. 12. Block diagram showing neutron detection instruments used, auxiliary instrumentation and the emergency shutdown actuators.

Three separate sensing systems operate to shut down the reactor and sound the alarm in the case of a reactor overload.

SHIELD

Figure 13 shows the biological shield which was designed to be adequate for the radiation field present, yet demountable in case varying experimental ar-

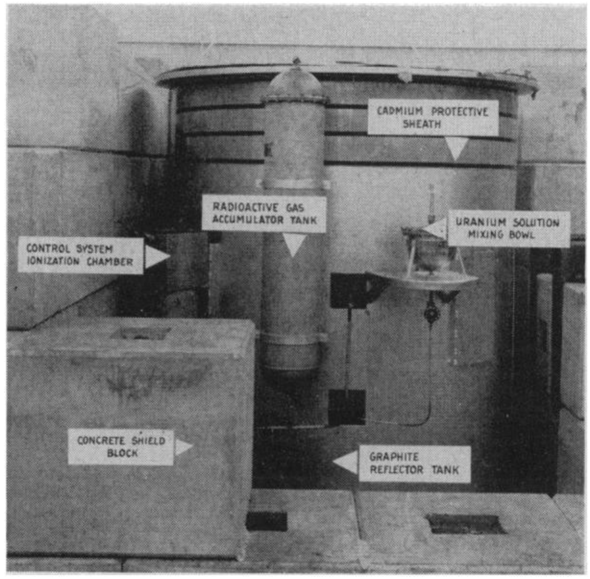

FIG. 13. Concrete shield blocks stacked to provide a biological shield to protect operators from radioactivity during reactor operation.

rangements of shield should be required or in case of a complete change of site for the reactor. Concrete blocks 2 feet square by 1 foot 10 inches high were selected. Vertical joints were staggered at assembly and the corner blocks were interlocked. Some of the

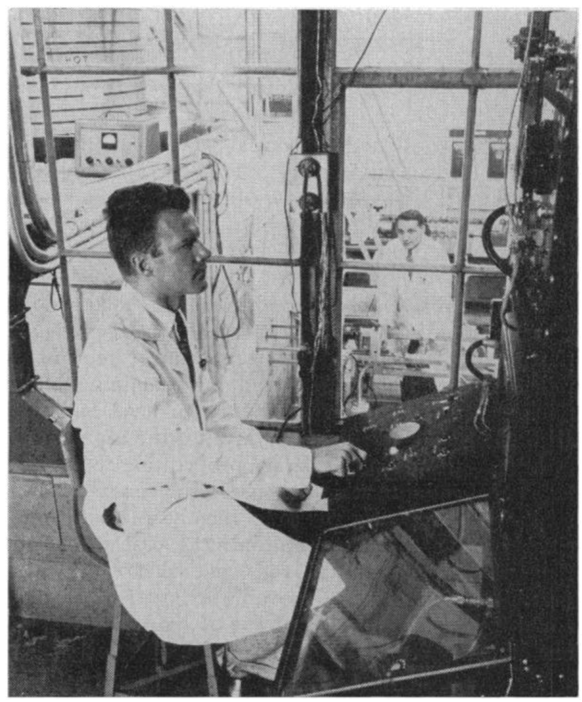

FIG. 14. Engineers check the operation of the control rods and instrument panel for the North American Aviation water boiler type atomic energy reactor prior to starting.

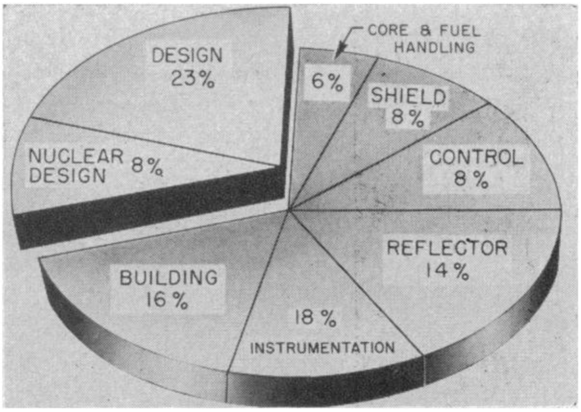

Fig. 15. NAA WBNS cost breakdown.

