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PERFORMANCE OF REACTOR PROCESS PUMPS WITH STARVED SUCTION CONDITIONS

D. R. MUHLBAIER

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by

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ABSTRACT

In tests with the large coolant circulation pumps in Savannah River reactors, no system damage occurred when the pumps were operated with starved suction. Pump flow was nearly constant as moderator level was lowered (suction head reduced) until air aspirated into the suction nozzle. Then the pump flow gradually decreased with further lowering of the moderator level until the suction pipe vented. Upon venting, pump flow was limited by gravity flow across the muff and suction piping. The centrifugal pumps then produced surging or pulsating flow with about a two-second cycle period.

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INTRODUCTION

In previous analyses of large process leaks in Savannah River reactors, it was assumed that the coolant circulating pumps would not contribute to cooling the fuel. Emergency cooling water (ECW) addition provided the only known means of core cooling. The tests described in this report were conducted to determine whether credit could be taken for coolant recirculation by the process pumps in the event of a large D_2O leak and starved suction conditions. Pump and system behavior under these conditions is used to calculate the coolant flow to individual assemblies and to estimate any damage resulting from an incident.

This report presents results of a test in which the large process water pumps in a Savannah River reactor were operated with starved suction. Data and analysis are presented for the pump performance and average and minimum flow delivered to the plenum. Assembly flows can be determined from the coolant level in the plenum. This information is required to calculate reactor hydraulic system operation following postulated improbable accidents.

SUMMARY

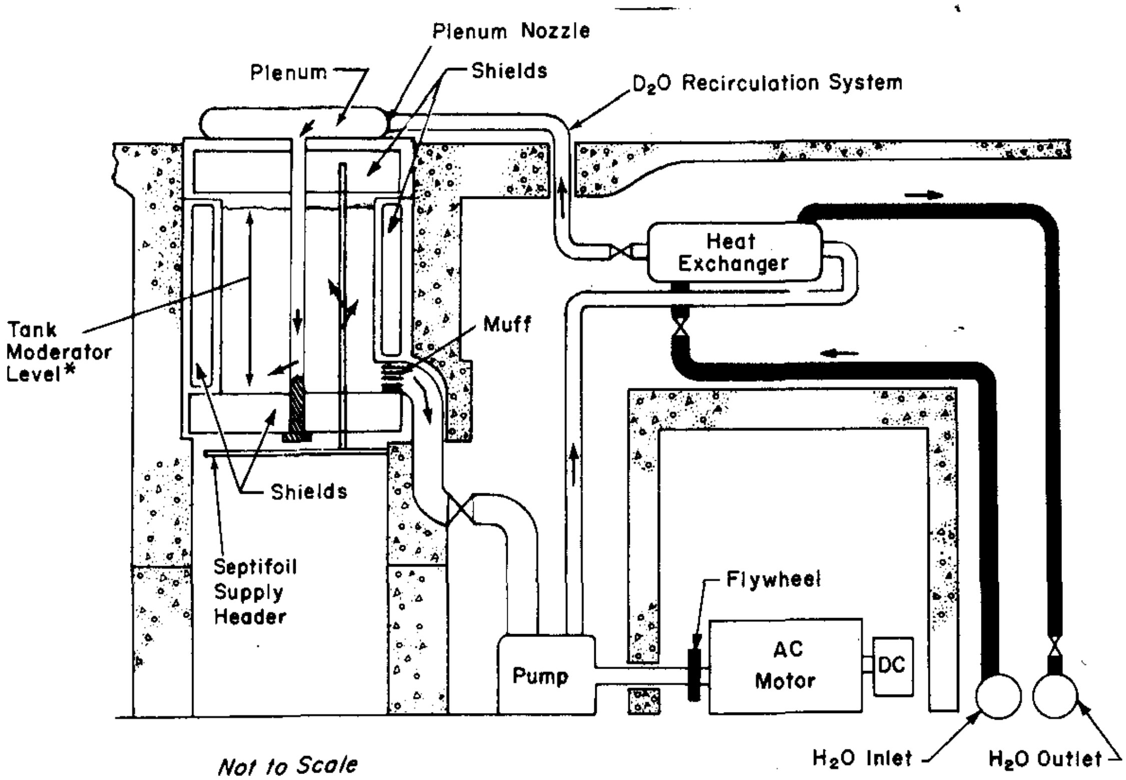
Tests established that operation of Savannah River reactor process pumps with starved suction would increase the available core coolant flow by at least 300% when compared to the nominal ECW supply. The tests demonstrated that the pumps were capable of satisfactory operation with adverse suction conditions and that credit could be taken for this additional coolant circulation in the accident analysis. Based on these tests and modifications to the ECW system, core damage would be less than 1% in the unlikely event of a major H_2O or D_2O leak.

The tests showed that pump flow decreased as the moderator level (suction head) was lowered in the reactor tank following aspiration of air into the suction piping. Pump flow was nearly uniform at a given moderator level until the suction pipe vented. Pump flow prior to venting was about 25% of initial flow. Immediately after the suction pipe vented, the pumps began to surge with pulsating flow. The average flow rate at start of surging was ∿4100 gpm (∿15% of initial flow). Surging flow was caused by rapid pumpout of suction piping followed by no pumping until the suction pipe had refilled to some degree. The pump surge period was about two seconds and is probably a function of both the pump suction side resistance and piping system design. Calculations predicted that gravity flow through the muff could not exceed ∿4400 gpm which shows agreement with experimental data.

