CHAPTER 6

Savannah Reactor Features

The *SAVANNAH* reactor represents the earliest type of reactor for nuclear merchant ships and, accordingly, a review of its design features is of interest. The *SAVANNAH* reactor is called a "pressurized water reactor." It is patterned after naval reactors using water as the primary coolant. For conservative safety reasons, the water does not boil in the reactor . . . with the result that the saturated steam delivered to the turbines approximates 460 psi, (32 bar, 520 K 475°F. This, we note, is appreciably below the 600 psi, 875°F 41 bar, 740 K) superheated steam delivered by standard marine boilers. The net effect is a retrogression of steam turbine technology. However, the *SAVANNAH* reactor contains many features basic to all reactor systems and, hence, is a logical starting-point from which to gauge future progress in marine reactor technology. Furthermore, water reactor systems permit a stepwise transition from familiar boiler technology and this is important in the training of design and operating personnel.

6-1 Basic Working Cycle

The basic working material—and neutron moderator—for the *SAVANNAH* reactor is demineralized and purified water. This "primary water" is circulated between the reactor and two heat exchangers (steam generators) as illustrated in Fig. 6-1. The water is force-circulated at the rate of 16,000 gallons per minute, at a mean temperature of 508°F. The water is pressurized to 1750 psi.* (120 bar) (538 K)

The maximum total heat generated by the reactor is 70 MW or about 240 million Btu/hr. This is approximately equivalent to the maximum total heat generated by the two conventional boilers on a *MARINER*-type merchant vessel. Consequently, the *SAVANNAH* and a *MARINER* ship have approximately the same speed and shaft horsepower, namely: 21 knots at 21,000 SHP. Table 6-1 shows the comparison.

The primary water enters the lower portion of the reactor, and leaves near the top. The circulation takes place in two independent loops. Each

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* Ref: "Design of the Power Plant for the First Nuclear Merchant Ship," R. L. Whitelaw, Paper No. 69, presented at Nuclear Engineering and Science Conference, Chicago, March, 1958.

coolant loop consists of a heat exchanger and two pumps. This two-loop arrangement provides ample flexibility to maintain reduced-power cooling of the reactor with one heat exchanger and one pump. Such cooling would be necessary after reactor shutdown or setback, to remove the decay heat from fission residues.

Table 6-1. Comparison of the SAVANNAH and a MARINER

	SAVANNAH	MARINER
Length (ft)	588	563
Displacement (T)	21,840	21,100
Shaft Horsepower (SHP)	21,000	19,250
Speed (K)	21	20.5

Each loop contains two electrically operated gate valves that can be closed to isolate the reactor. Appropriate interlocks are provided so that all four gate valves cannot be closed simultaneously once the reactor has started up in normal operation. Position indicators show the amount of gate valve openings at all times. The inlet gate valves (two) are positioned adjacent to the reactor, whereas the outlet gate valves (two) are adjacent to, and ahead of, the heat exchangers. The greater length of outlet piping thus provided acts as an overflow reservoir in the case of power surges . . . with one loop isolated.

The circulating pumps (total of four) are of the canned rotor type. The rotor is mounted vertically above the impeller, and has windings for two speeds, namely: half and full. At full speed, each pump will move 5000 gpm against a head of 70 psi. The pumps are located on the downstream side of the heat exchangers, to minimize problems of radioactivity and corrosivity from the primary water (recall Sec. 5-12). A check valve is placed on the discharge side of each pump to protect it against back-pressure surges in the primary piping. The pumps are separately cooled by water. The total pumping power required is about one MW (i.e., 250 KW per pump) . . . or 1.5% of the total reactor power.

The steam generators (total of two) consist of a U-shell, U-tube heat exchanger section, with a steam drum on top. The heat exchanger section contains about 800 stainless steel ¾-inch O.D. tubes. The steam drum is approximately 5 ft in diameter and 15 ft long. It is connected to the U-shell heat exchanger by risers and downcomers. The steam drum is equipped with cyclone separators and scrubbers which provide dry saturated steam at the main outlet. The total amount of steam generated is approximately 260,000 pounds per hour . . . at 460 psi, 475°F. Separate feedwater pumps (not shown in Fig. 6-1) supply make-up water to the steam generators. The heat exchanger water-to-steam cycle is called the "secondary loop" of the reactor plant.

All primary piping carrying water between the reactor and heat exchangers is of type 304 stainless steel, 12½-inch I.D. The design pressure

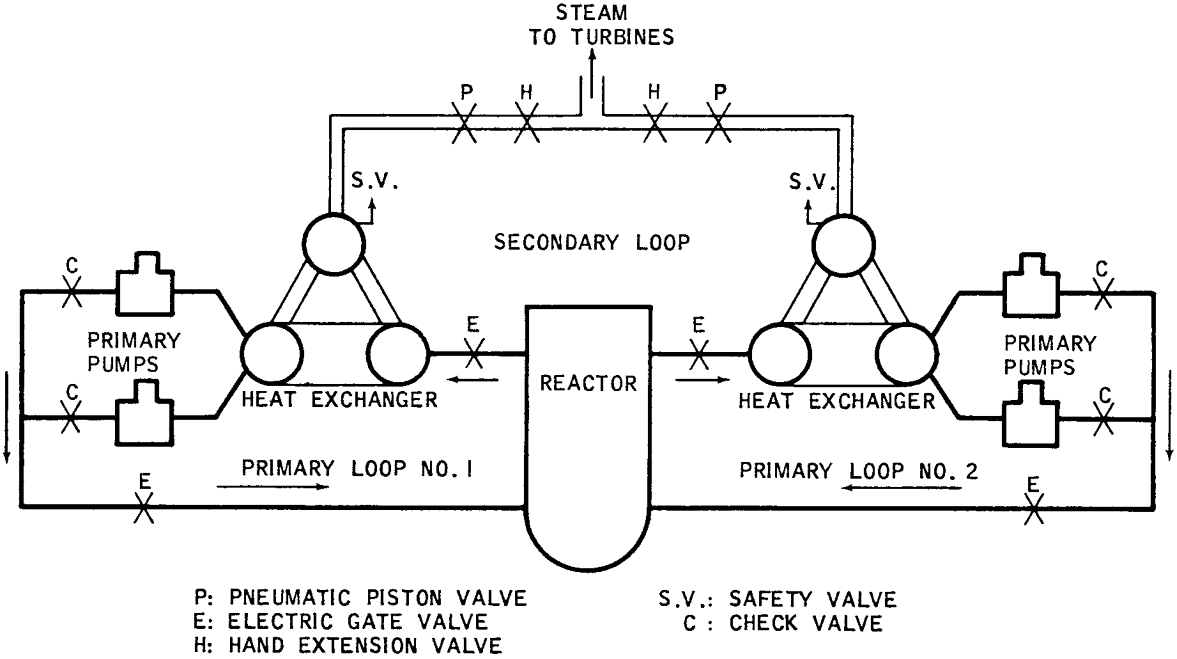

Fig. 6-1 Schematic Arrangement of Primary Coolant Cycle for *Savannah* Reactor

of this piping is 2000 psi. The secondary piping carrying steam from the generating drums to the turbines is 8½-inch I.D., designed for 800 psi. Appropriate steam safety valves and stop-check valves are provided..

6-2 The Pressurizing System

A fundamental design feature of the *SAVANNAH* reactor is that no boiling of the primary water is allowed (recall Sec. 5-10). As an initial safeguard against boiling, the maximum temperature of the reactor water is de-rated about 100° below its saturation value at the equilibrium pressure of 1750 psi. But the steam turbines don't know about this de-rating; their demands for steam rise and recede with the ship's operational requirements. Because of these load changes, the primary water pressure will be altered.

