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NUCLEAR METALLURGY LECTURES
CHAPTER 4

AUTHOR

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NUCLEAR METALLURGY LECTURES
CHAPTER 4

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NUCLEAR METALLURGY LECTURES . CHAPTER 4

PILE COMPONENTS

INTRODUCTION:

A reactor is essentially an assembly in which a controlled nuclear reaction is carried on.

There are several ways to classify reactors:

- A. By the type moderator used.
- B. By the speed of neutrons.
- C. By the manner of fuel dispersion.
- D. By the purpose of the reactor.
- E. By the type of coolant.

Most commonly used moderators are graphite, heavy water or light water although light gases, hydrogen, helium might be used. The energy of the neutrons used for fission is often used as a method of classification. Neutrons of energy below 0.1 ev. are referred to as thermal neutrons; intermediate or resonance neutrons have an energy from about 1 to 1,000 ev; and neutrons with energies greater than 1000 ev are generally classified as fast neutrons. If the fuel and moderator are intimately mixed, the reactor is referred to as homogenous reactor, whereas, a heterogenous reactor is one in which the neutrons are in form of lumps or discrete particles imbedded in the moderator. The A.E.C. further classifies reactors as to purpose, i.e. power reactors, production reactors, breeders, etc.

Reactors are sometimes given sub-classification as to the coolant used to remove the heat of fission. Most common coolant systems are water and heavy water, or liquid metal. Smaller reactors often use gas as a coolant.

At Hanford, of course, we have a graphite moderated, water cooled production reactor using a heterogenous fuel system.

GRAPHITE:

Graphite was chosen as the moderator for Hanford piles because of the ease of handling as contrasted to other moderating material. The stack is made of interlocking graphite blocks penetrated from front to rear for fuel channels; from near to far for horizontal control rods; and from top to bottom for vertical safety rod channels. A typical tube block stack is shown in Figure No. 1 for one of the old piles and in Figure No. 2 for K Pile.

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Figure No. 1

TYPICAL OLD PILE STACKING ARRANGEMENT

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Figure No. 2

MODIFIED GRAPHITE STACK (C AND K
PILES)

Note: Floating Tube Block, Trun-
nion Blocks, and Overbore
Tube Channels.

It is noted in Sketch No. 2 that the tubes are essentially floating, and that a gas gap exists in between the tube and the graphite blocks. This gas allows the graphite to heat more uniformly and decreases the possibility of growth problems.

Graphite growth was a problem that at one time threatened the pile life. When the graphite is maintained at relatively low temperatures a growth phenomena associated with crystal structure is encountered. It was discovered, however, that by heating the graphite to temperatures above 350 C that this growth phenomena was reversed and indeed that previous graphite growth could be annealed out. Temperatures were normally considerably below 350 C at the low powers encountered during early Hanford operation. This was largely due to the use of He as a pile atmosphere circulating through the graphite. The helium is a relatively good thermal conductor and the gamma heating in the graphite was insufficient to raise the maximum temperature above 200 - 250 C. It was discovered, however, that by using CO₂ as a pile gas, the graphite would heat considerably more and sufficiently to gradual anneal out the damage. It was also feared that energy stored in the graphite by irradiation, measured as much as 600 cal/g, might be released in a surge if the graphite become over-heated. This fear was shown to be baseless, however, as the graphite energy release was not autocatalytic as feared, but with heating reaching a peak around 200 C and gradually decreased.

Today the situation is somewhat reversed from the initial graphite problems encountered. The CO₂ as a pile gas is now gradually being replaced by He as increased powers of operation are encountered. At the elevated graphite temperatures now encountered, graphite burnout, CO₂ / C — 2 CO, becomes a problem, and rather than endanger the stack life, larger percentages of helium are being used. The growth and distortion problem may actually become one of shrinkage as tube powers and graphite temperatures are increased. A further problem that may be encountered are water gas reactions resulting from process tube water leaks.

The graphite is most important to the economy of Hanford irradiations. Of 100 thermal neutrons, approximately 9 are absorbed in the graphite at the old piles. In K Pile where the graphite to metal ratio is decreased this loss is slightly less than 8. As the temperatures in the graphite are increased these losses decrease since the metal resonance capture increases while the graphite cross-section for higher energy neutrons decreases. The losses in graphite at 500 C are probably 10 - 15 per cent lower than those encountered at low temperatures. Such gains do not represent a net gain, however, since the 240 isotope level is probably increased with increasing temperatures.

About six per cent of the total heat generated in the pile is generated in the graphite and must be transferred to the coolant. This heating is largely due to gamma heating from the fission products of uranium. Where aluminum alloy fuels are used instead of uranium, the heating is increased roughly fifty per cent since alloy elements absorb only a small fraction of the gamma irradiation. Greater graphite distortion and damage seems inherent to alloy fuel loads, such as the P-10 load at DR. Such loads from a production standpoint should be charged where flux is high and irradiation rates are maximized. However, this is exactly opposite to best graphite practices that would prefer uniform heating over the whole pile and can secure such uniform heating only by charging fringe areas with alloy fuel slugs.

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Water must be kept circulating through the pile for at least several hours after the nuclear reaction has stopped. Although this is largely to keep the metal cool, the graphite also cools slowly with a period of about one and a half hours.

SHIELDING

That the pile must be covered with protective outer layers is obvious when it is considered that the total ionizing power of the radiation produced in the pile is equivalent to several hundred tons of radium.

