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HANFORD CODE C.65

CHAPTER II:

DESIGN AND CONSTRUCTION OF THE HANFORD
PRODUCTION REACTORS

July 2, 1963

Prepared by:

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for

Reactor Personnel Certification
Irradiation Processing Department

Hanford Atomic Products Operation
General Electric Company
Richland, Washington

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CHAPTER II

DESIGN AND CONTRUCTION OF THE HANFORD
PRODUCTION REACTORS

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CHAPTER II

DESIGN AND CONSTRUCTION OF THE HANFORD
PRODUCTION REACTORS

STUDY GUIDE

The purpose of a chapter on design and construction is to provide an overview of reactor construction and an understanding of important design considerations . . . "How is it built?" "Why was it built this way?" "What is it supposed to do?" "What are the nuclear safety considerations?" "What do I need to know about its design and construction to properly operate it?"

The student will be expected to have a good over-all knowledge of the construction of his assigned reactor (for Supplemental Crews, the "home" reactor). He should know enough about how the reactor is built to be able to draw, in a rough diagram, a "typical" lattic unit and a process channel with tube, connecting hardware, sensing and sample lines and explain the function of each component.

He should be able to make rough diagrams of a VSR and an HCR (with a statement on the type of drive used), a Ball 3X hopper, a step plug, a VSR and HCR gas seal and a test hole.

He should be able to make rough sketches or line diagrams of the confinement system, the thermal and biological shields in relation to the rest of the reactor, and a simple diagram of process water lines in primary, secondary, and last-ditch cooling systems.

He should know the number of rods, crossheaders, tubes and cooled test holes and be able to discuss intelligently any unusual or experimental on-reactor facilities. Design features with safety implications should be well understood; e.g., front face check valves, cap detents, scram drive systems, coolant backup, etc.

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CHAPTER II

DESIGN AND CONSTRUCTION OF THE HANFORD PRODUCTION REACTORS

STUDY NOTES

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GENERAL

The design of the eight Hanford production reactors is remarkably similar. Since B Reactor was designed and built and through the K Reactor Program there have been refinements, but few major changes. The purpose of this chapter is to provide an overall view of reactor construction and an understanding of important design considerations.

The designer looks at a reactor in a somewhat different light than an operator or a technical staff. For example, he would ask, "How could the reactor or its components be built (modified) to operate

- a) more safely both from a personnel and nuclear safety standpoint?
- b) less expensively from the capital, maintenance and operating cost standpoints?
- c) more easily from an operator's standpoint?"

A production reactor is a complex of systems and equipment designed to sustain, control, cool and replenish a nuclear chain reaction over relatively long operating periods for the purpose of converting uranium to plutonium. Hanford production reactors are graphite moderated, horizontal tube, water-cooled reactors.

One of the prime reasons for operator certification training is to improve nuclear safety through a better understanding of the reactor - its processes and limitations. A study of the physical parts of the reactors helps this understanding. Procedures, automatic control systems, etc., are all designed to operate the reactor safely. However, as conditions change, the details of reactor construction need to be re-evaluated to insure that what was once a safe system is still safe.

Most of the time the reactor is operated by set procedures based on standards and experience. However, no set of rules covers all conditions or possible incidents so the operator must have some basic knowledge of the reactor in making on-the-spot decisions. These decisions can effect personnel safety, time operating efficiency, and radiation exposure as well as nuclear safety.

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This treatment of reactor design is certainly not intended to be comprehensive. It discusses in general terms the following components and their functions:

- 1) Moderator (graphite)
- 2) Process channels and hardware
- 3) Coolant system (water)
- 4) Poison systems (HCR, splines, VSR, Ball 3X)
- 5) Reactor shields (biological and thermal)
- 6) Instrumentation systems
- 7) Gas system
- 8) Fuel and fuel handling system
- 9) Ventilation and confinement systems
- 10) Power supply (steam and electrical)

Not all of these are discussed in detail and for more specific information, the reader is directed to References 1 and 2.

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MODERATOR

a. Properties

The fission of Uranium-235 releases high energy neutrons. If these neutrons undergo collisions with the atoms of the light elements, the neutrons will be slowed to thermal energy. At this energy level, they are readily captured by the Uranium-238 atoms to become eventually Plutonium-239 atoms.

Besides being a relatively light material, the moderator must have a low capture cross section for neutrons at all energy levels. For most reactors (including those at Hanford), good high temperature properties and stability under irradiation are required. Hanford reactors also require that the moderator have good structural properties to maintain the lattice, support the process channels, and provide openings for insertion of the controls. Three materials commonly used for reactor moderation are water (heavy and light), beryllium and

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carbon. Only the last two would be suitable for a Hanford type reactor. Beryllium, because of its cost and difficulties in fabrication must be ruled out. The one choice remaining, graphite, leaves something to be desired in radiation stability, but this can be overcome to some extent by the design of the "stack".

The reactor graphite is of a specially purified grade to eliminate undesirable elements that have a high capture cross section. Actually, graphite of different grades of purity is utilized in the moderator. The purest grades are used in the core and the least pure in the reflector. On construction drawings, these are often shown as zones, (red, blue and green). The purity of each lot of graphite bars is determined from reactivity measurements made on sample bars inserted into the 305 Test Reactor.

Graphite is made by extruding a mixture of *petroleum or coal tar and a pitch binder* through a die. This material is then baked. The higher purity graphites are subjected to an additional baking period in special atmospheres at very high temperature (2800 C) for an extended period to burn out the impurities. Less pure graphite can be used in the reactor, but at some sacrifice in initial performance. This then is a question of economics - the cost of furnace graphitization vs. the cost of the enrichment to burn out the impurities during reactor operation.

b. Graphite Stack

The general arrangement of the moderator in all of the eight production reactors is similar although there are differences of detail. (See figures 1 through 5) For the six old reactors the lattice (distance between centers of adjacent tubes in both the horizontal and vertical dimensions) is 8-3/4 inches and for KE and KW Reactors, it is 7-1/2 inches. The lattice need not be square. N Reactor has a 8" x 9" lattice.

The graphite moderator is made up of layers of graphite blocks. Each block is approximately 1/2 of a lattice square (4-3/8 or 3-3/4" square) by about four feet long. Some blocks may be shorter to fit openings in the stack or to permit staggering of the joints. One layer, containing the tube and filler blocks has the long axis of these blocks oriented in the front to rear direction of the reactor. Another layer, made up entirely of filler blocks has the axis of the individual graphite bars oriented in the side to side direction. In the tube block layer, a series of tube blocks laying end to end form the process tube channel. (See figures 6 through 10.) Adjacent

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to this is a series of filler blocks. This pattern of alternating tube and filler bar columns is continued across the core of the reactor. In the Hanford reactors this core approximates a right circular cylinder although its face is made by cutting the corners from square. Outside the core is a region of the moderator called the reflector. The function of the reflector is to reduce the loss of neutrons from the core of the reactor. In construction, the reflector is similar to the core except the tube block columns are replaced by solid filler block columns. A portion of the inlet and outlet sections of the process channels also serve as a reflector. This is one reason why the reactor fuel column length (active length) is less than the front to rear dimension of the graphite moderator.

The graphite stack is held together by a system of keys. These graphite keys, 1-1/4 to 1-1/2 inches square, run along the sides of the moderator in the reflector and across the front and rear of the reactor. The keys provided graphite stack continuity during original layup. Their strength is relatively low because of the brittle nature of graphite and the sharp notches in the keys and blocks. High tube removal forces, or an earthquake, will break them.

[REDACTED]

Keys are also used to keep the filler blocks spaced for the horizontal and vertical rod channels. Track blocks in the bottom of the HCR channels provide a bearing surface for the rod and keep the filler bars apart where there are no keys. The vertical rod channel keying varies from four to eight per channel depending on the reactor. The liner blocks in the B, D and F Reactors could be considered as super keys.

The ends of the tube blocks have a male-female connection to maintain the alignment of the process tube channel (see figures 6 through 10). At B, D, F and DR, this connection was machined directly in the ends of the tube blocks. In later reactors, trunnion blocks, having both male connectors, were used between the tube blocks with female connections. The trunnion block concept evolved as an attempt to control the effects of graphite growth during irradiation.

[REDACTED]

FIGURE 1
B, D, F - REACTOR
GRAPHITE LAYUP ARRANGEMENT

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FIGURE 2
DR REACTOR
GRAPHITE LAYUP ARRANGEMENT

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TUBE DIAM. 1.726" - 1.732"
 BORE DIAM. (TUBE BLOCK) 1.750" ± 0.002"
 TRUNNIONS 1.750" - 0.003"
 TUBE RESTS ON BOTTOM OF CHANNEL.

FIGURE 3
 H REACTOR
 GRAPHITE LAYUP ARRANGEMENT

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FIGURE 4
 C REACTOR
 GRAPHITE LAYUP ARRANGEMENT

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FIGURE 5
K REACTOR
GRAPHITE LAYOUT ARRANGEMENT

TUBE BLOCK LAYER

FILLER BLOCK LAYER

TUBE BLOCK LAYER

FIGURE 6
B, D, F-REACTOR
PROCESS TUBE AND HCR CHANNEL SECTIONS

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FIGURE 7
DR REACTOR
PROCESS TUBE AND HCR CHANNEL SECTIONS

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FIGURE 9
C REACTOR
PROCESS TUBE AND HCR CHANNEL SECTIONS

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TUBE BLOCK LAYER
FILLER BLOCK LAYER
TUBE BLOCK LAYER

FIGURE 10
K REACTOR
PROCESS TUBE AND HCR CHANNEL
SECTIONS

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c. Graphite Growth

After a short period of operation of B, D and F Reactors, it became apparent that the graphite was growing as a result of irradiation. Evidences of this were distortion of the process tube and rod channels and movement of the shields. Experiments indicated that graphite expands when irradiated at low temperatures and contracts when irradiated at high temperatures.