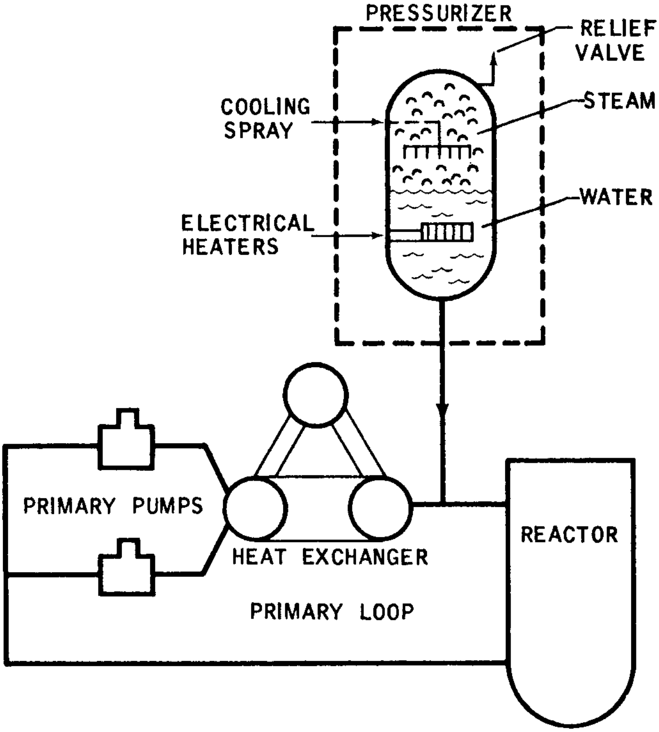

Fig. 6-2 Arrangement for Pressurizing the *Savannah* Primary Coolant

The demand for increased steam in the secondary loop means that more heat has to be taken out of the primary loop, thereby disturbing equilibrium conditions. As a result, the reactor pressure is reduced. At lowered primary pressure, some of the water inside the reactor could flash into steam and local or general boiling could occur. Depending on the frequency and severity of load changes, the neutron moderation could upset fission criticality conditions . . . with the ultimate possibility of fuel element burnout.

To prevent this possibility, a pressurizing and relief valve system is provided, as shown in Fig. 6-2. The "pressurizer" is an electrically heated pressure vessel in which an auxiliary steam space is maintained in pressure equilibrium with the primary water. The equilibrium pressure (1750 psi) is maintained by the alternate use of electrical heaters or spray-cooling as the transients of the primary system demand.

The electrical heaters are housed in heater wells which heat the primary water (in the pressurizer only) to the saturation temperature, thereby forming a vapor chamber above the water. Spray-coolers are located in the vapor region to reduce the vapor pressure when necessary. In the center of the tank, a standpipe (not shown) provides the reference leg for water-level control. To meet heavy transients, appropriate steam relief valves and water surge lines are provided.

Due to the reactor stability provided by the *SAVANNAH's* pressurizer, steam can be delivered to the turbines varying in pressure from 450 psi (at maximum power) to 730 psi (at zero power).*

6-3 The Purification System

Under equilibrium pressure conditions, the primary water will become radioactivated by the neutrons in the reactor core, as explained in Sec. 5-12. Also, because of the temperatures involved, corrosion products will accumulate. And, furthermore, there is always the possibility that some fission products may find their way into the primary water. To remove the radioactive and corrosive matter from the primary water, a purification system is provided (see Fig. 6-3).

A fraction of the primary water is by-passed through the purifier at the normal rate of 20 gpm. To permit a higher rate of purification, a by-pass rate of 60 gpm can be handled. The driving force through the purifier is the 1750 psi pressure head of the primary water. The 520°F primary water is "let down" through a combination of flash coolers and block orifices to about 65 psi, 110°F.

After letdown, the primary water passes through a demineralizer consisting of a bank of three ion exchangers. The resins in these ion exchangers chemically purify the water by removing the dissolved radiocontaminants and corrosive products. The undissolved radioactive and corrosive particulates are removed by effluent filters. Each ion exchanger and filter has a useful life of at least 50 days, after which it has to be removed and replaced. Appropriate valving permits sequential operation of the ion exchangers and filters for at least 150 days of continuous purification.

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* Ref: "The Power Plant for the First Nuclear Merchant Ship," J. W. Landis, Bulletin AER-54, presented at the Nuclear Merchant Ship Symposium, Washington, D. C., August, 1958.

The purified water is returned to the primary loop, via a surge tank and charge pump (Fig. 6-3 again). Ahead of the surge tank, primary make-up water is added. In the surge tank, any radioactive and corrosive gases trapped in the primary water will separate automatically, whereupon these gases are vented off. Beyond the surge tank, a hydrogen addition system maintains a minimum concentration of 20 cc/liter of dissolved hydrogen in the primary water. This excess hydrogen scavenges the free oxygen liberated by dissociation of the water when in the active region of the reactor core. The over-all result is minimum corrosion in the primary loops.

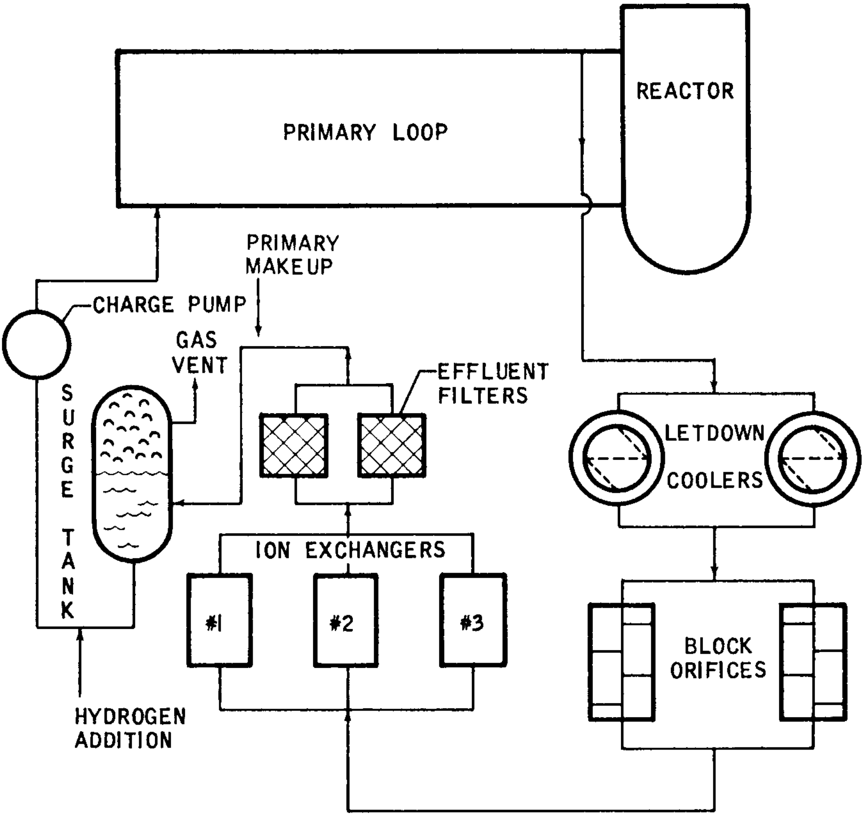

Fig. 6-3 Arrangement of Purification System for *Savannah* Primary Coolant

6-4 The Reactor Vessel

The reactor vessel through which all primary water passes is a cylindrical tank approximately 9 ft diameter, and 26½ ft height over-all (see Fig. 6-4). The nominal wall thickness is about 6 inches. This thickness is the design necessary to withstand pressures up to 2000 psi, and temperatures up to 650°F. The vessel is of carbon steel with an internal cladding of ¼-inch stainless steel (type 304). This cladding improves the reactor vessel's resistance to corrosion. The estimated dry weight of the empty vessel, which excludes the fueled core and control rods, is about 225 tons. This approximates the dry weight of the two oil-fired boilers on a standard *MARINER*-type ship.