The reflector, a graphite block surrounding the tube blocks turns back most of the neutrons and absorbs most of the gamma rays entering it. The thermal shield, a cast iron block approximately 10-1/2" thick, outside of the reflector, reduces the energy of entering particles 99.6 per cent. The rate of energy release in this shield is approximately 1 MW and cooling is provided.

To bring the level of radiation outside of the pile down to a safe level for personnel, the biological shield is provided. In the old piles this shield is composed of alternate layers of masonite and steel to a depth of four feet.⁽¹⁾ In K Pile, an ingenious change in construction was effected by using a concrete aggregated composed largely of iron ore. The highly hydrated structure slows by elastic scattering and the heavier iron molecules by inelastic collision.

PROCESS TUBES

Process tubes are aluminum tubes extruded with internal fins or ribs for fuel support. They extend the length of the pile and are connected to water supply by a flanged fitting to the nozzle. The diameter and annulus size have been increased for the newer piles, C and K. The tube is primarily 2S alumium but contains a 5 mil inner coating of 72S Aluminum which is co-extruded with the 2S. Some of the pertinent dimensions given are in Table No. 1.

TABLE NO. 1

<u>File</u>	<u>B, D, DR, H, F</u>	<u>C</u>	<u>K</u>
o.d. (in)	1.729	1.784	1.806
Horizontal i.d. (in)	1.611	1.646	1.686
Vertical i.d. (in)	1.598	1.633	1.673
Min. Wall Thickness (in)	0.055	0.055	0.056
Height Rib (in)	0.086	0.102	0.120
Angle Between Ribs	90° C	90° C	90° C
Thickness of 72S Layer (in)	0.0055	0.0055	0.008
Length Between Flanges	41'-7"	41'-7"	47'-2"

— Cont'd. on page 7 —

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TABLE NO. 1 (Cont'd.)

<u>File</u>	<u>B, D, DR, H, F</u>	<u>C</u>	<u>K</u>
Annular Area (in ⁻²)	.351	.431	.519
Typical Flow (GPM)	31	44	50
After Water Plant Expansion	40	44	50-58

The rib design is calculated to support the 1.440 inch fuel element symmetrically in the water annulus.

Tube corrosion can be a "localized" or "pitting attack" which often occurs at the lower temperatures in the front of the tube, or "uniform" at the higher temperatures encountered downstream. The 72S layer corrodes preferentially and until it has been consumed, largely prevents pitting damage. The so-called "uniform" corrosion rate increases with the outlet water temperature and roughly doubles with every 10 C increase. A tube leak can be far more costly than a slug failure since the water that penetrates to the graphite packing has three deleterious effects:

- (1) Valuable reactivity is lost.
- (2) External tube corrosion is initiated in which it is relatively impossible to generalize individual tube damage.
- (3) Graphite burn-out from water gas reactions may be sufficiently serious to cause concern.

It then becomes obvious that a tube replacement program is essential where corrosion rates are sufficiently high to penetrate the tube in a finite period of time. Tube replacement is costly, and were no other factor limiting, continually increasing the tube powers and bulk water temperature would result in a tube replacement so high that it would no longer be economically feasible, since the increase in production would not be worth the higher production costs from tube replacement.

With present corrosion rates, a bulk outlet water temperature of 105 C seems to be near the optimum point of operation. Such an outlet water might require tube replacement every four years. If this evaluation is realistic, then there is considerable incentive to either:

- (1) Find a new tube material that does not corrode as rapidly, or
- (2) To adjust water treatment to lower the corrosion rate.

The problem is being approached from both angles; but probably most promising are indications that the corrosion rate may be decreased by lowering the pH of the coolant.

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Raw Water Backup

B, C, D, WATER PLANT

K WATER PLANT

NOTE - TRANSITION TO PROCESS SPECIFICATION
FIGURE NO. 3

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The aluminum of the process tube absorbs some of the thermal neutrons, but the loss is small as compared to coolant and graphite losses.

COOLANT

Introduction:

Water supply facilities and water treatment have undergone considerable transition since the original plants were built under war stress by DuPont. For instance, the physical plant for B, D, F included four pumping stations backed by a steam turbine, whereas the K facility has only two pumping stations, as shown in Figure No. 3. The original treatment plant for B, D, F included a raw water reservoir, chemical treatment building, mixing chamber, settling basin, filters, clear wells, de-aerator, demineralizer, refrigeration, storage tanks and high tanks. All of these facilities have been eliminated at K with the exception of the filter plant and clear well.

Short Description of the DuPont Design:

Three of the reactors, B, D, and F were designed and built by DuPont during the war years. These three plants are in general very similar, although they do vary in some aspects. In general, the design used consisted of a pump house where water was screened then pumped to a raw water reservoir of about 20 million gallon capacity. Provisions were made to add chemicals at the reservoir to kill algae and small fish. From the reservoir the water was pumped to the chemical treatment building. Here chlorine, to make up for losses from the water due to evaporation, the coagulant ferric sulfate, and lime were added. The water with the treatment chemicals was then passed into mix chambers and settling basins, through the filters and then by gravity flow into clearwells. After filtration, sodium silicate in quantities of at least 5 ppm was added to inhibit film formation and sodium dichromate in the quantities of 2 ppm was added for corrosion inhibition. These chemicals, sodium silicate and dichromate, were added to the water as it was being pumped from the clearwells to the deaerator. Each area was equipped with facilities for deaerating the water. However, these deaeration facilities were never used. In two of the areas, B and F, there were also facilities for refrigerating a portion of the flow. Likewise, these facilities were never used. In addition to this one of the areas, D, even had facilities for demineralizing the water. Two-bed demineralizers were provided with sufficient capacity to demineralize the entire process water stream. These demineralizers would have supplied water essentially as pure as distilled water. This facility was never used.