Graphite temperature, on the front to rear axis of the reactor, approximates a cosine curve and explains the double hump traverses obtained on typical process channels. (See Figure 12.) Growth occurs in the fringe regions which are operating at low temperatures and contraction occurs in the center of the reactor.

At DR Reactor, an attempt was made to alleviate the effects of graphite growth by special machining of the tube blocks. Approximately one-eighth of an inch was machined from the height of these blocks to allow them to grow without affecting the moderator. This is commonly called undercutting. Since the side to side spacing of the bars had to be maintained for stack stability, undercutting of the sides could not be used. Instead, the sides of each tube block were dished to permit a limited amount of growth while still maintaining block spacing and did provide some relief.

Additional experimental data on graphite indicated that graphite growth occurred only in a direction perpendicular to the axis of extrusion. In fact, parallel to the axis of extrusion some minor amount of contraction will occur. This fact permitted undercutting all sides of the tube blocks if trunnion blocks were used to give the required stack spacing.

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The trunnion blocks are cut from regular graphite bars and the process tube hold is drilled perpendicular to the axis of extrusion of the original bar.

Axis of extrusion

The top of each trunnion is undercut because vertical growth will occur in the trunnion. In the side to side direction, the trunnion is full width (1/2 lattice spacing). Expansion in the front to rear direction is matched by axial contraction of the tube blocks. H Reactor made the first use of trunnion blocks.

d. Heat Transfer

There is considerable temperature variation in a typical reactor lattice unit. All the heat generated in the graphite as a result of the collisions with the neutrons must be removed. The heat sink for this removal is the water in the process tube. Since heat flow requires a temperature gradient, we would anticipate that the highest moderator temperatures exist in the inner layers. At B, D and F Reactors, the temperature variation is low because there is a good heat flow path in the direction to the process tube.

Undercutting changes the typical heat flow path. The gaps in the moderator, formed by the undercut sides of the tube blocks, resist heat flow. Thus, the most of the heat must take a path that involves direct contact with the top of the bottom of the tube block. This more circuitous path results in even higher temperatures in the inner layers.

Since the tube blocks are in direct contact with the process tube, they run the coolest. This explains why primary emphasis was placed on undercutting these blocks. The filler blocks, running at higher temperatures, could provide stack stability and would probably contract slightly during reactor operation.

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One other variable in graphite temperatures is the reactor atmosphere. The use of helium, the gas with the best heat transfer properties, reduces filler layer temperatures by increasing the heat flow across the gaps between blocks. The substitution of gases with poorer heat transfer characteristics can increase graphite temperatures.

Undercutting raises the temperature of the filler blocks but does not affect the tube blocks. Therefore, the concept of coring was used at C, KE and KW Reactors to raise the graphite temperature in the fringes and outlet of the stack. Coring is simply changing the annular gas gap between the process tube and the tube block by drilling a larger hole to hinder heat transfer and raise both the tube block and the filler block temperature. In this case, the heat transfer properties of the reactor atmosphere are even more important than for undercut blocks.

Calculations on the required core size are made to establish a uniform temperature profile along a process tube channel. The largest cores are required at the inlet and outlet with smaller cores in the control region of the reactor. The ideal core would be a skewed, cosine curve, but fabrication problems and cost consideration limit coring to about three diameters. These diameters are used to provide a coring pattern that is slightly skewed toward the rear of the reactor to account for the higher outlet temperatures. The coring of a typical process channel on the fringe of the reactor is somewhat different than for a central zone tube because of differences in tube power.

How is the process tube centered in a cored channel? Here the trunnions have a second role which is accomplished by having one of the collars with a smaller ID to center the tube in its channel and support it.

Chamfers on the corners of the tube blocks, and in some reactors on the filler blocks, provide the gas passage. B, D and F Reactors also had "weep holes" drilled from the chamfers on the tube block to the bore. The weep holes were to provide a path for water to leak from the process tube block.

e. Graphite Contraction

Undercutting and coring solved the graphite growth problem as evidenced by typical tube traverses. (See figures 12 through 16.) However, another phenomena occurs during irradiation - graphite contracts on irradiation at elevated temperatures. This effect is being investigated but as yet there is no experimental evidence to indicate the limit of contraction.

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The K Reactors, because of their higher flux, have graphite with the most total exposure. A total contraction of four inches is evident in process channel distortion measurements. (See figure 16.) Within ten years this may be extrapolated 12 inches and even this is not necessarily a limit because the maximum unit contraction has not been determined.

Experimental work in high flux test reactors permits irradiation of graphite samples ahead of the K Reactors but these have not yet located an end to contraction. An end point is probably somewhere short of the theoretical density of reactor grade graphite. The 1.7 g/cc density of reactor grade graphite falls far short of the theoretically attainable 2.26 g/cc density, and it could be disastrous if contractions of such an order of magnitude actually occurred.

The reactor moderator is stacked on a fixed base; therefore, the contraction of individual blocks is cumulative and the top graphite rows show the most displacement from their original position. In the front to rear direction, this displacement represents a cosine pattern - the same as the flux pattern. The side-to-side and top-to-bottom flux distribution is flattened and this results in a rather steep gradient in the distortion pattern in the fringes of the reactor. Evidence of this is noted in HCR and VSR channel traverses. The ideal mirror image of the flux is not attained because of gaps between blocks, VSR keying patterns and variation in the slip planes between adjacent layers of graphite. The many graphite pieces make a detailed analysis of stack movement difficult. Such theories as thermal ratcheting, cleavage planes, etc., have been proposed, but none of these fits all the available data.

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It should be noted that side movement of a channel should be one-half the vertical movement, because the graphite tends to contract about the vertical centerline of the reactor rather than the fixed base.

Measurements taken on the reactor indicate that there are large separation planes in the graphite. The migration of 3X balls from the VSR to the HCR channels seems to bear this out. Such separation planes could be the result of contraction of the core of the reactor while the reflector remained relatively unaffected. The keying action of the VSR channels could also provide some of the explanation.

Although the basic block arrangements are similar, the effects of distortion of the graphite will not be the same in all reactors. In B, D and F Reactors, the supporting structure is made up of the tube blocks and filler layers. The filler bars in the tube layers are probably free. In the undercut reactors, the support structure is from filler layer to filler layer by way of the filler blocks in the tube layers. This difference in basic support structure may help explain some of the difference in distortion patterns noted in rod channel traverse measurements.

Changing of stack dimensions due to irradiation of the graphite presents a very serious situation from all aspects - maintenance, operation, safety. The continued distortion is affecting operation of the rods and in some cases, limits fuel element charging. Much of the on-reactor maintenance revolves around alleviation of problems caused by graphite distortion. Future problems with the thermal shields and Ball 3X system may result. All in all, graphite distortion is the major key to continued operation of the reactor because of its effect on all other reactor systems. Since the graphite and the shields defy replacement or major modification, their deterioration becomes a matter of serious concern.

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FIGURE 12
F REACTOR
PROCESS TUBE DISTORTION CURVES

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FIGURE 13

DR REACTOR

PROCESS TUBE DISTORTION CURVES

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FIGURE 14

H REACTOR

PROCESS TUBE DISTORTION CURVES

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FIGURE 15

C REACTOR

PROCESS TUBE DISTORTION CURVES

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FIGURE 16
K REACTOR
PROCESS TUBE DISTORTION
CURVES

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PROCESS TUBE ASSEMBLY

For purposes of this chapter, the process tube assembly starts with the inlet connector and ends with the outlet connector. It includes the connectors, nozzles, caps, plugs, process tube, gunbarrels, thermal shield blocks, donuts, gas seals, temperature detectors, orifices or venturis, Van Stone gaskets and gunbarrel flanges, plus miscellaneous bolts. The functions of this assembly are to: 1) support the fuel, 2) channel the coolant, 3) seal the reactor atmosphere, 4) facilitate charge-discharge and 5) serve as a channel for control splines.

a. Aluminum Process Tubes

In the early reactors, aluminum was selected as a process tube material because of its low cross section, low residual activity, adequate strength, good corrosion resistance, low cost, availability and ease of fabrication. It was one of the few materials with which there was experience in forming long tubes having internal ribs. The early tubes were round on the OD but the ID was slightly elliptical. (See figures 17 and 18.) It was necessary to make the wall at the top of the tube thicker than the wall at the bottom to balance the volume of metal above and below a theoretical centerline to facilitate tube drawing. This, plus a wear allowance on the ribs, put the center of the fuel above the center of the tube, resulting in higher corrosion rates at the top because of higher water temperatures. This hot spot drops to the bottom of the tube as corrosion and wear decrease the rib height. As operating temperatures are raised, tube life is shortened. The control of water quality and pH provides some relief, but at present, the life of a tube may be less than two years. Tube replacement is expensive in cost and manpower and radiation exposure. It is also of concern because of the damage inflicted on the graphite during tube replacement. Tube splitting, pulling and broaching all tend to damage the graphite tube blocks - particularly at the weaker junctions.

b. Zirconium Process Tubes

Zirconium, a relatively new material in industrial use, can be utilized for process tubes as is presently the case in the K Reactors.