DISCUSSION

REACTOR HYDRAULIC SYSTEM

In the reactor hydraulic system (Figure 1), heavy water coolant enters the plenum chamber at the top of the reactor tank, flows across the plenum into each fuel or target assembly, and then flows down through the assembly to the bottom fitting where it is discharged into the bulk moderator space. Effluent D_2O is removed through six nozzles at the bottom of the tank and is pumped through six pairs of D_2O-H_2O heat exchangers at the sides of the reactor. [There are nine vanes (plates) located in each exit nozzle that direct with a nominal resistance flow to the suction pipe. This vane configuration is called a muff.] From the heat exchangers, the coolant re-enters the plenum chamber. A small side stream of D_2O upward flow cools the control assemblies (septifoils).



*During normal reactor operation the tank moderator level is maintained above the top thermal shield.

FIGURE 1. Reactor Coolant Circulation System

The process pumps* are high-efficiency, single-stage centrifugal pumps with a four-vane, closed, double-suction impeller. Impeller diameter is 39½ inches, and the impeller eye area is 248 in.^{2} per side.

AC and DC motors drive the pumps at ∿1000 rpm during normal operation. DC motors alone drive the pumps at ∿300 rpm for low coolant flow required during reactor shutdown. Additional descriptive information about Savannah River reactors is given in Reference 1.

TEST DESCRIPTION

Purpose

One postulated reactor accident, though very unlikely, is a large D_2O leak which results in a net loss of coolant from the reactor system even with the addition of emergency light water. Because of the large size of the leak, the accident is frequently referred to as double-ended process pipe break. The leak is generally assumed to be on the discharge side of a process pump, so the coolant is lost at a high rate if the pump continues to operate.

Following a large D_2O leak, the D_2O level in the reactor tank will begin dropping. If the leak is large enough, emergency light water will be added to the reactor for additional cooling. For large leaks (pump assisted), the reactor liquid level will continue to decrease until flow is limited to the pumps; at that time, the leakage rate will equal the light water addition rate. The equilibrium liquid level could be below the top of the reactor effluent nozzle, thus venting the pump suction leg and limiting pump flow to gravity flow through the suction piping.

During the postulated double-ended pipe break accident, the recirculated coolant flow from the process pumps would provide about 75% of the total coolant flow required to assemblies even for very large leaks. The emergency cooling water system would provide the other 25%. These flows were calculated from the size of the leak and the emergency coolant addition rate assuming the process pumps continue to circulate coolant. The calculations did not consider pump performance or mode of operation. Pump performance with such unusual conditions is extremely important because failure to circulate water even at low suction head could lead to fuel melting. The starved-suction pump tests were directed toward defining the process pump performance and operating characteristics when operated with adverse suction conditions that could occur following a large D_2O leak.

*Bingham Pump Co., type CD, size 16x24x43.

Instrumentation

Pump suction and discharge pressures for one system and the pressure drops across heat exchangers in all six of the systems were measured and recorded. The flow rate recirculated to the plenum was determined from the ΔP's across the heat exchangers. Process water D_2O levels were measured in the plenum and tank.

Transducers for pressure, acceleration, and displacement were located in various parts of the reactor hydraulic system as shown schematically in Figure 2. The signal sources for all data are listed in Table I. Each signal was recorded on one of three synchronized oscillographs. A reactor face map showing the pump nozzle locations and assembly index is given in Figure 3.

Procedure

Two calibration tests were conducted with the pump system to be operated singly prior to the starved suction tests:

- Heat exchanger ΔP was measured at different flows (as determined by the pump ΔP) to provide calibration curves for determination of flow recirculated to the plenum during the tests.