The water with chemical addition was pumped from the clearwells to water storage tanks of large capacity. These tanks fed the suction of the main process pumps. The process pumping system consisted of 10 sets of steam driven pumps and electrically driven pumps coupled in series. The water from the pumps flowed directly to the reactors and from the reactors through the effluent lines to retention basins. The retention basins were provided to allow decay of the radioactivity of the effluent water before it was returned to the river.

Changes in the Physical Plant:

After General Electric assumed operation of Hanford, it appeared that the D Pile would have to shut down because of graphite damage, and plans were made to construct a replacement pile. Originally it was planned to use the D plant water system to supply the replacement reactor. However, when it was found that D Pile could be continued in operation a second water plant was built. The D plant river pump house was enlarged so that no

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new pump house was constructed. Also facilities were made to pump some water from the D Pile raw water reservoir to the DR filter plant and no new reservoir was constructed. Another feature of the new plant was the elimination of the large storage tanks supplying the process pumps. In DR plant the clearwells and the storage tanks were combined and the process pumps actually take their suction from the clearwells.

H Pile, the first pile built in an entirely new area is quite similar to the old areas. The largest change at H was to decrease the size of the raw water reservoir by a factor of two.

When C Pile was built the raw water reservoir was completely eliminated, thus also eliminating one set of pumps. Furthermore, filtered water is pumped directly from a small filtered water reservoir into process pump supply tanks thus doing away with the clearwells.

A major change in physical plant philosophy was made in the design of K Areas. With this design water is pumped from the river directly to the filter plant, flows by gravity through the filters and into a clearwell. The process pumps take their suction from the clearwells and pump the water through the piles.

Change in the Chemical Treatment:

This section will be organized by considering each phase of the original process water treatment and describing any changes that have been made. The first step in the original water treatment process was the addition of chlorine at the raw water at the reservoir. This chlorine addition was made continuously. Experience has shown that the continuous chlorine addition at this point is not necessary and current practice is to add chlorine intermittently at about monthly intervals.

In the original treatment, ferric sulfate was added to the water as a coagulant. Experience at the Chicago Municipal water treatment plant showed that if aluminum sulfate (alum) were added as the coagulant higher flow rates through the filters could be obtained. Experience there also showed that if alum were used, during part of the year it was also necessary to add activated silica as a coagulation aid. On the basis of this, it was decided to evaluate the alum activated silica process. With the ferric sulfate process one of the most serious pile operating problems had been deposition of a film on slug and tube flow surfaces. This film consisted primarily of colloidal iron particles and becomes sufficiently thick to reduce water flow rates appreciably. The piles had periodic purges in which bentonite slurries were pumped through the tubes to remove the film. When the alum process was adopted the first significant effect noted was the cessation of this film formation. In fact, the film which had previously been deposited by the ferric sulfate treated process water sloughed off. In addition to this, experience at Hanford confirms the Chicago experience in that appreciably higher filter flow rates were possible. For example, the B, D, and F treatment plants were designed for a total flow of 30,000 gpm on the basis of the ferric sulfate process. When the alum activated silica process was adopted it was possible to increase flow rates to 71,000 gpm without constructing additional treatment facilities. Likewise the H treatment plant was increased in capacity from 40,000 gpm to 81,000 gpm and the C plant from 80,000 gpm to 105,000 gpm. In addition to this the K Plants were designed on the basis of higher flow rates obtainable with the alum activated silica process. By doing this fewer filter units were required and a capital cost savings of roughly \$10,000,000 were obtained. Though Hanford did not originate this alum activated silica process, it is a generally accepted fact that Hanford now leads the country in the development of extremely high filter rates.

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Originally hydrated lime was added to the water with the coagulant before the water was filtered. The lime was added to maintain the process water pH in the range 7.5 to 7.8. When the alum activated silica process was adopted the point of lime addition had to be changed to the filter effluent flume. This was necessary because the coagulation efficiency of alum is greatly decreased at pH's much over 7.4. Later studies had indicated that changing the point of lime addition may be largely responsible for the reduction in film formation obtained with the alum-activated silica process. It has been shown that the post filtration addition of a base causes a secondary coagulation of the impurities in the water. The resulting relatively large particles do not have a tendency to deposit out and cause film.

By the time that the K Plants were constructed, studies had shown that no detrimental effects occurred if caustic soda was used as the base instead of lime. The use of caustic soda tends to reduce the sludge deposition in the clearwells which was present when lime was added. Also about \$400,000 was saved because caustic soda facilities are much simpler and cheaper than lime addition facilities.

In the original process, sodium silicate was added to inhibit the formation of the film. Early studies undertaken after General Electric took over showed that this addition was not necessary and this phase in the treatment process was eliminated.