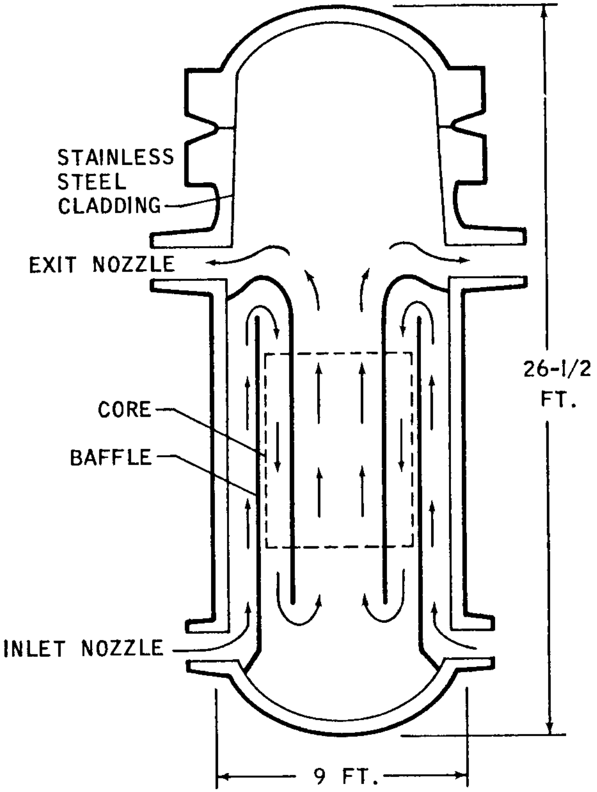

Fig. 6-4 Arrangement of *Savannah* Reactor Vessel Showing Three-Pass Coolant Flow

The reactor vessel has a hemispherical bottom through which two inlet ports, called nozzles, penetrate. Two corresponding exit nozzles are located in the upper portion of the vessel, just below a removable hemispherical head. Thus, an inlet and exit nozzle pair serves each of the two primary loops. In each loop, the inlet and exit nozzles are offset 15° from each other to facilitate external piping arrangements.

The removable head contains guide sleeve penetrations for the control rods. The head can be removed for refueling by means of standard boltand-flange techniques. A total of 48 five-inch studs and a double gasket are used for closing the vessel. A final seal weld is used to insure against leakage. The entire vessel is hung from its flange, thus permitting growth under thermal expansion.

The primary water makes a three-pass flow through the reactor vessel (see Fig. 6-4 again). It passes upward along the inside of the vessel, turns downward through the outer fuel elements of the core, then upward again through the center of the core. The water enters at 495°F and leaves at 520°F—a total temperature rise of only 25°. This certainly minimizes thermal stresses in the reactor . . . a feature of conservative design.

The three-pass flow through the *SAVANNAH's* reactor is a departure from one-pass flow through predecessor naval reactors. This new feature has advantages and disadvantages. On the advantageous side, a three-pass flow permits better heat transfer to the water, in that the water flows successively through regions of low, intermediate, and high heat generation. As a result, the flow rate is approximately one-half that of single-pass flow, thus reducing the reactor pumping power proportionately. On the other hand, three-pass flow adds complexity to the reactor internal structure due to baffles, and causes the water to dwell three times longer in the active region of the core. Increased radioactivity of the primary water results.

Also considered part of the reactor vessel are two concentric "thermal shields" around the inside of the vessel proper (see Fig. 6-5). The purpose of these shields is to protect the walls of the reactor vessel against so-called "gamma heating." If it were not for these shields, the core-generated gamma rays would severely heat up the vessel walls . . . to produce excessive thermal stresses. Gamma heating is internally generated heat within a gamma-stopping material; it is separate and distinct from any temperature effects of the primary water. The thermal shields (steel) intercept the gamma rays and the shields themselves heat up, instead of the reactor vessel walls. The shields, however, are cooled during the first pass of the primary water. The shields can be removed and replaced.

6-5 The Core Cage

The core cage is a cartridge-like cylinder which fits into the reactor vessel to hold the nuclear fuel elements and to guide the control rods in and out of the core. It is called a cage because of its "egg-crate" construction (see Fig. 6-5). The over-all dimensions of the cage are about 5 ft diameter by 5½ ft height. The cage height is only about one-fifth the over-all height of the reactor vessel! The cage—containing the fuel elements— is removable for refueling.*

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* Ref: "Reactor Physics and Core Design of the Merchant Ship Reactor," Wood and Levine, Paper No. 96, presented at Nuclear Engineering and Science Conference, Chicago, March, 1958.

The egg-crate cage provides the equivalent of a pressure can (open top and bottom) around each of the fuel elements comprising the reactor core. The walls of the "cans" are designed to withstand the thermal and pressure differentials arising from the three-pass coolant flow.

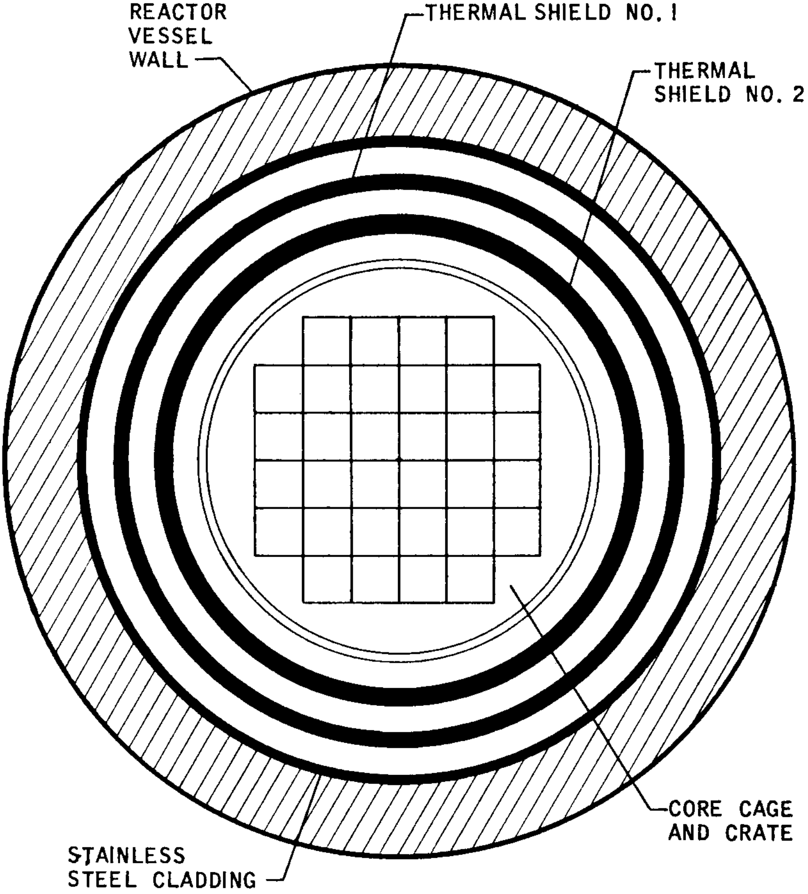

Fig. 6-5 Top Plan of *Savannah* Reactor Vessel and Core

The upper and lower portions of the egg-crate cage are separately designed and are called grid plates. The fuel elements fit into tapered guide slots in the lower grid plate; this wedges the fuel elements into correct alignment. The upper grid plate is fitted with locking arrangements for securing the fuel elements. Both upper and lower grid plates have cooling orifices through which the primary water passes. This grid plate cooling is necessary because of gamma heating. Otherwise, thermal stresses and distortions could build up in the grid plates and thereby dis-align the fuel elements.