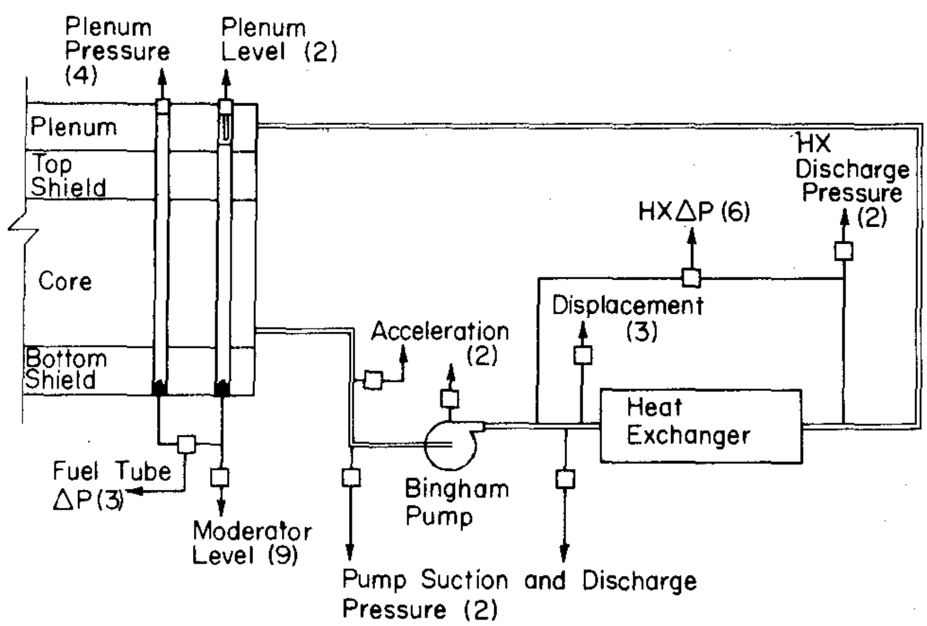


FIGURE 2. Transducer Location

TABLE I

Recorded Signal Source and Location

Signal	*Signal Source*	*Location*[b]
1	Tank Level[a]	X50-Y72
2	Tank Level[a]	X05-Y27
3	Tank Level[a]	X29-Y03
4	Tank Level[a]	X29-Y51
5	Tank Level[a]	X34-Y60
6	Tank Level[a]	X41-Y69
7	Tank Level[a]	X22-Y36
8	Tank Level[a]	X15-Y27
9	Pump Suction Pressure	Pump 4
10	Pump Discharge Pressure	Pump 4
11	Pump Acceleration (Suction Side)	Pump 4
12	Heat Exchanger ΔP	System 1
13	Heat Exchanger ΔP	System 2
14	Heat Exchanger ΔP	System 3
15	Heat Exchanger ΔP	System 4
16	Heat Exchanger ΔP	System 5
17	Heat Exchanger ΔP	System 6
18	Tank Level[a]	X41-Y09
19	Heat Exchanger Pipe Displacement (Horiz)	System 4
20	Heat Exchanger Pipe Displacement (Vert)	System 4
21	Heat Exchanger Pipe Displacement (Axial)	System 4
25	Plenum Pressure (Defective Transducers)	X29-Y51
26	Plenum Pressure	X22-Y36
27	Plenum Pressure	X34-Y60
28	Plenum Pressure	X05-Y27
29	Heat Exchanger Disch. Pressure	System 2
30	Heat Exchanger Disch. Pressure	System 5
31	Pump Acceleration (Discharge Side)	Pump 4
32	Plenum Level	X27-Y45
33	Plenum Level	X17-Y33
34	Fuel Assembly Monitor Pin ΔP	X30-Y54
35	Fuel Assembly Monitor Pin ΔP	X37-Y63
36	Fuel Assembly Monitor Pin ΔP	X49-Y75

a. Tank liquid level was determined by the static pressure on monitor pins in the bottom of the tank. No flow plugs were installed in assemblies over monitor pins to prevent confusion with assembly flow signal.

b. See Figure 3 for reactor lattice location.