One of the most expensive treatment chemicals originally specified was sodium dichromate. This chemical was added because it was believed that the dichromate effectively reduced certain types of aluminum corrosion. On the basis of some tests conducted in 1951 it was believed that the addition of dichromate was unnecessary. For this reason dichromate addition was stopped. Subsequent experiences showed that the addition of dichromate had indeed been effective in reducing localized corrosion attacks on the aluminum. When the dichromate was removed from the water severe pitting of aluminum slug jackets occurred causing slug ruptures. Also penetration of some of the process tubes occurred resulting in leakage of water into the pile graphite. Because of this, the addition of dichromate was reinstituted in 1952. Present studies indicate that the amount of dichromate added may be reduced without damage to the piles. By reducing the amount of dichromate, savings on the order of \$200,000 per year may be effected.

In addition to the changes already made as described above, investigations are now underway to better the water treatment process. One of the main investigations is aimed to determine the feasibility of reducing the pH of the process water. It is generally known that aluminum corrosion rates as measured by weight loss are markedly decreased as the pH is decreased in the range 6.0 to 8.0. However, the tendency toward pitting corrosion increases with decreasing pH. Furthermore, in the 1940's there was some indication that at lower pH's the dichromate would be reduced to trivalent chromium by the action of the pile fluxes. It was known that trivalent chromium in very low concentrations would cause very severe film formation. After considering all these factors it was originally decided to maintain the pH in the range 7.5 to 7.8. When it appeared possible that it was not necessary to add dichromate to the water an intensive program was made to determine the effects of lowering the pH on aluminum corrosion. These tests all showed that lowering the pH below 7.7 invariably reduced aluminum corrosion rates as measured by weight losses. However, at the lower pH's pitting became more severe and it was decided that it would be technically unfeasible to lower the pH of dichromate-free water below 7.7. Later it became

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evident that even at pH 7.7 pitting attack in the absence of dichromate was too severe. The next step in the program — since it was determined that it was necessary to have dichromate in the water — was to find out if the chromium film problem was real. Results showed that, contradictory to early fears, the pH may be lowered as low as 6.2 without any trouble from this aspect. Progress is now going on to determine the effects on aluminum corrosion at these lower pH's. Results to date show that the pH may be lowered to 7.3 without causing pitting attack and that such a reduction should markedly decrease overall corrosion rates. It is planned in the near future to change the process specification on pH adjustment to allow operation at pH 7.3. This reduction may save about a million dollars yearly by reducing tube corrosion rates, and hence, the frequency at which the tubes will have to be replaced. There will be additional gains available from the reduction of slug jacket corrosion rates. Investigations of this pH problem are still continuing. Operation at pH 7.0 appeared very promising and eventually it may be possible to lower the pH to 6.0 or lower. At these lower pH's the cooling water can be allowed to be heated to a much higher temperature without incurring excessive corrosion rates. This will directly increase production levels of the Hanford reactors.

In addition to the reduction in aluminum corrosion rate, lowering the pH of process water results in another large advantage. At pH 7.7 at temperatures much above 130 C the bicarbonate-carbonate equilibrium shifts and insoluble carbonates are deposited. These deposits are commonly called boiler scales and are characterized by having very low thermal conductivities. Furthermore, the depositions would soon almost completely block the flow annulus between tubes and slugs. The addition of acids to reduce the pH shifts the reaction to the bicarbonate side thus increasing the temperature at which boiler scale becomes a problem. For example, it has been found that at pH 6.5 no scaling occurs at temperature at least as high as 170 C. However some scaling was found at this pH at 190 C.

At the present rate of progress the pH program should be essentially completed in a couple of years and fuller advantages can then be taken of this work on a plant scale.

Process Water Back-Up System

The water in the reactor has two main effects. Primarily it serves to cool the slugs and tubes. A second net effect is that it absorbs a great deal of nuclear reactivity in all the piles except the two K Piles. This is true because the older piles have a relatively large lattice spacing and are more or less over moderated. Thus the extra moderation afforded by the cooling water is insignificant in comparison with its poison effect. The K Piles have a smaller lattice spacing and the moderation effect and the poisoning effect are probably roughly equivalent.

Now bearing the above effects in mind, it can be seen what would happen if the cooling water flow to the reactor would stop during pile operation. The slugs would no longer be cooled and would soon melt, soon the water would begin boiling and be removed from the tubes, the pile reactivity would then increase and the pile power level would increase within a very short period. The result would be a major catastrophe. Also, if water were totally lost during a shutdown, the fission heat generation would be sufficient to melt some of the pile components. To prevent this occurrence, a great deal of thought has gone to make the pile cooling water supply as reliable as possible.

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In general, the DuPont Company had a different philosophy than General Electric Company in assuring cooling supply. The DuPont Company provided for large storages of water at each pumping station. Thus, if the river pump house became inoperative, there was a 20 million gallon supply of water in the raw water reservoir available for treatment; if the reservoir pumping station became inoperative, the clearwells provided a large storage of water available for pumping to the process pump supply tank. Finally, if the clearwell discharge pumps become inoperative, the huge process supply tanks contained a considerable supply of water. These supplies become particularly impressive because if the coolant supply is threatened the pile will be shut down and the coolant flow rate can be markedly decreased. In addition to the water storages, the DuPont Company provided standby, steam powered pumps at each station. In the case of complete electrical power outage, the steam driven pumps could supply a portion of the regular shutdown flow to the reactors. The main process pumps in the older area, as mentioned previously, consist of electrically driven and steam powered pumps in series. In cases of an electrical power outage, the steam driven pumps automatically speed up to keep the coolant flow at a high level during the first critical minutes until the fission heat generated after the pile has shutdown decays. In addition, fly-wheels are coupled to the electrically powered pumps to keep flows up in the critical interim period.