The upper and lower grid plates also are the main structural members supporting the cage in the reactor vessel. Upper and lower grid plate flanges align with mating flanges inside of the inner thermal shield (see Fig. 6-6). The cage is held in place against the upward thrust of the coolant by means of hold-down springs, circumferentially around the upper baffle assembly which presses down against the upper grid plate. The use of springs permits self-adjustment of the cage against machining tolerances and differential thermal expansions. A total of 18 hold-down springs and struts is provided for this purpose. When properly secured, the core cage will not move (except under thermal expansion) under the worst possible conditions of roll, pitch, and heave at sea. Furthermore, the cage will not dislodge in the event of the ship's capsizal or sinking.

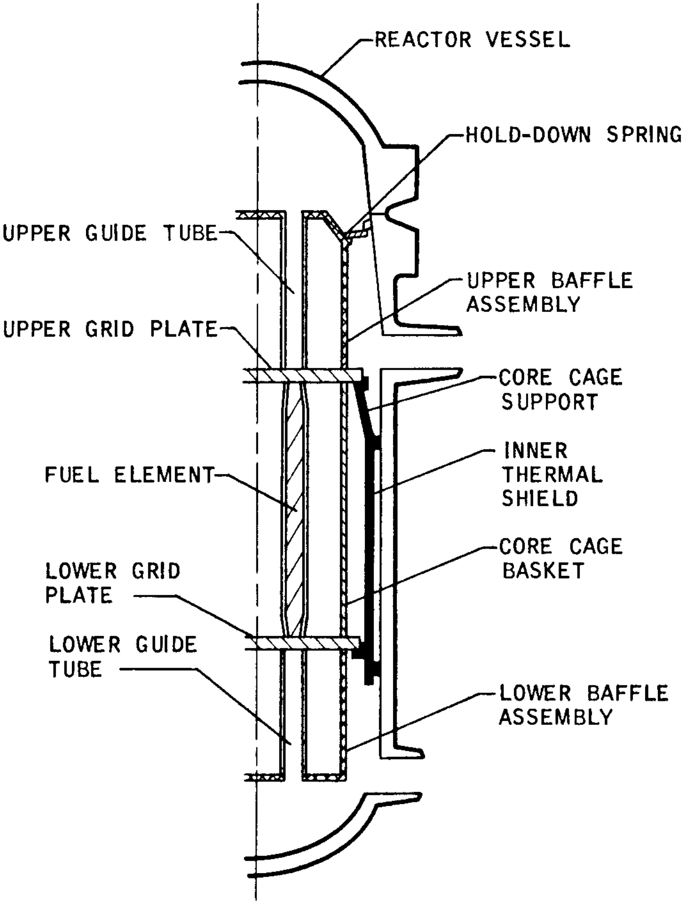

Fig. 6-6 Core Cage Structure, Supports, and Guide Tubes

Guide tubes extend above and below the core cage, forming upper and lower cage barrels. These guide tubes are extensions of the egg-crate "cans." Not only do they direct the flow of water in the manner desired, but they also guide the control rods and shroud them against hydraulic cross flows. The guide tubes terminate in upper and lower plenums where all of the primary water mixes homogeneously.

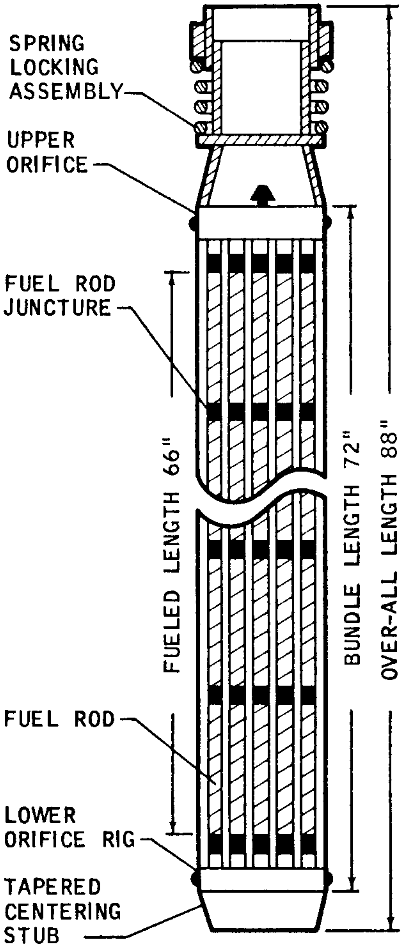

Fig. 6-7 Typical Fuel Element for *Savannah* Reactor

6-6 Fuel Elements and Rods

The individual fuel elements in the core cage of the *SAVANNAH* reactor are 8½ inches square, with an over-all length of 88 inches. The nuclear-fueled portion of this over-all length is 66 inches, leaving ample length at the top and bottom for end fittings (see Fig. 6-7). These end fittings facilitate positioning of the fuel elements in the upper and lower grid plates.

The lower end fitting of each fuel element contains a tapered centering stub, a pad spring (not shown), and an orifice rig. The stub (about 2 inches in length) wedges into the lower grid plate of the core cage. The pad spring permits a press fit to prevent any vibration or loosening that could be caused by the coolant flow or by thermal and pressure gradients. The orifice rig uniformly distributes the coolant flow into the individual fuel rod passages. About 25% of each fuel element is coolant passage.

The upper end fitting continues the orificing to discharge the coolant water into the guide tubes previously mentioned. The principal feature of the upper fitting is the locking collar and spring assembly. This assembly press-locks into mating connections in the upper grid plate. Special locking—and unlocking—tools are used during installation and removal of the fuel elements.

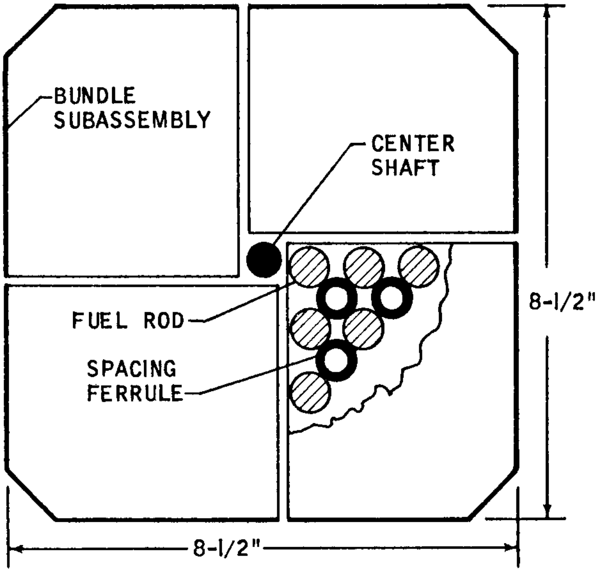

Fig. 6-8 Bundling Assembly for *Savannah* Fuel Elements

There are a total of 32 fuel elements in the core cage. The coolant flow bafflles are arranged so that 16 of the fuel elements lie in the second pass of the flow, and the central 16 lie in the third pass.

The fuel elements, including the fuel rod cladding and end fittings, and the core cage, all are constructed of type 304 stainless steel. Though the nuclear properties of stainless steel are not so good as other materials that could be used, the structural properties and resistance to corrosion of stainless steel are much desired. Hence, stainless steel gives better assurance of trouble-free fuel element service.

Each fuel element contains 164 fuel rods, each 0.500 inches O.D. Each rod is built up to its full length by welding smaller lengths end to end. The upper and lower ends of the rods are welded to orifice plates which attach to the fuel element end fittings. The center-to-center spacing of the rods is 0.663 inches.* The fuel rods are bundled together into four sub-assemblies which constitute the over-all fuel element (see Fig. 6-8). The cooling-passage clearance between rods is maintained by tubular ferrules brazed every 8 inches of rod length.