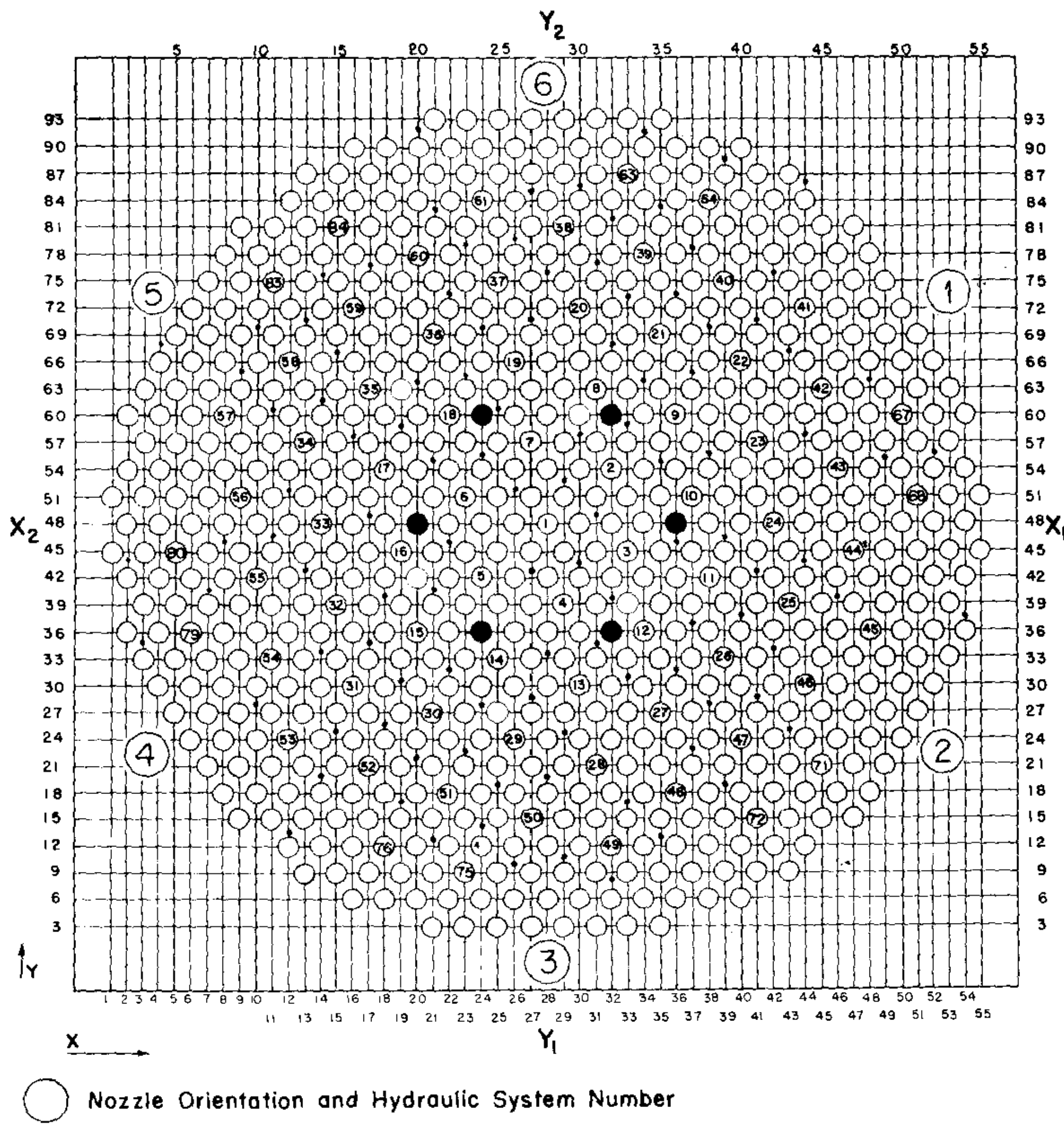


FIGURE 3. Reactor Face Map and Pump System Nozzle Orientation

- Vibration (acceleration mode) of the pump casing, suction, and discharge piping was measured at startup and under normal operation to provide a reference for comparison with the vibration signals monitored during the tests.

In the first test, one pump was run with DC motor drive (DC Test) as the tank moderator level was lowered. As the moderator level approached 60 inches from the tank bottom, pump flow and vibration were monitored. System data were recorded as the moderator level decreased from 60 inches. Pump and piping vibration was monitored during the test period.

After completion of the test with one pump, the tank was partially refilled, and the test was repeated for five pumps operated with DC drive (5 DC Test), one pump with AC drive, and five pumps with AC drive (5 AC Test). All six pumps were not operated because it was assumed that the leaking system would provide no significant flow to the plenum.

After completion of the tests, the moderator level was returned to normal, and pump vibration was measured with AC and DC drive for comparison with the pre-test measurements. No abnormalities were observed, and the pumps were returned to normal service.

Equipment Safety

No pump damage was anticipated based on previous test experience of smaller pumps and pumping systems in an experimental facility. Any significant damage would have been detected by changes in the pump vibration characteristics and/or the head-capacity curve which were monitored. A vibration (acceleration) limit of 2500 in./sec^2 was established at which the test would be terminated. This limit is more than twice the normal steady-state vibration. However, it is consistent with prior experience that indicated no vibration damage for continuous operation below this limit. During normal AC pump startup an acceleration of 2800 in./sec^2 has been measured at a heat exchanger inlet. Moderator temperature was maintained at $<25°C$ to prevent pump cavitation and resulting vibration.

The tests were conducted in P Reactor following charging with fresh fuel assemblies. No unusual conditions developed with the fuel and target assemblies because of these tests. The force exerted by the moderator cross flow at low tank levels was small compared with that at full flow conditions, as demonstrated by motion imparted to assemblies in a separate experimental hydraulic facility.

During operation of the pumps with starved suction, some air was entrained in the coolant recirculated to the plenum. Partial separation of the air-coolant mixture may have occurred in the plenum; however, the air was probably vented through the assemblies at low pressure and low velocity as additional coolant was supplied by the pumps. Highest coolant velocities through the assemblies were significantly less than those which prevail when the reactor is operating at full flow conditions; thus, the possibility of excess vibration of fuel or target components in the housings was minimized.

A preliminary test in a scale test facility was conducted with up to 50% air by volume (at STP) injection into coolant flows of 25 gpm to 70 gpm supplied to a mock-up fuel assembly. Air was injected upstream of the plenum to simulate entrainment and separation of air in the plenum. Tests were conducted at two moderator levels: one equivalent to the reactor tank full, and the other with about 15 inches of water in the tank. Results of the tests showed uniform assembly flow with no surges and no visible vibration of the assembly components.

The DC motor speed is load-dependent and could vary during the tests with DC drive. The DC motor speed was monitored but did not approach the limit of 1600 rpm established for the test.

RESULTS

Pump Operation During 5 AC Test

Flow Regimes

During the 5 AC tests, the pumps operated in four flow regimes. The initial flow regime was the normal single-phase pumping of water illustrated in Figure 4. This regime continued as the water level was decreased in the reactor tank to about the 65-inch level* where the second flow regime began. Because of the high flow rate and resistance to radial flow created by the assembly tubes in the tank, a steep gradient developed in the moderator height from center to edge of the reactor tank. At $\sim$65 inches in the tank center, the gradient was sufficient to cause entrainment of air in the water flowing across the tubes and/or direct aspiration of air into the pump suction line as by a vortex (Figure 5). The top of the suction nozzle is 15 inches above tank bottom so that there was about a 50-inch gradient from center to edge when the pumps started aspirating air into the suction pipe.