Thus it can be seen that DuPont provided for emergencies connected with electrical power outages or failure of complete pumping stations other than the main process pumping station. Additional safeguards were needed in case of failure of the entire process pumping system. DuPont provided this in two manners. First of all, emergency raw water is provided at each reactor for cooling during emergencies. This raw water system connects all 100 areas and thus the emergency raw water could be supplied by one of the areas to a pile in another area. One last emergency supply was also provided; two high tanks were built at each pile. In case of loss of the process water and the emergency raw water, water from the high tank would flow by gravity through the pile. The high tank water is pumped from the clearwells so if this pumping station is not totally inoperative, coolant could be pumped to the piles through the high tanks for an indefinite period.

The General Electric Company has approached the problem of assuring a supply of coolant to the piles in a different manner than did DuPont. This approach is characterized by the elimination of as many pumping installations and water storage stations as possible. Thus, the raw water reservoir was decreased in size at H Pile and discarded completely at C Pile. The clearwell and pump supply tanks were combined at DR Pile and C Pile to eliminate another pumping station. At the K Piles, another pumping station was eliminated by having the main process pumps take their suction directly from the filter clearwells. This new approach greatly simplifies the coolant pumping system with no sacrifice to safety. Loss of the river pumps at the K Areas would be no more serious than loss of the clearwell discharge pumps at the old areas.

At the K Areas, a new approach has been made to the problem of electrical power failure. In the case of an electrical outage, there is an emergency power of a steam powered turbine-generator set. This equipment will provide emergency power to the various pumps. This system eliminates the duplication of the electrically driven pumps with steam driven pumps.

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General Electric has retained the feature of backing up the process water flow with emergency raw water. The high tanks are eliminated at the K Areas but this loss in safety is more than compensated for by the fact that the two water treating systems of the two K Piles are interconnected. Thus, in emergency either water plant can supply coolant to both reactors. In addition a raw water back-up inter-tie is available to all plants.

Investigations are now going on still another safety back-up. In case of destruction of Coulee, cooling water flow to the reactors would be totally halted after a period of time because the river pump houses would be flooded. It is now proposed that a set of pumps powered by diesel engines be provided to supply coolant to the reactors in case of this extreme disaster.

Operational Considerations:

The amount of coolant in the last analysis governs the tube power since there is some upper temperature limit beyond which it is impractical to operate with liquid coolant. Various steps have been taken to increase the available cooling capacity. Restrictions to flow in the tube have been modified where possible, and upward changes in plant capacity are planned.

The tube orifices were originally used to conserve water. Now, we want all the water we can get through the tube. Consequently, the orifices were replaced with venturis — they being essentially an orifice with a pressure recovery section. Thus we get the flow indication needed for panellit control, but do not lose the pressure drop. The orifice replacement resulted in 10 to 15 per cent gain in flows with no increase in header pressure required. A small increase in flow has been achieved by the replacement of some of the downstream solid aluminum slugs by perforated pieces that do not offer the flow restriction inherent with a solid piece.

Pumping capacities will be increased and additional header pressures will allow greater tube flows in many areas after the completion of Project 558. Filter plant capacities, as previously mentioned, have been greatly increased by the use of activated silica and alum as a coagulating agent instead of formerly used ferric sulphate.

Increasing tube annulus either by increasing the process tube size or by decreasing the slug diameter eventually costs more than the increased production rates from higher tube powers. The loss of thermal neutrons to water and aluminum is about four per cent in the old piles and slightly higher in C and K Piles. Although there is a greater loss of neutrons to the process water due to the larger annulus at K Pile, this is more than compensated by the decreased loss in graphite, K Pile having a smaller graphite to metal ratio. Thus in K Pile the water serves a dual purpose as moderator and coolant. The old piles, however, are over-moderated and any increase in the water annulus is useless except as a coolant and results in a decrease in the percentage of neutrons used for useful production. Such a loss has to be made up by enrichment or results in a decreased number of effective tubes in the pile due to the decreased excess reactivity.

It has been pointed out that at temperatures near 105 C, the rate of tube replacement may be such that it is not economical to increase production by increasing power levels and exit water temperatures since the cost of tube replacement due to increasing

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tube damage from corrosion would be more than the worth of production gain. Some corrosion limit also exists for slugs. Both of the limits are presently below the outlet water temperature that could otherwise be achieved. Thus significant production gains are achievable not only by increasing the amount of coolant, but also, by decreasing the corrosion rate associated with the coolant at these temperatures. Decreased corrosion rates through changed water treatment will be a continuing goal of pile engineering groups.

File Controls - Vertical Safety Rod

The vertical safety rods are steel rods that are dropped into the unit to shut down the pile. They are not used as a control during operation, and the heat generated in the rod is not necessary of removal.

In old pile design the rods ran within aluminum thimbles. The thimbles were primarily designed to prevent gas leakage from the pile. They have now been removed from all piles and the pile gases are contained by means of gas seals on each rod. This has eliminated corrosion and structural problems inherent to their use, and decreased the pile neutron losses. In all piles except K the rods are supported by cable running to over-head winches. Upon a pile scram a magnetic brake circuit is broken, which releases the winches and allows the rods to drop by gravity. This design is changed at K Pile and the rod operates within an external pipe falling again by free gravity but being removed from pile by air pressure. Further acceleration could be obtained by this system if desired by the use of air drive to supplement the gravity drop.