The rods are pellet-in-tube construction, much as illustrated in Fig. 1-1. The tube wall thickness (cladding) is 0.035 inches. The pellets are pressed and sintered UO_2, containing approximately 5% U-235. The gap between the fuel pellet and tube wall is filled with helium gas. The maximum metal temperature allowed at the fuel rod surface is 620°F. (600 K) The maximum central fuel temperature, however, is between 3600°F (2300 K) and 4400°F (2700 K).

6-7 Control of the Fuel

The total U-235 inventory in the 32 fuel elements is 330 kg (725 lb). As pointed out in Sec. 4-7, this is in excess of the criticality fuel by about 18.5%. This excess fuel—plus a reasonable sub-critical fraction—is nuclearly controlled by two methods, namely: (1) the use of mechanical control rods, and (2) the use of burnable poisons. For the *SAVANNAH*, 15% is controlled by control rods and 3.5% by burnable poisons.

The burnable poisons are dispersed throughout the fuel-rod cladding in the form of boronated stainless steel. The poison used is boron-10: a strong absorber of thermal neutrons. As the neutrons are absorbed, the boron atoms are "burned out." The influence of boron on controlling the fission multiplication of the total fuel (i.e., k_e) is shown in Fig. 6-9. The reason for using a burnable poison is to reduce the number of control rods required.

The *SAVANNAH* uses 21 control rods. These are cruciform-shaped elements which run the full length of the core cage when fully inserted. Each flat of the cruciform is 8 inches wide and is a $\frac{3}{16}$-inch boronated stainless steel plate sandwiched between two $\frac{3}{32}$-inch ordinary stainless steel plates. The cruciform control elements fit into cruciform-shaped guide tubes in the active core region. Above the active core region, the cruciforms recede into a circular guide tube (Fig. 6-10).

Attached to each control rod cruciform is an extension shaft which reaches to the reactor vessel head. Where this shaft penetrates the pressure vessel head, there is a buffer seal, charged with purified water at (124 bar) 1800 psi. Each buffer seal is isolated with a back-seating valve. A buffer-seal pump "charges" all 21 seals.

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* Ref: "The Power Plant for the First Nuclear Merchant Ship," J. W. Landis, Bulletin AER-54, presented at the Nuclear Merchant Ship Symposium, Washington, D. C., August, 1958.

Each control rod in the reactor is actuated by its own drive motor and screw shaft, mounted outside of the reactor on the reactor head. Each motor is a canned electro-mechanical device with a ball-bearing drive gear mating the control-rod screw shaft. The control rods are raised or lowered at speeds proportional to the applied voltage (design speed 20 inches per minute). If electric power to one of the motors fails, the rotor "free-wheels" and the control rod screws down under its own weight. If a system malfunction or other reactor emergency should occur, each drive gear is disengaged by a tripping mechanism (not shown) and a cocked hydraulic cylinder rams home the control rod (at 200 ipm).*

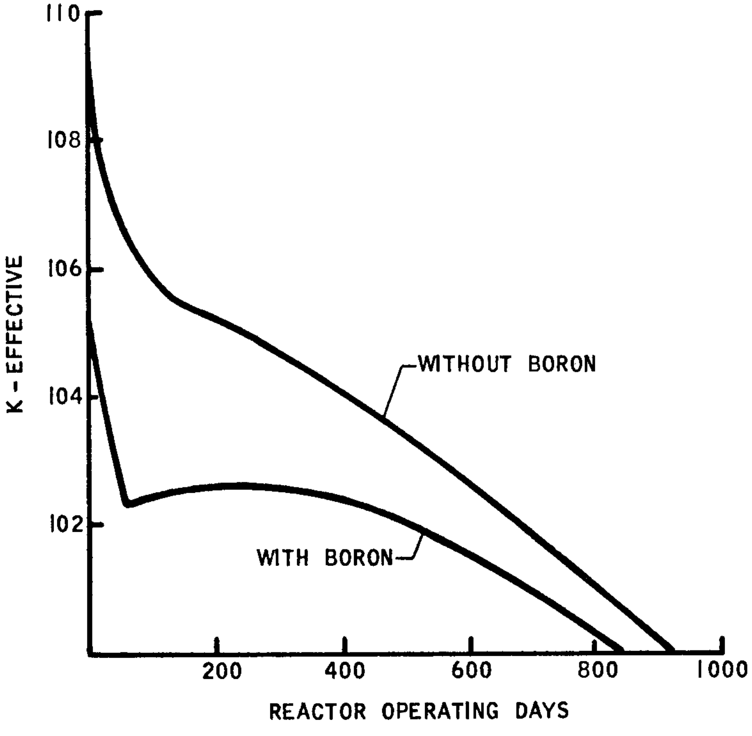

Fig. 6-9 Influence of Burnable Poison in Controlling Excess Fuel

All drive motors are programed so that the lower ends of the cruciform elements are in approximately the same plane. This produces a more uniform neutron flux profile across the core. Otherwise 21 irregularly positioned control rods could cause local flux shadowing and peaking that could lead to premature fuel element burnup. Position indicators tell operating personnel the control rod positions at all times. There is one position indicator for each control rod.

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* Ipm = inches per minute.

6-8 Display of Operational Controls

All controls and readouts concerning the reactor plant are channeled to a central control room, consisting of various instrument consoles. These consoles provide in audio-visual form all pertinent information (i.e., neutron fluxes, pressures, temperatures, flows, radiation, etc.) on the reactor loop, the steam loop, and the radiation monitors and auxiliaries thereto (see Table 6-2). Also, channeled to central control are important readouts on the propulsion plant, the electrical plant, and major cargo and hotel services. The display of operational controls is via meters, gauges, chart recorders, on-off lights, alarms, bells, buzzers—much the same as on any modern oil-fired ship.

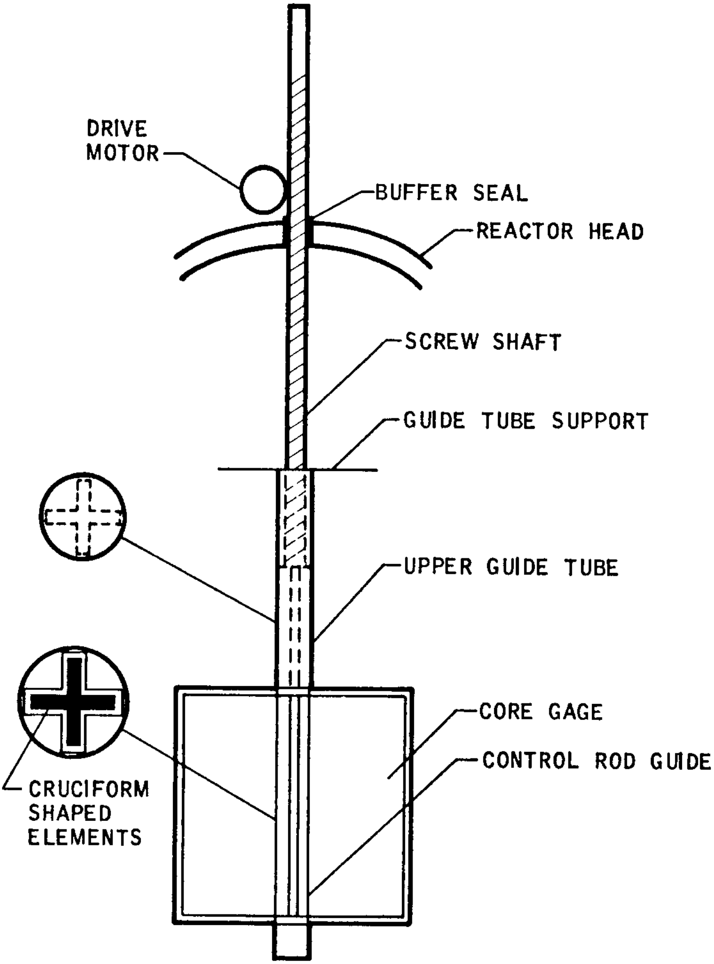

Fig. 6-10 Schematic Arrangement of Control Rod in *Savannah* Reactor

On the *SAVANNAH*, the central control room is located in the after end of the upper machinery spaces. All central controls and displays are housed in a glass-enclosed, soundproof room. A gallery is provided outside for visitors' inspection. This control room location is the farthest possible distance from the reactor compartment . . . without encroaching on cargo spaces. Of significance regarding the *SAVANNAH's* control room is its resemblance to a modern stationary power plant, with operators sitting at desk-type consoles.