Zirconium is more corrosion-resistant than aluminum, but it has disadvantages in cost and fabrication. This cost disadvantage may be overcome because the cost of a single zirconium tube plus installation is less than the cost of the three to

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five installed aluminum tubes that would be required over the same operating period. The fabrication of a ribbed zirconium tube is not easy and to reduce costs to reasonable levels, smooth bore tubes with self-supported fuel elements were proposed. In order to provide a reasonable temperature balance above and below the fuel and to permit reasonable manufacturing tolerances, a nominal clearance of 0.009 inches between the tube and fuel support feet was established. Because of its higher strength, the zirconium tube wall can be thinner, allowing the tube to flatten more at the points of extreme curvature in the stack. Tube flattening plus the close clearance are the primary limits in tube life.

With a ribbed aluminum process tube, the use of shorter fuel elements helps overcome extreme curvature, but at greater radii of curvature, the self-supported fuel hangs up in the zirconium tubes, and shorter elements will not relieve the situation. Thus, it is necessary to drill the graphite process channels to reduce the tube curvature. (See figure 19.) Unfortunately, this drilling, which will accommodate future distortion, must be done at today's distortions which seriously limits the amount of graphite that can be removed, and sets the limit on the fuel charging life for tubes higher in the reactor. Drilling the graphite increases the gaps between the process tube and the graphite and will result in higher graphite temperatures.

Two other side effects of zirconium tube use are increased radiation levels due to corrosion product or film release during discharge and gunbarrel travel for contraction. These problems are pointed out to indicate how one seemingly simple change may have important side effects.

Aluminum Tube

Min. Wall Thickness 0.035"

Zircaloy-2 Tube

FIGURE 17

FIGURE 18

Reactor Process Tube Cross Sections

BEFORE GRAPHITE REMOVAL

AFTER 1/2" GRAPHITE REMOVED

FIGURE 19
K REACTOR
1-2 TRUNNION SHOWING TUBE LOCATION

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c. Nozzles, Connectors, Gunbarrels, Seals

The gunbarrel runs from outside the shield into the first tube block and protects the relatively thin walled process tube from denting and scratching, supports the thermal shield, provides part of the gas sealing surface, and helps provide some shielding; but its primary purpose is to move in and out of the reactor to accommodate the thermal expansion and contraction of the process tube. (See figures 20 and 21.) It also provides for the effective shortening of the tube, relative to the shields, due to graphite growth and contraction. The total travel of the gunbarrel is restricted by keys to limit the movement of the gas seal and connectors. It is interesting to note that the difference in water pressure between the inlet and outlet could move a free tube toward the front. Loss of the inlet gunbarrel key would transfer this load to the connector causing it to distort and possibly fail.

A Van Stone flange is formed on the ends of the process tube. The inner surface of the Van Stone flange forms a gas seal with the end of the gunbarrel while the outer end, with a gasket, forms a water seal with the nozzle. Thus, as the process tube expands due to heating, the gunbarrel moves relative to the shield. If tubes are replaced relatively frequently, the gunbarrel setting balance between expansion and contraction can be readjusted.

Long life process tubes plus the extreme graphite contraction that is predicted make the present system eventually inadequate. This is further complicated by the fact that many outlet gunbarrels are "frozen" in the newer reactors due to corrosion. On the older reactors some of the inlet gunbarrels are stuck due to graphite growth. The "freezing" of one gunbarrel halves the allowable contraction and eventually results in Van Stone failure. This in turn admits more water to the reactor, freezes more gunbarrels, etc. - a good example of a self-aggravating problem.

FIGURE 20

K Reactor Process Tube Channel Cross Section, 105-K Building

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FIGURE 21

Process Tube Channel Cross Section

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Many types of nozzles have been used on the reactors. Construction has progressed from stainless steel weldments to aluminum castings to aluminum impact extrusions. (See figures 22, 23 and 24.) The latter are the strongest and have the lowest unit cost. These nozzles provide a sealing surface for the Van Stone gasket, a connector port, a nozzle attachment and in some instances, instrument connections. Besides strength and leak-tight construction, the nozzle material must be corrosion resistant and be compatible with the gunbarrel and connector.

The K Reactor nozzles, part of the zirconium tube program, are installed with a 60 ft. lb. limit on bolting torque. This limit on bolting torque may not be desirable from the standpoint of design, safety or operation but it is a true limit that exists. Using normal tools, it is possible to tighten the four nozzle bolts to torques in excess of 100 ft. lbs. and place a load of over 50,000 psi on critical parts of the nozzle assembly. With the installation of zirconium tubes and the close fuel to tube clearances, the bolting torque becomes more critical than it has in the past. High bolting torques can result in 1) Van Stone gasket extrusion, 2) bending of the gunbarrel flange, 3) failure of the gunbarrel flange retaining ring, 4) tube neck down, 5) nozzle seat failure and 6) improper gas sealing. The gunbarrel flange bolts may be clean and oiled or rusted. A sixty foot pound torque on the former will give a maximum assembly load while the same torque on the rusted bolts will result in a minimum torque. The 60 ft. lb. limit prevents damage to components, yet provides adequate sealing for both bolting conditions.

Extrusion of the ^{aluminum}~~asbestos~~ Van Stone gaskets into the process channel can be visualized and would seriously hamper passage of the self-supported fuel. It is natural for the bolting load on the joint to drop as the gasket extrudes. This is a normal occurrence, particularly on the rear face. Present plans call for aluminum rather than asbestos gaskets on the zirconium tube assemblies.

Bending of the gunbarrel flange can be noted easily, but it does not have any serious consequences. It serves mainly to illustrate the force that can be obtained by tightening the four gunbarrel bolts.

At the six old reactors, the gunbarrel flanges were threaded on the ends of the gunbarrels. A less expensive method, and one that allows easier removal of the flanges, is the use of snap rings as in the K Reactors. The snap ring is important

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because its failure by overloading or corrosion can result in loss of the inlet nozzle and the expulsion of fuel onto the charge work platform, so the retaining ring material is carefully selected. Overloading of the joint can push the ring off the end of the gunbarrel.

High torques on the gunbarrel studs will cause the process tube to neck down at the Van Stone. This is more serious than Van Stone gasket neckdown, because it can prevent the passage of fuel elements or seriously damage the fuel element feet. The high torques can also cause a bearing failure of the Van Stone gasket seat in the nozzle. A second variable in this case is the diameter of the Van Stone. Small Van Stones give a smaller bearing area, permitting lower bolting torques to cause failure.

Tests have demonstrated the above modes of failure. Fortunately the load to failure for any of the problems described is above the 60 ft. lb. limit, but not far above and does not contain and usual factors of safety that engineers like to use. Strengthening all the components is not possible because the gunbarrel flange retaining ring groove depth, one of the possible points of failure, is fixed. Therefore, torque limits had to be established. Fortunately, these limits do an adequate job for all conditions and do contain some margin of safety.

Water is transferred from the crossheaders to the nozzles by the connectors. Many types, shapes and sizes of connectors with different end seals have been tried. The problems generally revolve around the space available, limited pressure drop (connector size) and nozzle movement.

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FIGURE 22

K Reactor Standard Inlet Assemblies

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FIGURE 23

Inlet Nozzle Assembly, B, D, DR, F and H Reactors

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One important facet of the coolant flow is the submerged cooling provided by having the outlet risers go over the top of the reactor before being discharged into the downcomer. (See figures 25, 26, and 27.) This provides assurance that process tubes are not being operated partially filled, and provides for possible back flow on a process tube. This submerged cooling feature is not particularly important at operating flows, but it is extremely important at shutdown flows. Of course, during charge-discharge the submerged cooling effect is bypassed by the crossunder line. However, additional precautions are taken during this operation to insure adequate fuel element cooling.

Elastomers are used in the process tube assembly as O-rings and boots for sealing. Unfortunately, radiation and heat tend to break down the elastomers and thereby change their properties. On the inlet face, where radiation levels are low, this is not a serious problem and such parts have a reasonable life. On the rear face, the life of elastomeric compounds is limited and the use of such materials should be avoided wherever possible. However, this is not always possible. Development work continues, but unfortunately, individual radiation and temperature tests cannot exactly duplicate rear face conditions.

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FIGURE 25

K Reactor Outlet Coolant Piping, 105-K Building

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FIGURE 26

Typical Reactor Outlet Cooling Piping With a Single Downcomer
105 Building

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FIGURE 27

Typical Reactor Outlet Coolant Piping
with Two Downcomers
105 Building

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HORIZONTAL CONTROL RODS

a. Function and Description

The horizontal control rods are the primary operating control for the reactors. The four first reactors built, B, D, DR and F had nine control rods. At H and C Reactors, this was increased to fifteen rods for better geometric coverage of the reactor. A further increase to twenty rods was made at the K Reactors. The four early reactors utilized hydraulic drives for the seven rods called shim rods, and electric drives for the two regulating rods. The last four reactors built have all electric drives.

The HCR's are not counted as part of "total control" for incidents involving emergency shutdown of the reactor. The primary reason for this is that the rods and their drives are vulnerable to damage from accidents such as earthquakes and their insertion depends on maintaining a relatively straight, unobstructed channel in the graphite. Nevertheless, the hydraulic driven rods in the older reactors and the electric driven rods in the newer reactors are provided with emergency insertion power.