The total amount of reactivity absorbed in the vertical rod systems is approximately 1,000 for the old piles, 1800 at C and H, and 800 - 900 at K. It must be understood, however, that this amount of reactivity absorption is not in addition to that held in the horizontal control system. Since the two systems shadow each other, the net increase in reactivity absorbed after the other system is "in", is only a fraction of its value when used as the only control.

File Controls - Horizontal Safety Rod

The pile power is controlled by the manipulation of neutron absorbers. The horizontal safety rods are the primary control during operation. The individual horizontal rods will be essentially the same in all piles after CG-558 replacement program has been completed. They will consist of an extruded aluminum rod in which boron carbide rings are placed as a neutron absorber, and will contain inlet and outlet passages for coolant to the rods. A silicone seal prevents escape of pile gases. The initial rods were steel rods spray coated with boron and contained in aluminum thimbles. The thimbles limited operation because of their lack of strength at higher temperatures. The rod may be inserted or withdrawn using either of two different speed drivers. They can be inserted nearly the complete distance across the pile at C and K Piles, but only traverse roughly eighty per cent of the unit in the old piles.

With the advent of the use of carbide rings, the blackness can be varied; one important development directly related to this being the use of the so-called "half-rod". By only packing the far half of the rod, the center and far side can be better controlled without limiting the near side. Thus, where the far side control was largely permanent poison columns, some of these can now be replaced with the more flexible horizontal rod control.

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The number of horizontal rods has been increased from nine at the old piles to fifteen at C and H and 20 at K Piles. The amount of reactivity associated with one rod varies slightly but is roughly 40 to 60 ih, depending upon the location. Thus the newer piles have considerably more control than the old units. This is a major improvement in design and results in considerably improved operating efficiency for the newer units. The total number of inhours absorbed by insertion of all horizontal rods at the old piles is 320, at C and H 650 and K, 850. In cases of power failure at the old piles the horizontal rods are automatically inserted by a hydraulic drive from an accumulator. At H, C and K, battery power is standby for their activation in power failure.

Poison Columns

Pile operation is effected by reactivity transients that occur during normal operation and reactivity inherent to the type of metal being irradiated and the exposure goals of irradiation. Efficient pile operation generally takes care of transient changes with compensating rod movement. So-called "poison columns" are used to compensate for the reactivity effects due to loading and to control the far side of the pile which normally does not have as much rod control as the near side.

Poison columns are process tubes charged with neutron absorbers that result in a reactivity loss to the pile. They may or may not produce useful product. Examples of material that might be used for useful product are:

- 1) Lithium - Aluminum Slugs
- 2) Thorium Slugs
- 3) Depleted Uranium

Non-useful absorbers might be:

- 1) Water
- 2) Lead - Cadmium
- 3) Aluminum

It is probably apparent that the amount of reactivity absorbed is a function of the material used, and often the amount of absorption desired is the criteria in selection of the poison. Another property that is of importance is the radio-activity associated with irradiated poison. Often poison columns are used but a short-time before their discharge is dictated by pile operation. If the poison pieces are so radioactive that they cannot be recharged, or if processing to get a desired product from the slug must be accomplished before re-use; it is obvious that other absorbing material should be considered.

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The reason for poison columns other than to absorb excess reactivity above that normally carried in the rods, is to "flatten" the pile flux from its normal cosine curve.

In any pile that is limited by tube power, it behooves efficient operation to decrease the high-power central tubes in such a way that a large number of pile tubes can operate at the limiting power. This is generally accomplished by the placement of poison columns (generally referred to as "permanent poison columns" to differentiate from columns used in transient control) in or near the center of the pile. The arrangement of these tubes is generally referred to as the "flattening pattern". These tubes, then, can probably be irradiated for a considerable length of time unless pile operation dictates a change in the flattening pattern.

In general, the A.E.C. has often dictated the materials that should be used for poison columns. Thorium and lithium-aluminum have been used much of the time. Depleted uranium has not been used, but appears ideal for a low-cost poison.

Safety-Circuits

The safety circuitry varies from pile to pile, but is typified by Figure No. 4, showing a simplified flow sheet for one of the old piles.

The No. 1 safety circuit will be broken by the following events:

- (1) A maximum decrease of 40 lbs. in riser water pressure.
- (2) A high or low panellit trip.
- (3) A increased Beckman reading.
- (4) A power failure at 190 Bldg.
- (5) Low-Sensitivity Seismoscope Indication.
- (6) Manual Trip Manipulation

The No. 1 safety circuit may be opened in some piles by:

- (1) A pile inter-connect trips one pile when the other goes down.
- (2) Malfunctioning of a recirculation loop.

The No. 2 safety circuit is actuated only by manual trip and controls the horizontal safety rods. It is often used as an operating device to shut the piles down after power has been decreased to a nominal level, or it is occasionally used by an operator when he feels that the pile is getting out of hand, and that it would be most judicious to immediately scram the pile. Rapid heat cycling might be such justification.

The ball 3-X circuit, designated only for convenience as the No. 3 safety circuit, is in some respects a last-ditch safety device; although in K-Piles it can be used as a more routine control. Its operation is manual except for specific loss of coolant situations.