Table 6-2. Reactor Control Functions Displayed for Operating Personnel (Partial Listing)

Reactor Loop	Steam Loop
Neutron Flux	Exchanger Temperature
Reactor Period	Exchanger Pressure
Rod Positions	Steam Temperature
Reactor Pressure	Steam Pressure
Inlet Temperature	Feedwater Level
Outlet Temperature	Feedwater Flow
Coolant Flow	Steam Valves
Pump Speeds	Turbine Pressure
Isolation Valves	Turbine Temperature
Drain Valves	Condensate Return
Radiation Monitoring	Auxiliary Monitoring
Primary Coolant	Pressurizer Pressure
Shielding Water	Pressurizer Level
Rod Seal Water	Pressurizer Makeup
Pump Cooling Water	Flash Tank Temperature
Ion Exchangers	Flash Tank Pressure
Containment Air	Flash Tank Makeup
Containment Valves	Letdown Coolers
System Drains	Ion Exchanger Flows
Sampling System	Ion Exchanger Temperatures
Waste Tanks	Seal Water Pressure

Once the reactor is at normal operation, automatic control is set. The central feature of this control is the detection and correction of the average temperature of the primary water through the reactor, in conjunction with the thermal neutron flux level (see Fig. 6-11). Voltage signals from temperature sensors in the hot and cold legs of the primary coolant loops are averaged and compared to a reference temperature (508°F). The correction signal thus produced is damped by logarithmic signals from neutron sensors adjacent (externally) to the reactor vessel. The resulting correction signal then actuates the control rod drive motors, to move the control rods in or out.

Control rod motion is initiated upon a temperature variation of plus or minus 3°F from the reference value of 508°F. This is a 6-degree spread in the 25° temperature rise through the reactor. For variations in temperatures less than 6 degrees, that is, for steam load changes less than 25%, automatic control is inherent in the reactor itself. This "inherent control" results from the sensitivity of neutron moderation to small temperature variations in the primary water.

During auto-control, operating personnel are on the alert for warning lights, alarm buzzers, flux limits, radiation limits, etc. They take readings, switch auxiliaries, take samples (of the primary water, waste collection, and containment air) and they check out instrument and control circuits to acquire the necessary familiarity for startup, setback, shutdown . . . and emergencies.

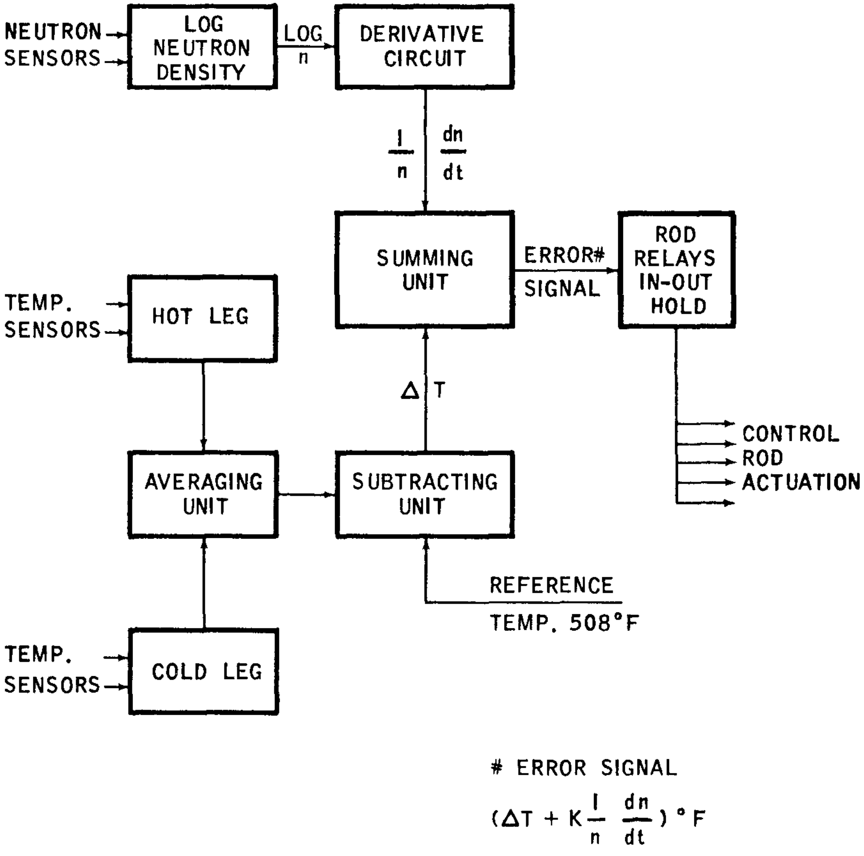

Fig. 6-11 Block Diagram of Automatic Control Rod Actuation

These latter functions are performed by manual control. For example, during reactor startup, operators manually adjust the control rods to warm up the plant slowly, at around 200°F per hour. The usual procedure is to actuate the control rods for about 0.5 sec on and 4.5 sec off. This allows a safe margin for the "coast-up" of the neutron flux, which is faster than operator response.

In emergencies, manual control can override any automatic device except certain maximum limits against self-destruction of the reactor. The primary limitation in this respect is the reactor period (i.e., the time in seconds for the power to increase 2.7 times). Period meters are on continuous display. When the period attains a preset limit—say, 10 sec—the reactor is automatically "scrammed" (shut down). Thereafter, operating personnel must manually restart the reactor.

6-9 The Containment Shell

"Containment" is the enclosing of all vital parts of a reactor plant into a separate over-all pressure vessel of its own. The philosophy behind containment is that should an internal reactor disaster develop, all radioactive vapors, liquids, and solids would be locally contained.