The HCR's have the advantage over control splines in that they are remotely operable. Fine adjustments in position can be made during all periods of reactor operation and the rod position is indicated in the control room at all times. The control rods have a relatively long life, but repair or replacement can be a time consuming and expensive operation.

As mentioned previously, graphite contraction in the vertical direction is distorting the rod operating channels. (See figure 28.) A flexible rod tip is required to follow the distorted channels. The rod tips at B, D, DR, F and H Reactors are relatively flat. (See figure 29.) The outer rod skin is an aluminum extrusion; inside this are three aluminum cooling tubes, one supply and two return. The space between the cooling tube and the extrusion is filled with pressed and sintered rings of a boron carbide-aluminum mixtures. These tips, because of their flat shape, have more flexibility in the vertical than the horizontal direction, allow more vertical clearance, and enhance operation in vertically distorted channels.

The C and K Reactor rod tips are round, hollow aluminum extrusions with channels for packing in the control material. (See figures 30 and 31.) The K rods have two pockets while the C rods have four. In both areas a central cooling tube,

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supported by an intermittent rib, provides a coolant channel in the center of the rod. The circular HCR is less flexible than the flat HCR. Furthermore, there is less clearance and more difficulty is encountered with rods sticking in operation. To this, of course, must be added the fact that these three newest reactors are experiencing the most graphite contraction.

The HCR's as a group have several drawbacks. The materials from which they are made require cooling to prevent melting by the heat generated as the control material captures neutrons. A reliable water supply is required, and the reactor must be shut down if the cooling supply to any rod fails. The aluminum used in the rod tips must be relatively pure to reduce the residual activity of the rods for maintenance. Materials suitable for use at higher temperatures could be used in rod construction to improve corrosion resistance but these would make rod maintenance and replacement more difficult because of the higher radiation levels involved.

The sintered boron carbide-aluminum control material has good physical properties, is a good heat transfer media and can be fabricated to close tolerances. The flat rod tips require these properties. The powdered boron carbide used in the round tips is not required to have the attributes listed above. A sufficient quantity of boron must be contained in the rod tip to compensate for that burned up during the time the rod is performing its control function. Since boron gives off helium after capturing a neutron, the poison volume of the rod tip must be vented to prevent a pressure buildup.

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VERTICAL BOWING MEASUREMENTS
KW REACTOR

DRAWN ON: 6-27-63 DRAWN BY: DH FRELING

* "Half Rods" (2&6) have poison in only first $13'-8\frac{1}{4}"$ of this section.

HCR Layout

FIGURE 29

Horizontal Control Rods, B, D, DR, F, and H Reactors

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Note: Beginning 4 1/2" from tip, there is 39'-5" of poison packing in a full rod. A "half-rod" contains poison in extreme 24' 4" of this section.

FIGURE 30

K Reactor Horizontal Control Rod Cross Section

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FIGURE 31

Horizontal Control Rod Assembly, C Reactor

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b. HCR Stack Penetration

A typical horizontal control rod for the old reactors has two sections; a tip section and a rack section. The tip, or poison section, enters the reactor and provides the control. The rack or drive section, when mated with the drive motor and pinion, moves the rod in and out of the reactor. The drive is in the outer rod room where radiation levels are low to extend rod drive life and facilitate maintenance.

The rod enters the reactor block through a step plug in the side biological shield. In the original installation, the reactor gas seal was provided by a thimble that enclosed the rod tip. Thus, the rod tip was actually operating in air; it was sealed out of the reactor atmosphere. However, higher power levels and graphite distortion required removal of the thimbles to prevent melting and to alleviate sticking problems. Removal of the thimble required the installation of a gas seal at the face of the biological shield. Other locations (i.e. at the wall between the inner and outer rod room) were ruled out because the rack section of the rod does not lend itself to sealing. Actually the tip section of the rod is not ideal either because it is thermally hot when withdrawn; it gets scratched by the graphite, thermal shield and step plug and it is *not round at the five old reactors.*

The function of the seal is to prevent the loss of reactor atmosphere. Theoretically, the reactor atmosphere should be at pressure higher than that in the inner rod room to prevent the inleakage of air. In practice, this is not always possible, so in some cases, a double seal was used. By pressurizing the space between the two rod seals with CO₂ it is possible to exclude air. Some CO₂ will escape to the atmosphere and some will leak into the reactor. However, it is cheaper to pressurize 9 or 15 rod seals, and lose a small amount of CO₂ than it is to pressurize several thousand reactor seals and lose large quantities of CO₂ and helium.

During the original design of the K Reactors, the solution of the problem of an external rod seal evolved into the three section HCR; a tip section, a drive section and a seal section. The seal section can overcome the disadvantages listed earlier. It can be thermally cooled, have a mirror-like sealing surface, and be of an optimum shape for sealing. Furthermore, a seal section permits locating the seal at a more accessible joint; at the face of the wall separating the inner and outer rod rooms. It was necessary to extend the reactor gas envelope from the face of the reactor shield to the seal location using external thimbles.

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Installation of the seal section required a bigger building; the rod is half again as long and work on the tip section or its guides means disassembly of the thimble, but the improved sealing efficiency appears to override these disadvantages.

The 2X Safety Circuit inserts the rods for several conditions including trip of the 1X Safety Circuit and dropping of any one VSR. Half rods, regulating rods and rods on bypass do not scram on a 2X circuit trip. Normal rod operation is at very low speeds in either the in or out direction. This speed is variable in some cases. The deadman circuit on the rod operating switches limits rod withdrawal to one foot increments when the reactor is operating near equilibrium power levels. Scram insertion is done at relatively high speeds and is accomplished by a special drive motor.

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SPLINES

Splines help reduce startup losses, improve operating efficiency and provide more flexibility in the use of the safety systems during planned outages. In general the splines are very adaptable, the only requirement being a special inlet nozzle cap assembly and a ribbed aluminum tube.

The use of splines requires a channel under the fuel elements such as exists with the ribbed aluminum tubes. Originally this channel, and a corresponding spline groove in the inlet nozzle, were designed to facilitate fuel element removal out the front of the reactor. This feature was adapted for the supplementary control system. At the K Reactors the installation of zirconium tubes will reduce the flexibility of the spline system because only a limited number of aluminum tubes will be retained in the central region of the reactor. As yet there has been no development of either ribbed zirconium tubes of the K size nor a means of using splines with self-supported fuel.

The development of suitable water seals, equipment for disposal of irradiated splines and changes in methods of fabrication have enhanced the operating flexibility of the system. The original splines were flattened aluminum tubes filled with boron carbide and their cost was relatively ~~high~~. Leaks in the aluminum sheath caused swelling, making removal difficult and causing stuck fuel material. As the use of splines has increased, new fabrication techniques have been developed and the cost per spline reduced. Costs should be reduced even more as re-use techniques are developed.

Work is underway to provide grey (less poisonous) splines, half splines and flux traverse splines. Control flexibility provided by splines has resulted in increased production for a nominal cost. It has also brought significant personnel exposure increase. One major disadvantage of the splines is their dependence on procedural control. There is no control room indication of spline coverage of the reactor. Furthermore, operation of the spline insertion and removal equipment has, in one instance at least, resulted in nozzle failure when the front work platform was moved.

At the K Reactors, spline breakage is a major problem. These failures have been attributed to the fact that the coolant port of the inlet nozzle is directly below the spline, whereas, in the other reactor areas, the water enters on the side. This demonstrates how an apparently inconsequential difference between reactors can result in operating problems (such as scrams and outage time to retrieve broken splines).

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2 - 6 VERTICAL SAFETY RODS

a. Safety Circuit

Shutdown of the reactor for conditions beyond set limits is generally accomplished with the vertical safety rods. The insertion of these rods, dependent only on gravity once their latches are released, was chosen for fail-safe operation. The latches are also of fail-safe design, because loss of electrical power or burnout of the latch solenoids will permit the rods to drop. The IXX safety circuit utilizes two sets of closed contacts in series from the primary sensing elements such as power relays, Beckmans, Panellit, etc. The opening of any one contact will de-energize the associated IXX or IXXA relay and scram the VSR's. This is a form of parallel redundancy*. In this case, fail safe operation, i.e. rod insertion, will occur for almost any circuit contact or relay malfunction.

The VSR system strength is such that a wet, xenon-free reactor can be held sub-critical by the VSR's alone, with at least 90 per cent of the system control strength effective on demand in two and a half seconds or less. The VSR's may be scrambled into the reactor at any time, even from a partially withdrawn position. The failure or malfunction of any single rod, or group of rods, does not interfere with the operation of the remainder of the system.

b. Construction

The selection of VSR materials depends on several factors. The vertical safety rods are not cooled because heating from the capture of neutrons is limited by shutdown of the reactor, and, since burnout is low, the VSR's need contain little neutron absorbing material (1-1/2 per cent boron). Although there is little nuclear heating, the rods do have to withstand the graphite temperatures, and each rod section should be vented to prevent pressure buildup.

* Redundancy - The existence of more than one means for accomplishing a given task, where all means must fail before there is an overall failure of the system. Parallel redundancy implies two or more means are working at the same time to accomplish a given task and either can do the required job by itself. Standby redundancy applies where a second or alternate system is switched into operation when the primary device fails.

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The rod must be made of corrosion resistant materials. Early rods utilizing boron steel rusted excessively and the spread of irradiated rust particles caused radiation problems. Warping of the K VSR's due to heating is a problem indicating one type of material instability. Failure of the early H and DR VSR's may have been caused by volume change in their plastic cores, indicating another type of instability. The rod surfaces should be resistant to scratching or galling by the close fits in the step plug and graphite. Excessive scratching reduces the effectiveness, and could destroy the gas seals. The rod surfaces are also subject to a peening action as the 3X balls clatter down the channel.