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Typical Safety Circuitry
(Old Piles)

Figure No. 4

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If the riser water pressure drops at a rate in excess of some set value, the 3rd. circuit is actuated and the balls are dropped in the VSR channels. The 3X control is also actuated by a delay switch from an integrator that records VSR's drop, and should one or more of the VSR's not function the ball drop would be initiated. This integrator mechanism is by-passed in some of the units. The reactivity held in the VSR channels filled with balls is only slightly greater than the VSR absorption. However, at K Pile extra channels are provided and an increase in the reactivity absorbed is obtained.

The ball 3-X system replaces the "ink" facility at the old piles. In these units a boron salt solution was stored and intended for flow into the old VSR thimbles. Because of the increasing pile temperatures this poison system was of doubtful value since it was felt that steam might block the flow sufficiently that only some portion of the reactivity intended to be taken up would actually be absorbed. The step-plugs, which are a rather large laminated structure at the entrance of each rod channel, were drilled so as to allow a flow of balls from the hoppers above. At C and K Pile the balls can be removed by a gate opening beneath the pile for each channel. In the old piles, however, no efficient manner of removal exists and after a ball drop they are removed by vacuum from the VSR channels.

Panellit Controls

One of the most important pile controls is the panellit gauge. It records the pressure at the throat of a venturi or after an orifice restriction of the coolant entering the process tube. As a pressure device then it does not measure flow, but is used for flow calculation when the header pressure is known and dimensions of the slugs and process tube are specified. Some of the basic technical criteria concerning panellits are discussed and a brief resume of the "trip before boiling" vs. "excess header pressure" theory is given.

A. Basic Technical Criteria

In order to simplify this write-up, the basic technical points necessary for a reasonably complete understanding are presented at this point.

It is found both experimentally and theoretically that a plot of tube inlet pressure necessary to maintain a given flow through a tube looks as follows:

Sketch No. 1

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Sketch No. 2

Sketch No. 3

The above curves represent the pressure required or necessary to maintain any given flow.

We can also plot tube inlet pressure vs. flow considering only the front cross-header pressure and the pressure drop across the orifice or venturi. It looks as follows:

Sketch No. 4

Sketch No. 5

Where p represents the pressure at the tube entrance and where p_a represents front crossheader pressure. Note that p for this figure is the pressure available at the tube inlet.

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Combining Sketches 1 and 4, we might get any of the following:

Sketch No. 6

Sketch No. 7

Sketch No. 8

The first important point to note is that flow can be established only where the available pressure equals the required pressure, or where the two curves cross. Thus, flow can exist at all of the points a., b., and c., in the three figures.

A second important consideration to note is that liquid water is flowing through the tube when the flow rate is greater than X in Sketch 6. A steam-water mixture is leaving the tube when the flow is less than X. Finally, when the flow rate is at or below Y, the slugs are blanketed by steam, and burnout occurs (Jackets, tube and slugs melt, etc.). Thus, point a. of Sketches 6 and 7 represent "normal" flows. Point b represents a steam-water mixture coming out of the tube. Points c represent flow rates at which burnout will occur.

A third important factor concerns stable flow vs. unstable flow. Points a and c of Sketches 6, 7 and 8 are stable flow points. This is so because if the flow fluctuates in the positive direction, the available pressure is less than the required and the flow rate will decrease to the original value; if the flow fluctuates in the negative direction, the available pressure is greater than the required and the flow increase to the original value. By similar reasoning, flow b. of Sketch 7 is unstable and the flow rate will progress from b. to either a. or c. This progression will occur in a matter of seconds.

C. What was the excess Header Pressure Limit

The boiling disease limit was a tube power limit rather than a t limit, and it said that available pressure had to be greater than the required as shown in Sketch 11 and could not be as shown in Sketch 10.

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Sketch 9

Sketch 10

Note that orifices were used to conserve water, and the curves were usually drawn as follows:

Sketch 11

Sketch 12

Reasons for Utilizing Excess Header Pressure Concept: (1) If the flow fell temporarily to or below Z for some reason, normal flow, a., would be restored in Sketch 9, but burnout flow, b., would probably be established in Sketch 10. (2) Unless normal flow, a., was quickly restored, burnout would occur.

Fallacy: The concept assumed that the abnormal condition which caused the initial flow reduction would be quickly rectified. In practice, rectification of the abnormal condition would seldom occur in time to prevent slug melting, vaporization, etc.

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From the above, it can be seen that a point would be reached (about 450 KW/tube at H Pile in practice) where power could be raised only by increasing header pressure or decreasing tube resistance.

D. Trip Before Boiling Limits

Why Did We Go to It?: (1) We really weren't getting any protection from the excess header pressure requirement. (2) we could increase tube powers under this concept and still be safer than at low powers with excess header pressure protection.

What Was the Basic Criteria?: Each Panellit was set so that, if the flow rate in the tube were decreasing, the Panellit would scram the pile before boiling developed in the tube. It was believed that the point at which unstable flow developed was the same as the point at which boiling started.

Why Use that Criteria?: For most cases of abnormal flow, the pile would be scrambled in time to prevent tube boiling and thus prevent jacket, tube and slug melting. Thus, we could have termed the whole concept, "trip in time to prevent melting".

What Were the Technical Bases?: There are two common causes for abnormal flow: cone screen plugging and tube plugging. The P^2/g diagram for these cases as well as the normal case look as follows (assuming a venturi rather than an orifice).