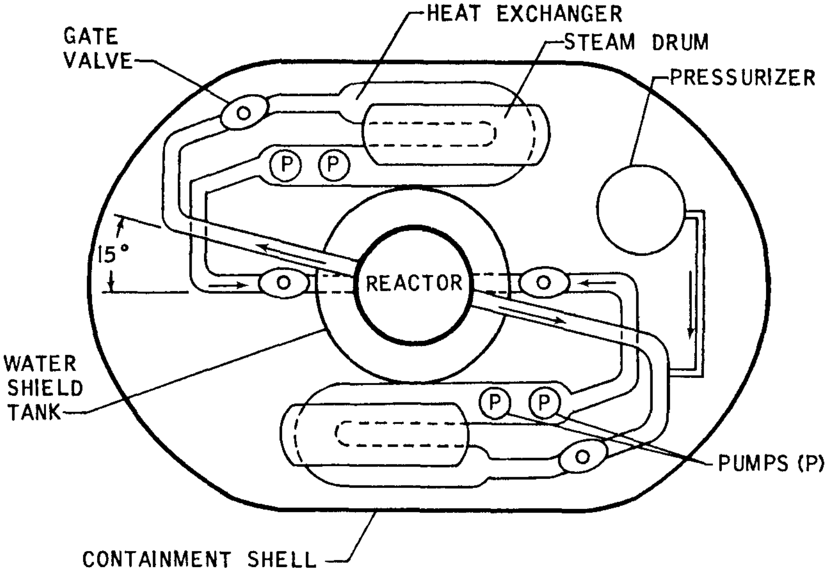

Fig. 6-12 Arrangement of Reactor Plant in *Savannah* Containment Shell

Should core meltdown occur, for example—due to some rare catastrophe—large quantities of radiocontaminants would immediately mix with the primary coolant. These contaminants could be transported outside of the reactor vessel to the heat exchangers. Here, due to the additional heat of radioactive decay, leaks could be accelerated in the heat exchanger tubes, and the radiocontaminants could be carried over to the steam side . . . thence to the propulsion machinery. To isolate these contaminants and prevent their spreading into the propulsion machinery, a special containment shell is constructed around the reactor plant. Within this shell are "contained" the reactor, the primary piping, heat exchangers, primary pumps, and steam drums (see Fig. 6-12). The water purification system is located external to the containment shell.

The *SAVANNAH's* containment shell is approximately 35 ft diameter by 50 ft length, over-all. A 13½ ft diameter cupola extends upward over the reactor to house the control rod drive shafts. To withstand the vapor pressure buildup from major ruptures in both the primary and secondary piping systems, the containment shell is designed for 185 psi. During operation of the reactor plant, the containment shell is completely sealed. Remotely operated, quick-closing valves can shut off the efflux of steam and inflow of water.

Also enclosed in the containment shell is a blower and cooler system to continuously recirculate the air therein. The air temperature is maintained at about 130°F (at atmospheric pressure) and at a humidity of about 72%. When necessary to discharge air from the containment shell, suitable filters insure against the release of any radioactivity to the outside. Quick-closing valves are provided on the air intakes and exhausts, and on the cooling water inlets and discharges.

After reactor shutdown and cool-off, access into the containment shell is possible. This can be done through a central cupola (for refueling), through a hatchway over each heat exchanger (for replacement of primary pumps or valves), and through a lower manhole (for inspection purposes).

6-10 Biological Shielding

The containment shell is surrounded externally by a concrete shield (not shown in Fig. 6-12). Above its equator, the concrete thickness is 30 inches; below it is 48 inches. Around the cupola and hatches, there is a 12-inch shielding of lead and polyethylene. The polyethylene is a hydrogenous material effective against neutrons. This containment shield is called the "secondary shielding." Primary shielding is used around the reactor proper.

There is a great quantity of steel in the reactor vessel (i.e., 6-inch-thick walls, two thermal shields, plus the core cage). All of this steel is a shield in itself . . . particularly against gamma rays. Since neutrons get through this steel quite easily, the only special shielding required is a neutron shield. One of the best neutron shielding materials is water. Consequently, the *SAVANNAH's* primary shield is a tank of water, annularly surrounding the reactor (see Fig. 6-13). The annular tank is approximately 18 feet high and 36 inches thick.

The primary shielding tank does not enclose the upper and lower portions of the reactor vessel. There are two reasons for this. First, the thickness of water inside the reactor vessel, above and below the active core, is an adequate neutron shield. Secondly, the shield tank is the primary structural member supporting the reactor vessel. The reactor "hangs" from the shield tank, and the shield tank in turn is tied-in to the ship's strength structure. By keeping the upper and lower portions of the shield tank open, there is access to the control rod drive mechanisms, and the reactor vessel can grow and contract at will.

Between the reactor vessel and the shield tank, there are about 4 inches of glass wool insulation . . . packed tightly. This is thermal insulation to help keep the shield water from boiling. In addition, however, the shield water is separately cooled (via coils) to about 130°F. The pressure in the shield tank is about 100 psi.

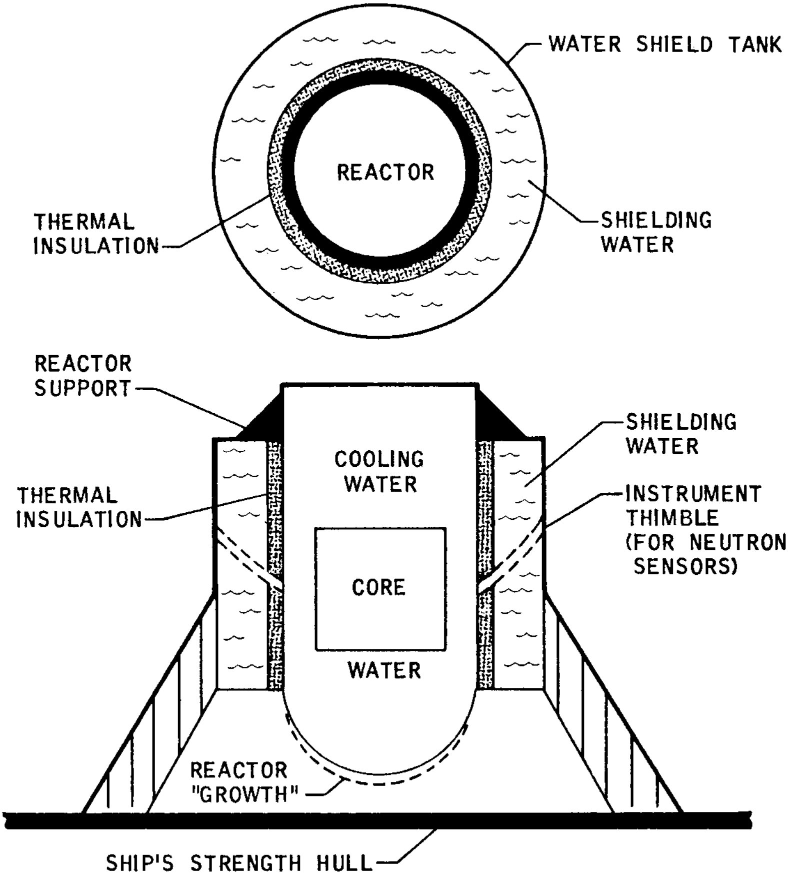

Fig. 6-13 Representation of Neutron Shielding Tank for *Savannah* Reactor

Inasmuch as the shielding water is subject to neutron fields, it becomes radioactivated. Though to a lesser extent, this is the same type of neutron-induced radioactivity that occurs in the primary water inside the reactor. Consequently, the shielding water has to be purified and hydrogenated . . . the same as the primary water. To do this, a fraction of the shielding water continuously passes through the purifier system in Fig. 6-3.

6-11 Reactor Location in Ship

The containment shell—together with its reactor plant—forms an integral self-contained reactor steam generating unit. Except for reactor controls and certain auxiliaries, the only contact with the "world outside" is the steam produced. Consequently, it is only logical that the reactor plant be isolated from the rest of the ship in a separate compartment all of its own.

Aboard the *SAVANNAH*, the reactor plant is located amidship and forward of the propulsion machinery space (see Fig. 6-14). This location has several advantages. Foremost, there is free access for fueling and refueling. Nuclear fuel and other reactor equipment can be lowered into and removed from the containment shell directly, without any ship's structure intervening. Secondly, the reactor vessel proper is positioned almost in the exact geometric center of the ship: fore-and-aft, athwartships, and deck-to-keel. Here, it receives the maximum possible protection from external damage, such as ship collisions, groundings, etc. In this position, also, the reactor is a more than safe distance from personnel operating areas, and from the passengers' and crew's quarters. And, thirdly, the Fig. 6-14 location is the strongest structural part of the ship. It needs to be!