There are twenty-nine VSR's in B, D, DR and F Reactors and forty-five in C and H Reactors; forty-one VSR's were originally installed in each of the K Reactors. Later, six additional VSR's were installed in extra channels, but graphite distortion has prevented the routine use of these rods.

Several types and sizes of VSR's have been installed in the reactors. (See figures 32 and 33). The B, D, F Reactors used tubular boron stainless steel rods approximately 2-1/4 inches in diameter with pinned joints. Later flexible rods with shorter sections and more flexible joints were installed to overcome distortion problems. With flexible rods, cable guides are required to keep the rod straight as it falls into the reactor.

The original DR and H rods were approximately three inches in diameter and were composite construction with a thin outer shell, a core of boron powder and a polyethylene center. The core was to thermalize the neutrons and thus make the rod more effective. Several failures of the outer shell resulted in replacement with VSR's having a relatively heavy, chromium-plated steel shell filled with cylinders of boron carbide-graphite compact.

The C VSR's, also approximately three inches in diameter, were made of tubular boron stainless steel sections with pinned joints. Boron stainless steel is expensive, requires a long lead time to procure, is difficult to machine and tends to be brittle. Therefore, its use has been largely discontinued.

The K VSR's are thick walled stainless steel tubes, approximately 2-5/8 inches in diameter, filled with boron carbide-graphite cylinders with screwed joints. The screwed joints can make disassembly difficult. Furthermore, the stainless steel is subject to scratching by the graphite and step plug, denting by the balls, and warping from contact with hot graphite. Some of the K VSR's have been given an experimental coating (nitriding) to reduce scratching and improve the sealing surface.

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As discussed earlier, graphite contraction and movement is increasing the distortion of the VSR operating channels. (See Figures 34 and 35.) In some of the reactors, this distortion is causing significant VSR operating problems. Extensive maintenance efforts such as channel broaching and the installation of more flexible VSR's are required to keep the VSR's operating.

A universal flexible VSR is now being purchased for rod replacement in all areas. This will be a B, D, F size boron stainless steel rod filled with boron carbide cylinders and having extra flexible joints. The rod has been demonstrated by test to be as effective in neutron absorption as the three-inch rods. The smaller size of these rods, plus their increased flexibility will help overcome, at least temporarily, some of the effects of increasing graphite distortion.

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FIGURE 32

K Reactor Vertical Safety Rod Diagram

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Vertical Safety Rod Structural Details

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FIGURE 34

C REACTOR

VSR CHANNEL NO. 41

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c. Operation

The VSR drives at the six old reactors consist of winches located some 40 feet above the top shield of the reactor. The VSR's at B, D, DR, F and H are attached to the winches by two cables. At C Reactor a flat steel cable is used. An electrically actuated clutch keeps the rod in the up position and when de-energized, allows the rod to fall into the reactor. As the rod falls, the cable unwinds from the drum. At approximately the half-way point in the rod travel, an orifice in the hydraulic brake attached to the winch starts to close, acting to decelerate the rod and bring it to a smooth stop at the full in position. If the brake or cables fail, shock absorbers, located on the top shield of the reactor, will stop the rod.

As with the horizontal rods, the VSR's were originally encased in an aluminum thimble which served as a gas seal. As operating temperatures and graphite distortion increased, it was necessary to remove the thimble. The sphincter seal, a long rubber boot sealed against the rod by air pressure, was developed to seal in the reactor atmosphere at the face of the top biological shield. Although the rod has a rough and hot surface, the seal acts on a round rod section and, with the air pressure back-up, it is fairly effective.

The disadvantages of the winch operated rods are 1) slow insertion speed and 2) weight of the winch. In dropping, the rod has to accelerate the winch drum in addition to overcoming the gas seal, step plug and graphite channel friction. Secondly, location of the heavy VSR winches 40 feet above the reactor requires a substantial and expensive building structure. The air operated VSR's used at the KE and KW Reactors were developed to overcome the two disadvantages listed and reduce overall system costs.

The K Reactor VSR raising mechanism can best be visualized as a large air cylinder mounted above the reactor. The top of the VSR is attached to a piston. The rod is raised by air pressure below the piston and is held in the full up position by a solenoid operated latch.

Raising air is admitted by a normally-closed (closed when de-energized) solenoid valve located at the bottom of the cylinder, along with a solenoid operated, normally-open bleed valve and orifice and a spring operated relief valve. A large, normally open solenoid exhaust valve with an orifice is

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located one-quarter of the way up the cylinder. A large vacuum relief check valve and decelerating orifice are at the top. When raising the rod, the air supply valve is open and the exhaust and bleed valves are closed. As the rod rises, air is trapped above the piston by the vacuum relief valve. The decelerating orifice controls the rod raising speed to facilitate latching. At any time in the raise cycle, de-energization of the solenoid valves will cause the VSR to drop into the reactor. When the latch solenoid is de-energized, the rod starts to drop. The vacuum relief valve opens as a partial vacuum forms above the piston. This admits air and prevents the vacuum from appreciably slowing the rod insertion. The air below the piston is vented for the first 3/4 of the rod travel, but as the rod piston passes the exhaust port, air is trapped below and the air cushion acts to stop the rod. However, at some pressure, the relief valve opens to vent the air trapped below the piston to prevent driving the rod back out of the reactor. The small bleed valve and orifice allow the rod to settle rapidly during the last foot of travel. As with the winch operated VSR's, there is a bumper at the bottom of the cylinder to stop the rod should all other controls fail.

The K VSR's require both an air and a reactor gas seal. The washer type gas seal is located at the biological shield face. Above this in the VSR housing is the air seal. The air seal prevents leakage of air into the reactor during rod raising and the gas seal prevents the loss of reactor atmosphere at all times.

The seal and graphite friction forces are similar to those at other reactors, but the pressure and vacuum below and above the piston are less restraining than the winch. Thus, air operated VSR's can fall into the reactor in 1.6 to 1.7 seconds, neglecting extreme graphite distortion, compared to 2.0 to 2.3 seconds for winch type rods. Even faster insertion, up to 1/2 second total insertion time, is possible with air accelerated VSR's.

d. Channel Sleeves

Investigations are underway to study the installation of sleeves in the vertical rod channels. The purpose of these sleeves would be to keep the 3X balls in the channel and to prevent graphite blocks from migrating into the channel. In order to install sleeves and maintain the existing channel volume, it will be necessary to enlarge the VSR channel, the hole in the thermal shield, and even the hole in biological shield in some cases. Graphite distortion has progressed to

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such an extent that the channel enlarging equipment could endanger process tubes and thermal shield cooling tubes.

A program of this type illustrates the need for constant evaluation of the reactor components. The amount of distortion and trends are necessary to evaluate the problem, provide a solution, run development tests and perform the actual work. Such data taking interrupts reactor operation for the present but is a necessary part of the long term operating requirements. This information may help predict when some action must be taken and its extrapolation permits verification tests for future operating conditions.

Sleeve materials may be polycrystalline graphite, pyrolytic graphite or ceramics. The first is readily available, but has low strength. The second has very high strength but is expensive and has not been fabricated in the required shapes and sizes. Ceramic sleeves would be of average cost and have high strength, but would have some fabrication problems, would be the most difficult to remove, and require enrichment to compensate for the poison effect. Only the first material has demonstrated properties on irradiation. One difficulty is that the required strength of the liner cannot be established precisely.

This choice between materials illustrates a common design problem: balancing first cost, operating costs, physical strength requirements, maintenance problems, etc. In most cases there is no one right answer to the problem; rather, there are several good answers each of which has certain advantages and disadvantages. After one material or solution is accepted, work continues to design around the drawbacks or overcome them by development or a re-evaluation of the requirements and objectives.

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BALL 3X SYSTEM

Shifting of the graphite moderator and partial obstruction of the VSR channels occurs slowly as graphite distortion increases. Such blockage might occur rapidly under emergency conditions such as an earthquake. Therefore, a second safety system has been provided for the Hanford Production Reactors. In order to minimize the possibility of the control medium not being able to enter the reactor, this system depends only on gravity for insertion and is fluid in nature.

The original 3X systems were a true solution - borax and water - which was admitted to the VSR thimbles. Removal of these thimbles required replacement of the system. Operational problems included,

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1) caking of the solution in storage, 2) possible boiling away of the water with a corresponding reduction in poison material dispersion and 3) leaks in the thimbles which could result in permanent reactor poisoning.

A semi fluid system utilizing 7/16" and 3/8" diameter boron steel and stainless steel balls was devised to replace the liquid 3X system. Sizing of the balls was a compromise between a small size to maintain the ability to flow into distorted or obstructed channels and a large size to prevent excessive loss in voids and openings in the graphite stack. Some considerations for selection of the ball material besides control strength were physical strength, residual activity, resistance to breaking or spalling on impact, resistance to corrosion and high temperature stability.

At the five oldest reactors, the balls are stored in hoppers located above the shield (See Figure 36). These hoppers provided for passage of the rod through their center and mounting of the rod shock absorbers. A special step plug was required with spiral chutes around the rod hole to permit flow of the 3X balls during a rod drop. Removal of the balls is accomplished with a vacuum system.