* All moderator level data refer to the moderator height in the center of the reactor tank.

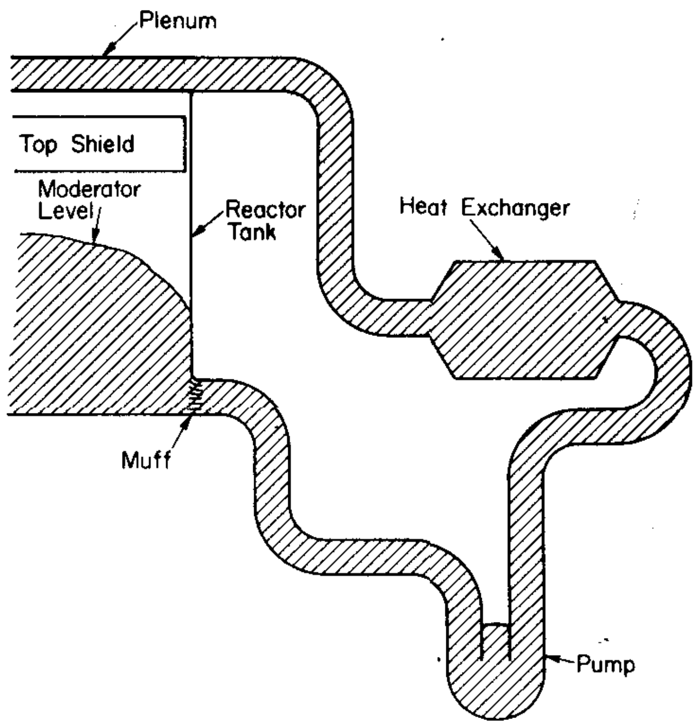


FIGURE 4. Single-Phase Flow Regime

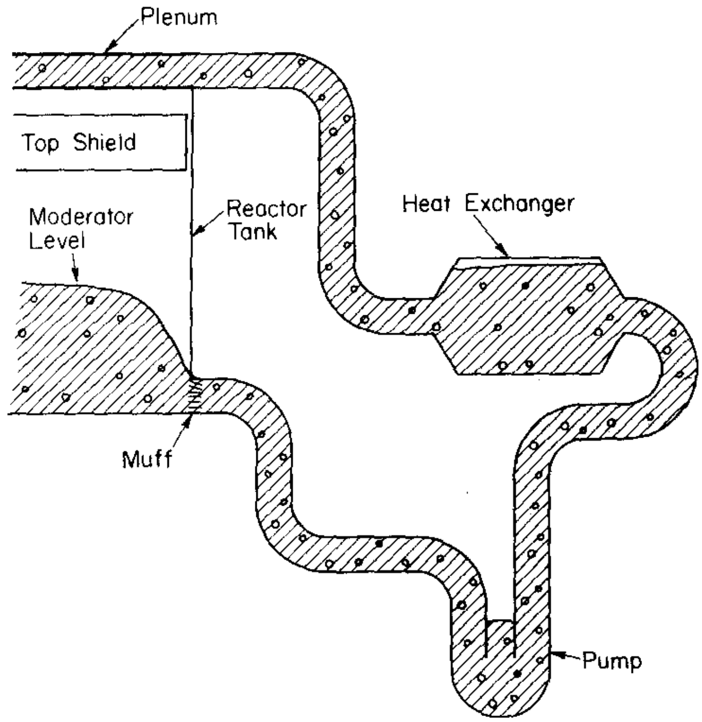


FIGURE 5. Two-Phase Flow Regime

The second flow regime continued until the moderator level was lowered sufficiently (28-inch level) to permit venting the suction piping directly to the atmosphere. The amount of air aspirated into the pump suction is unknown, but it increased (based on flow reduction) with decreasing liquid level until the suction pipe vented.

The third flow regime was surging or slug flow. This regime occurred immediately after the suction line vented to the atmosphere causing the pumps to lose continuous suction. The vented suction line reduced the liquid flow to the pumps to gravity flow only (Figure 6). Gravity flow causes the pump to pump intermittently on a uniform cycle. Figure 7 shows the indicated flow (based on heat exchanger ΔP) for pump 4 immediately following the start of surging. Note that the flow reverses periodically indicating fluid movement toward the pump rather than toward the plenum. All data verify this condition.

The cause of pump surging cannot be associated solely with the pump, but is apparently a systems effect which includes both the pump and suction piping arrangement. The suction piping is