Sketch 13 Normal

Sketch 14 - Cone Screen Plugging

Sketch 15 - Tube Plugging

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It can be seen from Sketch 14 that as screen plugging processes, the tube flow rate decreases from a. toward b. When the plugging gets worse than indicated by (3), the flow rate will suddenly jump from b. to c. and burnout will occur.

Likewise, it can be seen from Sketch 15 that as tube plugging progresses, the tube flow rate decreases from a. toward b. When the plugging gets worse than that indicated by (3), the flow rate will suddenly jump from b. to c. and burnout will occur.

It can be concluded from Sketches 14 and 15 that if we scram the pile at or slightly above flow rate b., then we can rapidly reduce the heat generation rate and either prevent tube boiling or (possibly) restore normal flow before melting occurs if boiling does occur. That is the basis for the trip-before-boiling concept.

We could easily scram the pile at rate b. if we had a flow meter. We can also (but not as easily) scram at b. with a Panellit. This is so because each change in flow rate is accompanied by a specific change in tube inlet pressure (tube inlet pressure corresponds to Panellit pressure in the case where an orifice is used.) With Panellits we operate as follows:

Sketch 16 - Low Trip and Screen Plugging

We set the low trip about 10 psi above the tube inlet pressure which exists at flow b. The 10 psi is a safety factor to allow for Panellit calibration errors plus errors in determining the shape of the required pressure curve. It should be noted that if the low trip were 15 psi lower, it is probable that the low trip would never be activated in the case of slow screen plugging and burnout would tend to occur. (The high trip would eventually be activated but only when the flow were well below b. into the boiling region. We don't know whether or not melting would occur for sure, but there is an excellent chance. This will be discussed more below.)

For the case of tube plugging (without screen plugging) the Panellit pressure would be constant at a value equal to front crossheader pressure in the absence of orifice and venturis. Consequently, to show how the Panellit operates for tube plugging, an orifice will be assumed present.

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Sketch 17 - High Trip and Tube Plugging

We set the high trip about 5 psi below the tube inlet pressure which exists at flow a. The 5 psi is a safety factor to allow for Panellit error. In this case an error in Panellit setting is not too critical because the tube inlet pressure continues to rise with decreased flow and the Panellit is sure to trip within a few pounds.

Thus, we set the Panellit trips to scram the pile at a flow rate slightly above that rate at which the flow would suddenly drop from b. to c. where burnout occurs.

Points Regarding Orifices and Venturis: Orifices were originally used to conserve water. Now, we want to use all the water we can get through the tube. Consequently, we removed the orifices. However, as indicated above, this left us with no sensitivity on the upper trip and necessitated the use of venturis. The venturis are really only orifice with pressure recovery sections. Thus, we get the sensitivity we need and still don't lose the pressure drop.

How Does Tube T come into the Picture?: The flow rate at which boiling occurs is directly proportional to tube power. Thus, to set a Panellit trip to trip-before-boiling, we have to know the tube power. Since the flow and power are fixed, the tube T is fixed.

OPERATIONAL COMPONENTS

Fuel Elements

Since the fuel elements will be the major study involved in the course, only a sufficient description will be given at this time to suffice as an introduction to later discussion. Three classes of fuels will be mentioned:

- (1) Natural uranium.
- (2) Slightly enriched uranium.
- (3) Aluminum alloys of highly enriched uranium.

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Natural Uranium as found in nature and processed for Hanford piles contains .7114 per cent U-235, a trace of U-234 and the major isotope, U-238. The most important nuclear reactions are the fission of U-235, the absorption of a neutron by U-235 to form U-236, the absorption of a neutron by U-238 to form U-239 which decays by β emission to Np_{239} , which in turn decays to Pu_{239} , the desired product of irradiation. There is also some U-238 fission by fast neutrons. Normal uranium cannot be made critical in an un-moderated lattice.

Slightly Enriched Uranium contains an increased percentage of U-235 isotope. This is accomplished by conversion of the uranium to UF_6 and partial separation of isotopes by the gaseous process of Oak Ridge. It is obvious that with increasing amounts of fissionable U-235 the power of the fuel element is increased when subject to a constant neutron flux. The increased power is gained by a decrease in U-238 absorption resulting in decreased Pu production.

U-235 Aluminum Alloy contains essentially pure U-235 isotope alloyed with uranium. Such a slug produces no product, but manufactures neutrons for use in other metal. The U-235 content varies with the application desired. For enrichment associated with normal production a 4-1/8 per cent alloy is used. Where greater production of neutrons is desired to irradiate poison pieces, the U-235 content is increased to roughly seven per cent. The lower percentage alloy is referred to as a C-slug, and presently is charged in a peripheral area a few lattice in from the edge of a pile. This manner of obtaining more reactivity is called "Spike" enrichment as contrasted to the case where we might use slightly enriched uranium through-out the pile to boost the activity by so-called "uniform enrichment". The alloy containing the higher percentage of U-235 is called a J-slug and has in the past normally been used as an alternated slug charge with a poison slug. For a thorium irradiation this is commonly called a J-Q column and consists of alternated alloy fuel pieces and thorium slugs. The heat generated from U-235 fission in J-slugs is more than that from normal uranium. Thus when these pieces are alternated with poison slugs or non-power producers, the net heat generation in a tube may be approximately that of a normal uranium column.

 Process Technology Unit
 Pile Technology Section
 ENGINEERING DEPARTMENT

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