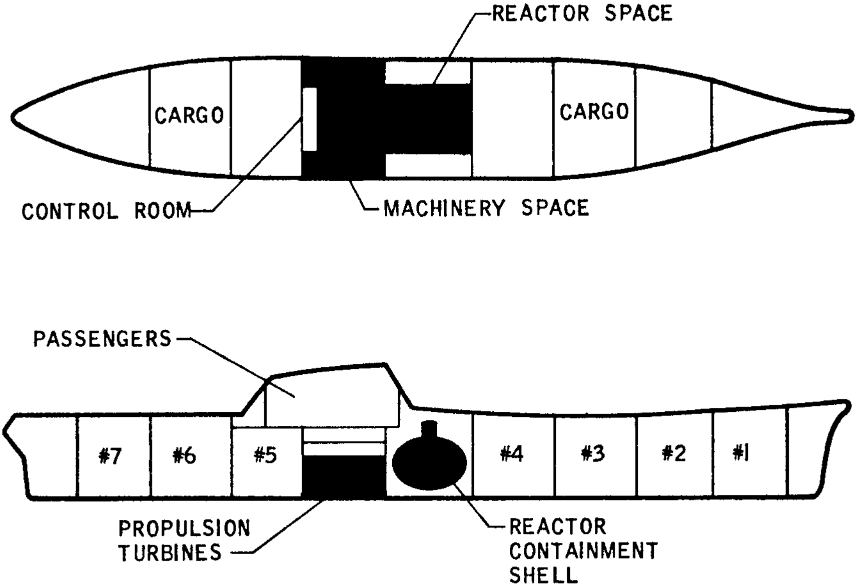

Fig. 6-14 Location of Reactor Compartment in Nuclear Ship *Savannah*

The reactor and its auxiliaries weigh approximately 600 tons; the containment and shielding approximately 1900 tons. The total: 2500 tons or about 5.6×10^6 pounds. This weight is localized in a horizontal area of approximately 2250 sq ft (i.e., the plan area of the containment shell and its external concrete). This results in a unit structural loading of about 2500 lb/sq ft—rather severe as merchant ships go. For example, on a *MARINER*-class ship, which has a comparable hull to the *SAVANNAH*, the maximum design loading (at the tank tops) is 1800 lb/sq ft. Thus, the *SAVANNAH* requires considerable strengthening of her center hull section beyond that of comparable oil-fired ships.

6-12 Emergency Take-Home

Seafarers are adamant against accepting a new propulsive power without some emergency provision in the event of loss of that power . . . thousands of miles from home. The precedent for this began during the transition from sail to steam. For years, early steamships carried an auxiliary sail in the event of steam plant failure, and it was a good thing that they did. The same parallel holds true today in the case of the transition to nuclear ships. The reactor plants of such ships must be backed up by "conventional" power sources.

On the *SAVANNAH*, the emergency power backing up the reactor plant consists of two 750 KW diesel generators, a bank of constantly charged batteries, and a 7500 lb/hr 150 psi package boiler. These power sources are normally idle but are designed to start up automatically upon loss of the reactor plant.

In any emergency involving loss of the reactor plant, the predominant role of operating personnel is to get the reactor cooled down, and to cool off its containment shell. For this purpose, the two 750 KW diesel generators supply immediate electrical power to the reactor control console. Simultaneously, the battery bank energizes the vital nuclear instrumentation (i.e., reactor period meters, neutron flux meters, and the radiation detectors). With ample emergency power at the control console, operating personnel can manually switch on, off, or reduce, as appropriate, the primary pumps, the pressurizer heaters, the electric valves, the auxiliary pumps, the containment shell blowers, etc. For emergency cooling of the containment shell, salt water can be cut in directly to the coolers from sea intakes.

Once the reactor plant is safely cooled down, most of its electrical equipment can be put on reduced power. This frees enough of the emergency power to drive a 750 SHP electrical take-home motor. Means are provided for hand coupling this motor into the propeller shaft reduction gears. The take-home speed would be a respectable 6 knots.

SUMMARY

We recognize that the *SAVANNAH* reactor, using water as the primary coolant, is the logical transition from modern high-pressure marine boilers . . . which also use water. With the *SAVANNAH*, however, the total reactor steam generated is about 260,000 pounds per hour at 460 psi, 475°F. This dry-saturated steam proceeds to the propulsion turbines via conventional steam stop and check valves.

To prevent boiling of the primary water, a pressurizer is used. This device controls the water pressure at 1750 psi by alternate use of electrical heaters and spray coolers, as the transients of the system demand. Because the primary water becomes radioactivated while in the fission region of the core, a purification system is provided. This consists of letdown coolers, block orifices, ion exchangers, and effluent filters which remove radiocontaminants and corrosive matter. The purified primary water is returned to the reactor via a surge tank and charge pump. At the same time, make-up water, off-gassing, and hydrogenization are provided.

The reactor proper consists of a 6-inch-thick pressure vessel (9 ft diameter by 26½ ft height), two thermal shields, a core cage, and baffles which direct the coolant flow in three passes through the reactor. Water enters the reactor at its lower regions, passes up along the thermal shields and core-cage support flanges down through outer fuel elements, then up again through the central fuel elements. This three-pass arrangement minimizes the coolant pumping power required, and maximizes the heat absorption by the coolant. The baffling adds complexity to the internal construction, and the increased dwell time of the coolant in the fission zone increases its radioactivity. The total temperature rise through the reactor is 25°.

The core cage (5 ft diameter by 5½ ft height) is of "egg-crate" construction and fits into the reactor vessel to hold the 32 nuclear fuel elements, and to guide the 21 control rods in and out of the core. Upper and lower grid plates perfectly align the fuel elements and lock them in place against the worst possible orientations of a ship at sea. Above and below the grid plates are guide tubes which protect the fuel elements and control rods against hydraulic cross-flows, and against thermal and pressure differentials.

Each fuel element in the core cage is an 8½-inch square of 85 inches over-all length. The nuclear-fueled portion is about 66 inches, thus leaving a top and bottom for end fittings. Each fuel element consists of 164 fuel rods, each 0.50 inches O.D. Each fuel rod is of pellet-in-tube construction; the pellets are UO_2 containing about 5% U-235.

The total U-235 inventory is 330 kg (725 lb) of which about 18.5% is fuel in excess of criticality. This excess fuel is controlled by burnable poisons (3.5%) and by mechanical control rods (15%). The burnable poison is boron-10 in the form of boronated stainless steel fuel-rod cladding. The mechanical control rods are cruciform-shaped boronated elements, 8 inches across the flats. The position of each of the 21 control rods is telegraphed to reactor operators in a central control room. Under normal operation, the control rods move in and out automatically when the reactor temperature varies plus or minus 3° from its median value of 508°F.

The reactor, heat exchangers, and principal auxiliaries are housed together in a separate pressure vessel called the "containment shell." The philosophy behind containment is that should an internal reactor disaster develop, all radiocontaminants would be locally contained. This philosophy also leads to the separate location of the reactor plant in the ship's hull. Remotely operated, quick-closing valves can isolate the reactor compartment from the rest of the ship. Access to the containment shell is not possible during normal operation.

There is ample biological shielding (concrete) around the containment shell . . . to the total of approximately 1900 tons. The shielding around the reactor vessel is water in an annular tank approximately 18 feet high and 36 inches wide. The reactor "hangs" from this tank, and the tank in turn is tied-in to the ship's strength structure. The reactor plant and primary shield weigh about 600 tons. The total reactor compartment weight is approximately 2500 tons, resulting in a unit structural loading of about 2500 pounds per square foot. This is rather severe as merchant ships go. Thus, the *SAVANNAH* requires considerable strengthening of her center hull section beyond that of comparable oil-fired ships.