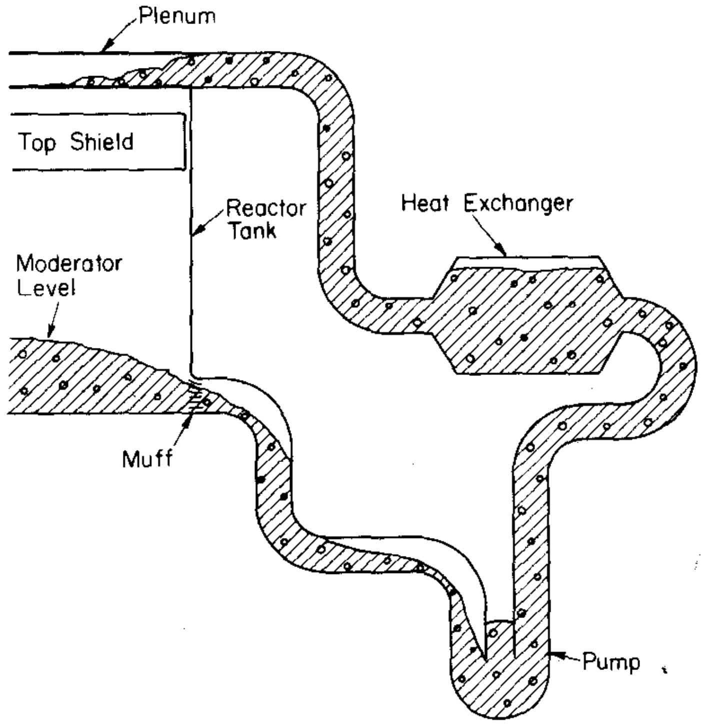


FIGURE 6. Flow Regime with Vented Suction (Nonuniform Flow)

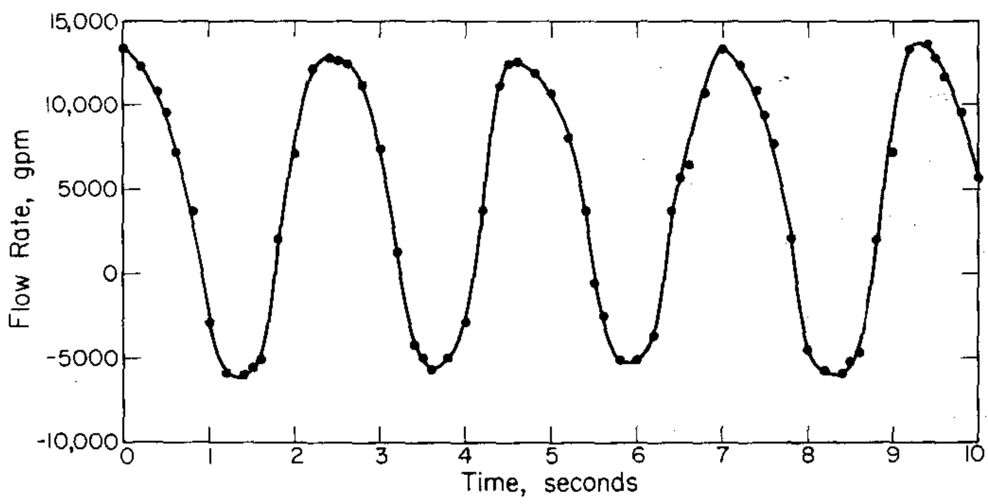


FIGURE 7. Flow from Pump 4 at Start of Surging

important because it alternately vents and then fills with water. When the pipe is full of water, the pump can pump at a very high rate until the water is pumped out and air reaches the impeller. On the discharge side of the pump, the high pump rate causes an increase in the water momentum which allows air to be drawn through the pump when the suction pipe vents. Following loss of the liquid momentum, backflow results until water reaches the pump impeller from the discharge sides. At this point, the pump is full of air on the suction side, there is water and air on the discharge side, and the suction line is filling with water. The flow of water into the pump allows it to begin pumping both water and some of the air trapped in the suction side of the pump. This process started slowly, but the flow rate increased rapidly as more and more air trapped in the pump was discharged. However, the suction line is soon pumped out, and the process is repeated. The geometry differences in the suction piping among the different hydraulic loops explain why different pumps surged at different rates (Table II).

The fourth pump flow regime was similar to the second except that the suction piping was vented. This flow regime followed the surging flow when the moderator level was extremely low. The apparent condition was uniform flow from the reactor tank through the suction piping to the pump while the suction piping was continuously vented from the tank to the pump (Figure 8). This condition was possible because a pump impeller will sling out any water that reaches the impeller eye.

TABLE II

Average Pump Surge Period During 5 AC Test

Tank Moderator Level,[a] inches	*Pump Surge Period,[b] seconds*					
	Pump 2	*Pump 3*	*Pump 4*	*Pump 5*	*Pump 6*	*Avg*
27	2.1	1.5	2.4	2.0	1.5	1.90
24	2.1	2.2	2.5	1.5	1.4	1.94
21	1.8	1.9	2.3	1.6	1.3	1.78
18	1.9	1.4	2.0	1.4	1.2	1.58
Avg	1.98	1.75	2.30	1.63	1.35	1.80

a. Tank moderator level measured at center.
b. Pump Systems 2, 4, and 5 have similar hydraulic loops as do Systems 3 and 6.