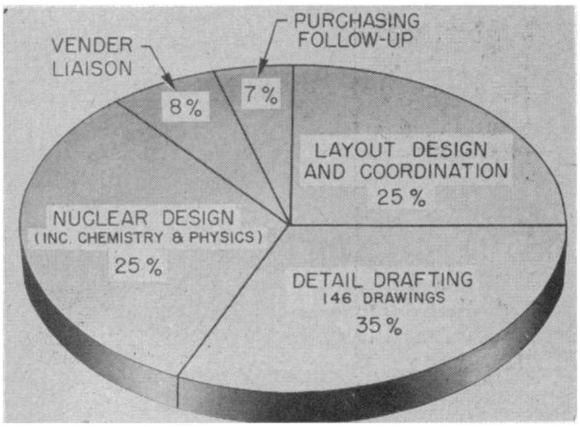

Fig. 16. Cost breakdown of engineering.

blocks were designed in special shapes to give passage for control rods or the movable graphite stringers. Accurate dimensions were essential to the success of such a shield and an appraisal of fabrication facilities was undertaken by visiting many concrete product plants.

When final assembly time was reached the key blocks which were adjacent to the control and safety rods and the special blocks opposite the experiment holes in the reflector were first located and the remaining blocks filled in to suit. It was necessary to level and shim all the blocks of the lowest layer until the top surfaces of all were in one plane before progressing to the next layers. By doing this a successful assembly was achieved and a source rod could then be passed through shield block and reflector and into the exposure hole in the sphere; the control rods passed freely within graphite walls and the removable stringers of graphite could be transferred in and out of the reflector without difficulty from outside the shield.

Building

A roof and housing of corrugated steel lined with insulation, covering a floor area 20 by 40 feet in size was provided adjacent to existing laboratory buildings in the North American Aviation plant in the city of Downey, California. A one-ton bridge crane was provided to serve the entire building. The elevation of the hook at the maximum height position was 20 feet. This height was required to withdraw lattice members about 6 feet long from a 6-foot experiment tank set on top of the graphite. Figure 14 shows the control console placed in an adjacent room whose floor level was very convenient as the operator seated at the console could see through a window all over the reactor room and check control rod responses to adjustments made at the console.

A cost breakdown of the North American Aviation WBNS is shown in Fig. 15. These percentages are given to indicate the relative costs of the various components of the one-watt power reactor previously described and include the total cost of manufacture, installation, and testing of the respective components. The cost of the fuel is not included. For a higher-powered reactor, the cost of a cooling system, additional cost of a more complete gas handling system and a more adequate shield would change the figures materially. The largest single cost is for engineering and design (31 percent) and is representative only for the first unit. A further breakdown of the design costs is shown in Fig. 16. Although the engineering design costs appear to be high, it must be remembered that this was the first reactor designed to be operated as a part of an established industrial plant located in a heavily populated district. Thus every possibility was thoroughly explored in order that those responsible could be certain of the complete safety to the populace around the project. Careful exploration therefore involved study and consideration of many design layouts that were eventually discarded.

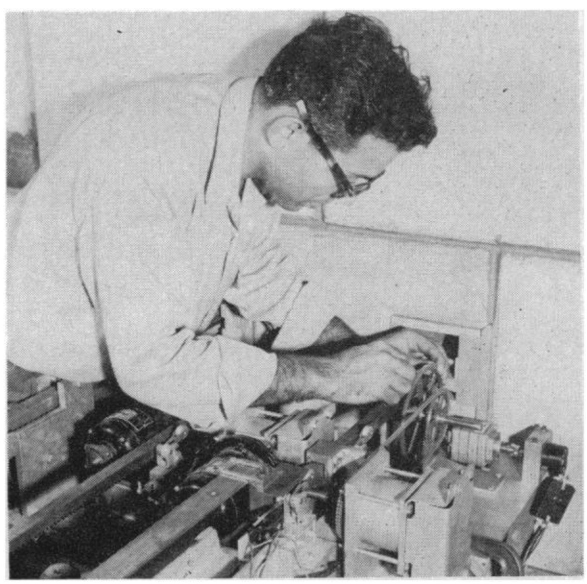

Fig. 17. Installation on the WBNS of an automatic control system designed for operating a 2000-watt reactor.

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

A. Macneil Stelle

Atomic Energy Research Department, North American Aviation, Inc., Downey, California

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-