At the C and K Reactors, significant improvements were made in the Ball 3X Systems (see Figure 37). These include building of the storage hoppers into the top shield, beside the VSR step plug, and provision for removal of the balls from the bottom of the channel. Shielding of the ball flow channels through the top shield is provided by a special split section called the Dutchman's Breeches. An outlet pipe, curved for shielding purposes, runs from the bottom of the graphite stack through the reactor foundation to the room below the reactor. This ball drain pipe is closed by a diaphragm valve. There are sufficient balls stored in the hoppers to fill the drain pipes and the graphite channel. Inadvertent opening of a ball drain valve would fill the ball exit system, but this volume is small compared to the total volume in the system.

The balls are held in the hoppers by gates actuated by two independently powered solenoid latches. Each of these solenoids is on a different d-c power supply. De-energization of both solenoids is required to drop the balls. This can be classed as a parallel fail-safe redundant system; two components operate in parallel, and the failure of a single power supply or solenoid will not permit the balls to drop. Fail-safe in this instance has a somewhat different meaning than for the VSR system where a similar failure would result in rod insertion. An inadvertent ball drop, however, presents

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many serious problems and should be avoided insofar as possible. The primary sensors for a ball drop at the K Reactors are the three seismoscopes. The trip contacts from these instruments are being changed to a coincidence circuit. That is, two out of the three seismoscopes must indicate an earthquake intensity of level 4 before the 3X relays will be tripped. A similar coincidence circuit is utilized in the Beckman contacts in the 1XX safety circuit. The use of coincidence trips permits one instrument to fail or be readjusted without tripping the safety circuit. Such coincidence circuits increase operating continuity and reliability for only a very small decrease in reactor safety. Even then, the definition of safety must be precise as this term may have different meanings as were covered by "fail-safe" for the VSR's and Ball 3X System.

Graphite distortion is causing operating problems with the Ball 3X system. One problem is the loss of balls in the stack after a ball drop. The large separations that have been opened in between moderator blocks permit the balls to migrate from the VSR channels to the HCR channels. This problem is particularly bad in the lower regions of the K Reactors where the balls wedge under the HCR's and cause them to stick. Graphite sleeves are being installed in the bottom HCR channels to try to overcome this problem.

Between the upper surface of the thermal shield and the lower surface of the biological shield is a gap which is increasing as the graphite contraction continues. In those reactors with the ball hoppers mounted on top of the shield a sleeve bridges the gap. Continued graphite movement will require removing the ball hoppers and step plug and inserting a longer sleeve.

At C, KE and KW reactors a stainless steel bellows is used. The predicted graphite contraction will result in more than doubling the gap and complete failure of the bellows. Some means of bellows repair will have to be developed to insure that the balls enter the VSR slot rather than being spread on top of the thermal shield. The fact that the Dutchman's Breeches with their curved ball flow channels are cast into the shield makes repair extremely difficult. As a last resort, it may be necessary to abandon the present ball system and install new hoppers on top of the shield.

The potential problems illustrated above indicate how conditions change requiring a continual re-evaluation of systems and components to determine how they might be effected by

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the change. In this particular case, reactor safety is directly involved so a concerted effort is being made to evaluate the problem and its solutions.

The use of a control element, called the fuseable slug, which utilizes gaseous poisons has been proposed. In these fuel elements the gas is compressed into a small volume and is sealed in place by a fuseable link that melts at a high flux level. Melting of the fuse permits the gas to expand in a large chamber and increases its control strength. The disadvantages of such control elements are the difficulty in determining whether or not they have fired and the cost which would be considerable for the large numbers utilized.

FIGURE 36

Ball 3-X Safety System
B, D, DR, F, and H Reactors

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FIGURE 37
Ball 3-X Safety System,
K&C Reactors

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REACTOR SHIELDS

a. The Shielding Process

The function of the reactor shields is to reduce radiation from the reactor core to levels that will permit personnel to work near the reactor faces and prevent the activation of components and materials near the reactor faces. The three shielding components that combine to perform this function are the graphite reflector, the thermal shield and the biological or B Shield.

The basic shielding process can be thought of in four steps - scattering, capture, Gamma emission, heat removal. The graphite reflector, as its name implies, keeps many neutrons from reaching the shields; hence, its inclusion as a shielding component.

Many materials, among them cast iron, have a relatively high cross section for thermal (.025 ev) neutrons. Thus the thermal shield is able to capture most of the thermal neutrons escaping from the moderator. When the neutrons are captured, they emit energy in the form of gamma rays. Approximately 97 per cent of the heat generated by gamma radiation in the shields is released in the thermal shield.

All four steps in shielding process also occur in the primary shield. The high energy neutrons impinging on the biological shield undergo inelastic scattering by the heavy elements and the low energy neutrons undergo elastic scattering on collision with the light elements in the shield. As an example of the latter, one can think of hitting two masses together. For equal masses, one half the energy of the incident particle would be transferred to the target particles. As the target mass increases the proportion of energy lost by the incident particle decreases. This can be illustrated by comparing the number of elastic collisions with atoms of different elements required to thermalize a 2-Mev neutron.

<u>Element</u>	<u>Collisions</u>
Hydrogen	18
Carbon	114
Iron	510
Lead	1870

The table shows why hydrogen is one of the necessary constituents of a neutron shield.

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Capture of the thermal neutrons in the biological shield is accomplished by steel. All the heavy elements provide shielding for the decaying gamma rays. About three per cent of the total heat generated in the shields is released in the biological shield.

b. Biological Shield

The reactor rests on a concrete foundation. This foundation, of ordinary concrete, supports the reactor and provides shielding for the rooms and equipment below. Generally, there is an insulating layer between the bottom thermal shield and foundation. Only the K Reactors are provided with foundation cooling pipes.

The front, rear, sides and top thermal shield are surrounded by the biological shield. The six old reactors, except for the top shield at C Reactor have laminated biological shields with alternate layers of 3-3/4" steel and 4-1/2" masonite for a total thickness of slightly over four feet, four inches. The steel provides a heavy material for gamma attenuation, neutron capture, and inelastic scattering. The masonite provides hydrogen for elastic scattering.

The inlet and outlet shields are made of "B" blocks. These blocks are approximately four feet square with steel plates on each side. The process tube holes were machined to close tolerance, the blocks were laid side by side and the vertical joints welded. Tie straps, four feet high and the full width of the reactor, were then welded over the faces. The horizontal joints in the tie straps were welded only for a short section to anchor the tiers of blocks in the center of the reactor and permit expansion toward the sides. A tongue and groove arrangement was used to keep the B blocks in vertical alignment. The inlet and outlet B blocks were only approximately three feet thick including the tie strap. Sub blocks of the same laminated construction hanging on extensions of the shield tube sleeves make up the inside 16 inches of the shield. The reason for the use of slab blocks is not entirely clear, but it may have been an attempt to prevent major shield structural damage that might be caused by the higher operating temperatures of the inlet and outlet shields.

Omega seals, thin flexible carbon or stainless steel strips, were welded over the horizontal joints between the tie straps to form a gas seal. The carbon steel omega seals at the three old reactors have rusted and permit gas leakage. A foaming technique is being tried to stop the gas leaks.

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The side shields were made by first vertically lining T-shaped sections with four foot stems, then alternate layers of steel and masonite were pressed and welded into place and finally the cover was put on. The top shield was similar with the beams spanning the side shields. The bottom flanges of the beams form a continuous steel cover over the top thermal shield.

Where the shield faces join (i.e. top to side, side to front, etc.), provisions had to be made for shielding and differential thermal expansion. Stepped joints were used at the edges of the shields to prevent any direct radiation paths. The gas seal between shield faces is formed by long rubber strips clamped over the junction to each of the shields. Deterioration of these gas seals has been a problem. However, the flexibility required rules out all materials except rubber which has a limited life when subjected to radiation, high temperatures, and the reactor atmosphere.

Heavy aggregate concrete was used as reactor shielding for the first time in the top biological shield at C Reactor. Large beams, whose bottom flanges formed a continuous membrane after welding, were supported from the side shields. After placement of the step plug, the ball hopper casings and the Dutchman's Breeches, the shields were filled with heavy aggregate concrete; approximately twice the weight of normal concrete. The added weight is obtained with steel punchings and/or shot plus ore containing iron and/or water hydrides. Typical of these ores are limonite and magnetite, both of which are iron ores with water in their molecular structure.

The heavy aggregate shields must be thicker than the iron-masonite shields for the same shielding effectiveness. The top shields at the C and K Reactors are over six feet thick, partly because of shield effectiveness and partly to permit imbedding the Bali 3X System. Both types of shield construction use essentially the same elements for shielding purposes. Although the concrete shields are thicker, they are considerably cheaper to construct than the laminated shields.

The front, rear and side shields at KE and KW Reactors are made up of steel crates (forms) approximately five feet high, filled with heavy aggregate concrete. Any penetrations are welded to both faces of the crate. In addition, there is considerable cross bracing to support the two steel plates that form the faces of the crates. After welding the joints between the crates, they are filled with heavy aggregate concrete. The side shields extend around the corner to the front and rear faces. A special radiation labyrinth provides shielding and permits movement of the two shields. A rubber gas seal is installed over the labyrinth. Cooling is provided by pipes, imbedded in lead channels on the inner face of the top and side biological shields

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at the K Reactor and the top biological shield at C Reactor. The top cooling pipes run from side to side on the reactor and the side shield cooling pipes run front to rear.