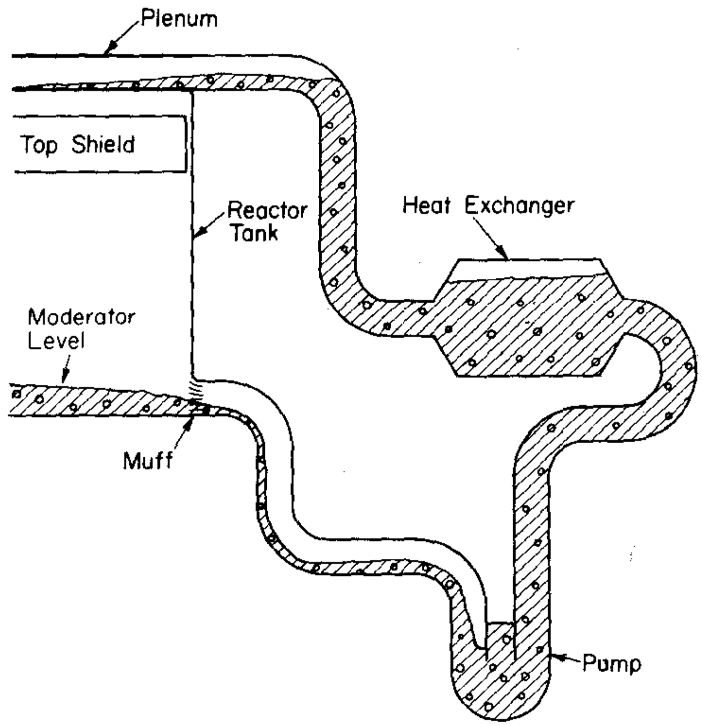


FIGURE 8. Flow Regime with Vented Suction (Uniform Flow)

Flow Rates

The pump flow rate decreased gradually as liquid level in the tank decreased, except when the suction pipe vented and the pump entered the surging flow regime at the 28-inch moderator level (Figure 9). At moderator levels above this point, the pump was able to develop suction to draw the water through the pipe. At moderator levels below this point, the suction pipe vented, the pump could develop no suction, and flow was limited by gravity flow to the pump; hence, the discontinuity in pump flow rate.

The pump flow rates indicated in Figure 9 were determined from the heat exchanger ΔP during the test and a calibration of heat exchanger flow versus ΔP. The calibration was obtained for the reactor heat exchangers with single-phase water flow before the test. It is known that the presence of entrained air in the water will increase the heat exchanger ΔP. Thus, the flow rate indicated on Figure 9 for tank liquid levels between 28 and 55 inches are subject to error because of the two-phase flow.

Tests with a small pump and heat exchanger before the reactor tests showed that the heat exchanger indicated flow would increase

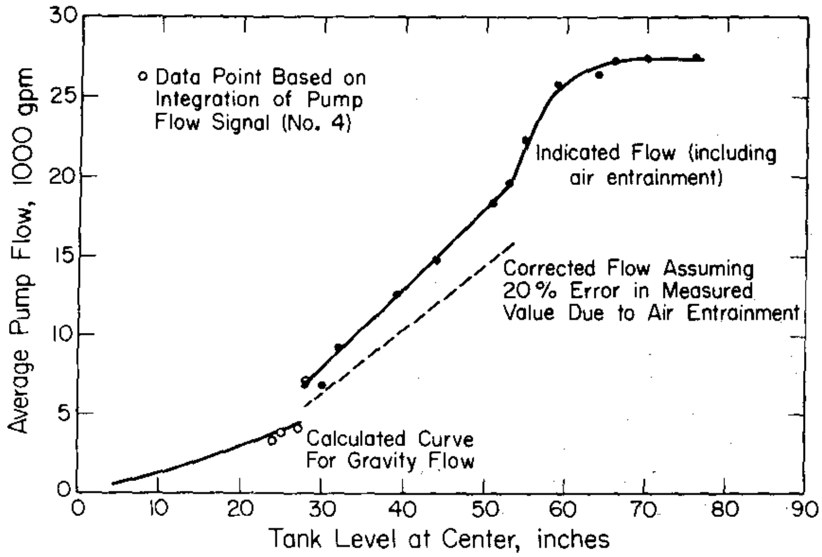


FIGURE 9. Pump Flow Variation with Liquid Level (5 AC Test)

by about 20% for 20% by volume of air added to flowing water. The model tests also indicated that a pump operated with starved suction (suction pipe vented) could pump only ∿5% air. Air pumpage with unvented suction is unknown. Thus, the pump flow rate in Figure 9 for moderator levels below 28 inches are considered quite accurate. Flows for moderator levels between 28 and 55 inches are subject to an unknown error because of the unknown quantity of entrained air. The dashed curve represents pump flow in this region for 20% flow error.

The pumps delivered uniform flow until the liquid dropped below 28 inches. The pump flow varied uniformly from over 27,000 gpm to less than 7,000 gpm. The reduction in flow was apparently due to increased air entrainment. The air entrainment was probably due to aspiration at the tank effluent nozzle and to the moderator gradient across the tubes (initially ∿50 inches and decreasing to ∿13 inches when suction pipe venting occurred). The fact that the pumps were able to produce uniform flow over such a wide range of flows is probably a systems effect of suction piping and nozzle arrangement rather than just a pump characteristic.

Vibration

Pump 4 was monitored for vibration during all phases of the test. Accelerometers were mounted on the suction piping and pump, and displacement transducers were located on the pump discharge piping near the heat exchangers. Acceleration measurements were also taken at various points with a portable instrument. Limits of 2500 in./sec^2 for acceleration and 0.150 inches for displacement were established for the test, and these limits were not exceeded. Figures 10 and 11 show the maximum measured values of acceleration and displacement caused by vibration. The maximum acceleration was about 1000 in./sec^2 and occurred on the pump discharge line at a reactor moderator level of about 34 inches. The maximum displacement was 0.110 inches and occurred in the axial pipe direction at a reactor moderator level of about 46 inches. Over this range of levels, the pumps were aspirating large amounts of air, and considerable system audio noise was apparent.