All openings in the shield require special provisions for shielding. For access holes, test holes, etc., the step plug is generally used to prevent direct radiation paths through the shield. By using large steps the tolerances on the sleeve and plug dimensions can be reduced to facilitate the removal and insertion of these heavy cumbersome objects. The early step plugs were of laminated construction similar to the shield, but recent plugs have been made more cheaply by using welded steel shells filled with heavy aggregate grout.

There are cases where steps cannot be used for shielding; for example, the VSR's and HCR's must move through the step plug. Close fits are required to narrow the gap or annulus through which radiation could stream from the reactor core. Streaming is minimized because of the random motion of neutrons. As a general rule, the closer the fit between the two parts the shorter the annulus required. For maximum effectiveness, the limited length, close fit shielding annulus should be in the outer third of the shield.

Shielding of the process tube gunbarrels is another special case. (See figure 20.) Provision has to be made for slow, limited horizontal movement of the gunbarrel due to thermal expansion of the process tube. Vertical and horizontal flexibility must be provided to accommodate graphite growth. This is accomplished with the donut train on the process tube assembly. A steel sleeve, running through the biological shield, is welded to the inner and outer steel cover plates. The gunbarrel fits inside the sleeve and the space between is filled with cast iron donuts which are short right circular hollow cylinders. At all reactors except KE and KW, the innermost donut has a larger outside diameter than any of the others to provide a typical shielding step for the ID of the shield sleeve. The shield sleeve is counterbored to receive this large donut which is tack welded in place. The clearance between the OD of the gunbarrel and the ID of the donut ranges from .2 to .33 inches depending on the reactor. The remaining donuts alternately fit tightly to the OD of the gunbarrel and the ID of the shield sleeve with the clearances being reduced toward the face of the shield. A step is provided in the gunbarrel at the start of the outermost donut to provide a step shield for the outside diameter of the gunbarrel. The last donut fits the shield sleeve tightly and has approximately 0.1 inch radial clearance with the gunbarrel at all reactors except K which has a tight fit on both diameters. The donuts are held in the shield sleeve by the centering flange attached to the face of the reactor.

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Some interesting points on the donut shield are that the alternate gaps between the gunbarrel and shield sleeve permit vertical and/or horizontal movement of the innermost end of the gunbarrel. At the six old reactors, all but the innermost donut can be removed by removal of the centering flange. The close fits between the components do permit some axial movement of the gunbarrel. However, the materials are subject to rusting and these same close fits can be rusted shut resulting in stuck gunbarrels. This in turn puts additional stress on the process tube and its Vanstones. Failure of the Vanstone flange allows more water to enter the reactor, more rusting, more failed Vanstones, etc. This is one reason gunbarrels should be "freed up" when process tubes are replaced.

Donut type of construction is relatively expensive and cannot be justified for corrosion resistant materials having adequate shielding properties. Therefore, the use of a tapered bore shield sleeve with large ID at its innermost end and a tight ID at some point one to two feet from the outer face of the shield has been considered. Such a sleeve provides for the flexibility of movement of a donut train with only a slight reduction in shield effectiveness. At N Reactor, sleeves of this type were rolled directly in the shielding crates. This type of construction greatly reduces the cost for flexible shielding penetration.

Before leaving the subject of shielding, it should be mentioned that the water in the process tube has a shielding function. Without the scattering that occurs in the water, a direct beam could emanate from the reactor core.

Cooling of the biological shields has been discussed briefly. Only three per cent of the heat generated in the shields is in the biological shield. At the old reactors, heat is transferred by conduction through the shield to its inner and outer faces where heat is transferred to the air and to the thermal shield. Cooling tubes were provided for the heavy aggregate concrete shields. High temperatures in the shields will cause a loss of the hydrogen. The masonite chars and the concrete dries out, both of which cause a reduction of shielding effectiveness and may have structural repercussions. The shield temperatures can be reduced by poisoning the fringes of the reactor, to reduce the neutron flux incident on the shields.

The inlet and outlet biological shields are cooled by the water in the process tubes. Because of the annular gaps in the donut system, the heat transfer path is rigorous. All reactors except B, D and F have an aluminum reflector between the biological and thermal shields to reduce heat transfer between the two shields.

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Construction of the shields was a demanding task. The holes in the B blocks and crates had to be accurately spaced to match the holes in the moderator and required special welding procedures to control the spacing between adjacent blocks. After the front, rear and side shields are erected, accurate location measurements are made to permit tailoring of special filter layers of the moderator to insure alignment. In some instances, the moderator was stacked high or low relative to the shields to compensate for expected graphite growth and contraction.

c. Thermal Shield

The thermal shield is a cast iron box that encloses all six sides of the graphite stack. The iron is approximately ten inches thick on the front, rear and bottom and eight inches thick on the top and sides of the reactor. The shield is made up of many small blocks with stepped, overlapping edges. The small size makes handling easier and limits the effects of thermal expansion and the steps prevent radiation beams between the joints.

The bottom cast iron blocks were machined flat to a closely controlled elevation to provide the surface on which the graphite moderator was stacked. The side cast iron blocks are supported from the inside surface of the biological shield. The top cast iron is laid directly on top of the moderator.

The bottom, top and side shields have slots cast in the blocks for the lead embedded stainless steel cooling tubes. Thermal expansion and sealing are provided by bellows and packings at the face of the biological shield. The low melting point of the lead is the limit on shield operating temperatures. On the top of the reactor, the weight of the cast iron blocks tends to permit the lead surrounding the cooling pipes to creep thus further decreasing and perhaps eventually destroying the cooling system's effectiveness.

The inlet and outlet cast iron blocks are supported by the gunbarrels and must be placed as the moderator is stacked. Cooling is provided by process water and heat transfer through the process tube and gunbarrel. Because of the rather poor heat transfer path and the higher temperature of the outlet coolant, the outlet shield tends to run hotter than the other shields. Not all the heat generated in the thermal shield comes from gamma decay. Some quantity heat is transferred to the shield from the graphite and may be transmitted to or received from the biological shield depending on the temperature differen-

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tials. However, these heat gains and losses are not large compared to that generated by gamma decay.

The inlet and outlet blocks at B, D and F Reactors were a single piece ten inches thick. These blocks are held against the graphite by pins which bear on the inner surface of the biological shield.

At the other reactors, the inlet blocks are 1/2 the thermal shield thickness stacked in two layers. The thinner blocks were easier to handle and present a cooler surface to the biological shield because the innermost blocks run hottest; however, the primary reason for the half-blocks was cost reduction. Full thickness blocks require the casting of steps. Half thickness blocks can be cast plain and the steps obtained by sizing and moving the location of the support hole.

There is nothing at DR, H and C Reactors to keep the cast iron thermal shield blocks against the graphite and they could move to partially obstruct the gas plenum. The blocks at the K Reactors are kept in place by keys along the top and bottom.

There are 1/8 to 1/4 inch nominal gaps between the blocks to allow for thermal expansion and reduce fabrication tolerance requirements. The removal of a gunbarrel at the six old reactors will therefore permit that thermal shield block to drop. If too many blocks in a column drop, it may be difficult to get the top gunbarrel in because of misalignment and the weight of blocks above may prevent insertion of the bottom gunbarrel. This problem does not exist at the K Reactors because the keys span adjacent blocks and limit the total drop to a single gap width.

The selection of cast iron for the thermal shield was based on several considerations. Cast iron has good thermal conductivity, is relatively stable under irradiation and has a fairly good capture cross section for thermal neutrons. However, its primary advantage was ease of fabrication to the shapes and tolerances required and a relatively low cost. At the time the original reactors were built, its immediate availability may also have been an important factor.

Better materials are available for thermal shields. The N Reactor utilizes boron steel plates one-inch thick with the cooling tubes welded in place. This material has all the assets of cast iron plus a lower potential cost. With a 1-1/2 per cent boron inclusion, only a one-inch thick thermal shield is required. This means other cost reductions such as smaller biological shield, shorter rods, etc.

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CONFINEMENT SYSTEM

a.. Function

The confinement system provides for confining the fission products that might be released from a reactor during a nuclear incident. It is important to note that this is a confinement rather than containment system. The familiar total containment sphere is not utilized. The confinement approach is necessary because of the massiveness of the Hanford Production Reactors and the fact that containment vessels must be built before or with the reactor.

The objective of the confinement system is to restrict the flow of the ventilation air to definite paths and to exhaust it through the filters before its release from the stack. (See figures 38, 39 and 40.) To achieve this objective, two general principles were used to develop the system: 1) the confinement zone is maintained at a pressure slightly less than atmospheric, and 2) the exhausting equipment is designed to provide the highest feasible degree of reliability.

The negative pressure insures that air leakage is into the confinement zone and all air leaving critical parts of the building will pass through the filtering facilities. The confinement zone in the reactor buildings includes all areas adjacent to the reactor block: the discharge area, work area, top of the reactor, X-levels, inner rod room and the tunnel leading to the exhaust fans.

The quantities of air exhausted vary from 85,000 to 150,000 cfm for the various reactor buildings or zones.

System reliability is accomplished by 1) a separate power supply to drive the emergency exhausting equipment, 2) automatic controllers for this emergency power supply and for the ventilation dampers, and 3) emergency power-driven pumps to furnish water to the fog spray.

b. Components

The basic features of the confinement facilities are:

1. A dense, finely atomized water spray system (fog spray) within the rear face enclosure of each reactor.
2. A filtering facility to remove a high percentage of all particulate matter and most of the halogens from the exhaust air.

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3. Instrumentation to monitor, record, and where necessary, control critical equipment to insure passage of the exhaust air through the filter building.

The fog spray is designed for automatic or manual operation with the following purposes:

1. Absorb a portion of the halogen vapors released during a uranium fire.
2. Settle out a portion of the airborne particulate matter released during fuel element fires.
3. Wash down exposed surfaces within the rear face enclosure for removal of contaminated particles.
4. Provide some degree of cooling of exposed fuel elements.
5. Condense steam that may be formed to prevent unnecessary pressure buildup within the area.

A scintillation detector system continuously monitors the reactor building exhaust air and actuates the spray system whenever radio-iodine is detected in the exhaust air stream. The fog spray system is effective in: 1) reducing spread of contamination, 2) reducing airborne contamination during periods of reactor maintenance and 3) cooling exposed irradiated fuel. During a recent incident that involved the partial burning of an irradiated fuel element, there was no detectable spread of contamination to ventilating equipment downstream of the rear face enclosure, although before the installation of the fog spray, similar incidents had resulted in noticeably greater radiation levels emanating from this exhausting equipment.

The filter building is of reinforced concrete construction and is almost entirely below ground. (See figure 41.) Although the normal radiation activity on the filters should be quite low, the underground installation was used since earth is cheap shielding, the building and associated ductwork would cause less hindrance to movement of vehicles and personnel within the area, and abandonment, in place, would be simpler should this ever become necessary.

The filters are housed in the two cells of the filter building, either of which can be isolated by means of water seal pits, from the exhaust air flow for filter replacement. Both cells have provision for three banks of filters in series and each bank is composed of two structurally integral halves. Each

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integral unit consists of an aluminum frame holding from 24 to 40 individual absolute or activated charcoal filters rated at 1000 cfm each. (See figure 42.)

The original design proposed three banks of filters in each compartment, namely, roughing filters, fine or "absolute" filters, and halogen collectors. As a result of filter life tests, it was found that the roughing filters added little to the effectiveness of the system and were nearly as expensive as the absolute filters. This, with the development of a method for testing the filters in place, eliminated the need for such filters.

The filters are rated for emergency operation at 200 F and a relative humidity of 100 per cent for a period of two hours without loss or decrease in filtering efficiency. The halogen removal filter consists of filters whose filter media is a bed of activated coconut shell charcoal one inch in depth.

All the filter banks are designed so that normal filter replacement can be accomplished by a portable crane and without the need for access to the interior of the cells. In order to prevent the spread of contaminated particulate matter, an exhaustor is provided to create a positive sweep of outside air into the cell and through the cell in service when the cell covers are removed. After isolation, the selected frame of filters is withdrawn into a plastic bag and transported to the disposal ground for disposal of the filters and recovery of the frame.

While the probability is very low, an incident involving several tubes of fuel elements would no doubt contaminate the filters to the extent that immediate replacement would be impossible. Although the incident itself would not dictate immediate replacement of the filters since they are well shielded, the pressure drop through the filters may be great enough to make continued operation of the ventilation system untenable and a decision would have to be made to replace the filters or construct a new filter building. To provide for this possibility, the filter building design has included means for making an extension and space has been reserved for a possible new building.

Because the confinement facilities were added to existing buildings, maximum use was made of existing facilities and equipment. During normal operation air is supplied to the ventilated areas of the building by two supply fans. (See figure 45.) This air passes over the reactor block surfaces and is drawn into a common plenum on the suction side of the exhaust fans. This flow path, plus the air balancing, was designed to induce ventilation flow to increasingly more contaminated zones. Modifications

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to the ventilation system were as follows:

1. The exhaust fans were upgraded to maintain the same general volume of air flow but at an increased static pressure (approximately six inches water gage) caused by addition of the filter facility.
2. Ventilation barriers were installed and the ventilating system was balanced to maintain the confinement zone pressure slightly less than atmospheric pressure.
3. Alarms were provided to warn operating personnel of any significant change in ventilation balance.
4. Dependable emergency power, either steam turbine or diesel engines, was provided to drive the emergency exhaust fans in the event normal power was lost.
5. Instrumentation was provided to automatically shut down the supply fans in the event of a reactor incident to insure that zone pressures are maintained negative with respect to atmospheric pressure.

The confinement system instrumentation includes provision for measuring system flow, pressure and radioactivity, activation of the fog spray and fans, and alarms in the control room for off-standard conditions.

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FIGURE 38

Confinement Facility Layout, B, D, and F Reactors

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FIGURE 39

Confinement Facility Layout, C Reactor

FIGURE 40
K Reactor Confinement Facility Layout

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FIGURE 41

Reactor Confinement Filter Building

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FIGURE 42

Typical Filter Bank Arrangement

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FIGURE 43

Reactor Confinement Flow Diagram

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GAS SYSTEM

a. Function

The purpose of the reactor gas atmosphere is to provide an inert, non-radioactive environment in the reactor, to remove moisture and foreign gases from the reactor in order to prevent graphite burnout, to serve as the heat transfer media between the graphite and process tubes and to detect water leaks within the reactor. To perform these functions to control graphite temperatures and to meet reactivity requirements mixtures of helium and carbon dioxide or nitrogen are used.

The provision of a reactor atmosphere, disassociated from the fuel element coolant, is a design feature that is peculiar to most graphite moderated tube type reactor. Exceptions to this rule are the British production (Windscale) and power (Calder Hall et. al.) reactors that use air and CO₂ respectively primarily for a fuel element coolant and secondarily as a moderator atmosphere.

The "Windscale Incident" illustrates the need for an inert reactor atmosphere to prevent graphite burnout. During irradiation of the graphite moderator, collisions between high energy neutrons and the graphite atoms cause some of the latter to be displaced from their normal location in the lattice. This reaction takes place at relatively low temperatures and results in the storing of energy in the graphite. In order to release this stored energy, the Windscale reactors periodically underwent thermal annealing during which the graphite temperature was raised to release the stored Wigner energy. The annealing reaction continued on a more or less self-sustaining basis until most of the energy was released. By using air as a coolant, the British were supplying oxygen to the hot graphite and in effect "caused" a fire. This is an extreme case of graphite burnout.

The Wigner effect was once a potential problem in the Hanford reactors. However, since the graphite operating temperatures have been increased, the stored energy is released during the normal operating cycle and special annealing runs are not required.

The reactor atmosphere should not react with the graphite moderator at any temperature. One of the worst foreign materials, oxygen, leaks into the reactor as air or results from the disassociation of water or carbon dioxide. At high graphite temperatures, the free oxygen reacts with the graphite forming carbon monoxide. Thus, atoms of graphite are removed from the reactor.

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This mechanism is called "burnout" and has to be restricted to very low values over the life of the reactor in order to insure that the moderator will retain its structural integrity. Thus, oxygen and water vapor are two of the gases that must be kept below specified concentrations during reactor operation.

Impurities must be kept out of the reactor to prevent poisoning of the reactor and to reduce hazards to operating personnel. Xe₁₃₅ and BF₃ are not suitable gases for a reactor atmosphere because they have high cross sections.

The argon in the air becomes radioactive on irradiation and its subsequent leakage from the recirculating gas system could cause personnel exposure problems. There are other gases that must be ruled out as reactor gases for the same reason.

The reactor atmosphere enters the reactor at the bottom front in the space between the thermal and biological shields and flows to the rear of the reactor through the graphite block chambers and other openings. Flow paths under, above and beside the reactor core are blocked by baffles. At the bottom rear of the reactor, the gas is collected to return to the blowers, etc. The circulating reactor atmosphere will pick up moisture on its trip through the reactor, thus it can be utilized for removing water from the stack. Instrumentation permits the detection of moisture in several of the vertical plenums that are formed between the rear thermal and biological shields.

Since there are numerous gaps in the heat transfer path, the heat transfer properties of the gas have a considerable effect on graphite temperatures. Of all the gases, helium has the best heat transfer coefficient, so its use results in the lowest graphite temperatures.

Aside from the problem of graphite burnout, the most pressing problem with the reactor gas system is operating cost. Leakage, purging and composition changes all result in helium loss. Since helium is a relatively rare and expensive gas, many techniques have been devised to reduce its consumption. Helium is a hard-to-contain gas when compared with other gases because its relatively small molecules can flow through openings that would stop other gases.

For the Hanford Production Reactors, the gas system protects the moderator. In NPR, the reactor atmosphere must also protect the zirconium process tubes from hydrogen embrittlement by maintaining the oxide film on the OD of the process tube. At the present operating temperatures, hydrogen embrittlement of the zirconium tubes in KE and KW Reactors will not be a problem.

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Very briefly, the recirculating gas system consists of distribution ducts, circulating gas blowers, silica gel dryers, filters, heat exchangers, vacuum and pressure relief seal tanks, instrumentation valves, and piping. Makeup gas comes from storage tanks and excess gas is vented to the atmosphere via the stack. On its trip through the reactor the gas is heated, picks up moisture, is diluted by the leakage of air at the seals and is lost through leaking seals. Only 0.02% of the heat generated in the reactor is removed by the gas system, so only small heat exchangers or condensers are required for heat removal. Moisture is removed from the recirculating gas by adsorption in the silica gel drying towers. When the water removal capability of a drying tower is exhausted, it can be regenerated by the circulating hot gas through the silica gel. Solid impurities are removed by the filters. Gaseous impurities not removed by the silica gel are controlled by continuous makeup and bleed from the circulating stream.

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