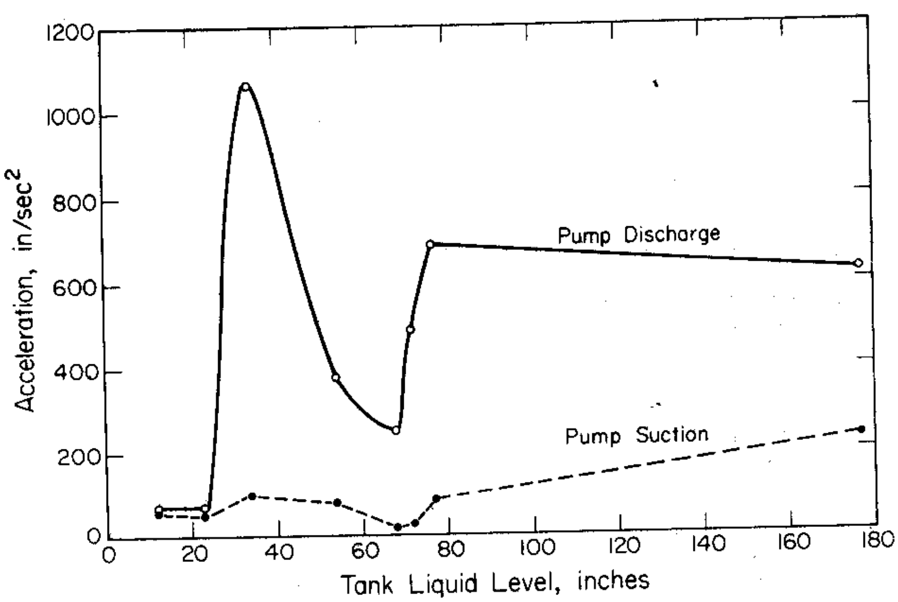


FIGURE 10. Pump Vibration-Acceleration Mode

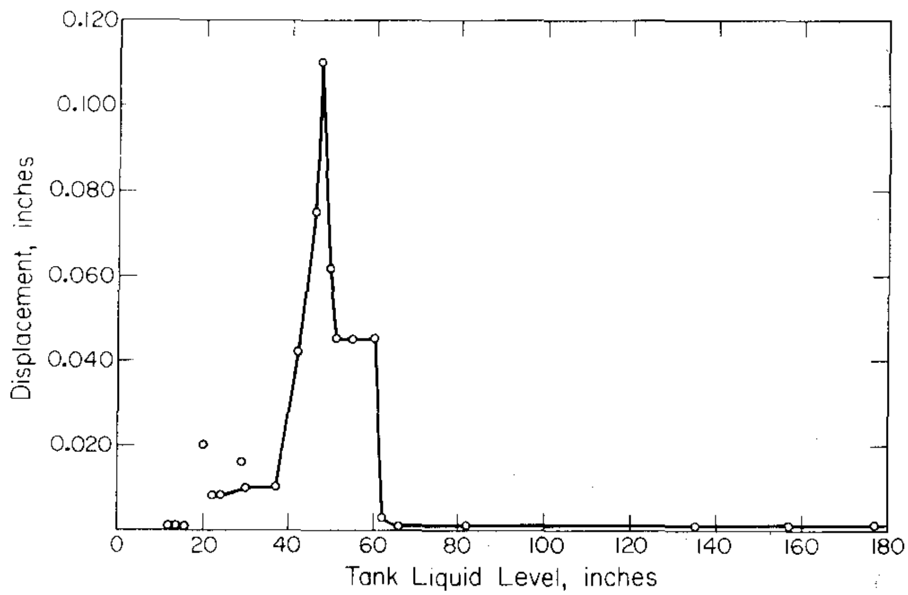


FIGURE 11. Pipe Vibration-Displacement Mode

Pump Suction and Discharge Pressures

Pump suction and discharge pressures for the 5 AC test are shown in Figure 12. Rapid reduction in suction pressure at about the 65-inch moderator level was apparently caused by increased suction pipe ΔP due to entrained air (two-phase flow). At lower moderator levels, flow and pressure drop decreased, and suction pressure increased accordingly. The discharge pressure curve shows inflection points at the same relative moderator levels as the suction pressure curve and in general follows the shape of the pump flow curve.

Effect of Pump Operation on Plenum Flow

Before starved suction conditions occured, pump flow was uniform although less than normal, and the pumps contained entrained air as previously discussed. At starved suction conditions, the pumps produced surging flow as previously discussed. These surges produced waves in the plenum. Because the edge of the plenum was full, the surges did not produce wave crests. However, at the end of the surge following buildup of flow momentum, the rapid collapse of pump flow caused flow reversal in the pump discharge which in turn sucked water from the plenum and caused the formation of a wave trough in the plenum. An analysis and application of test data verifying this behavior are presented in the Appendix. The wave

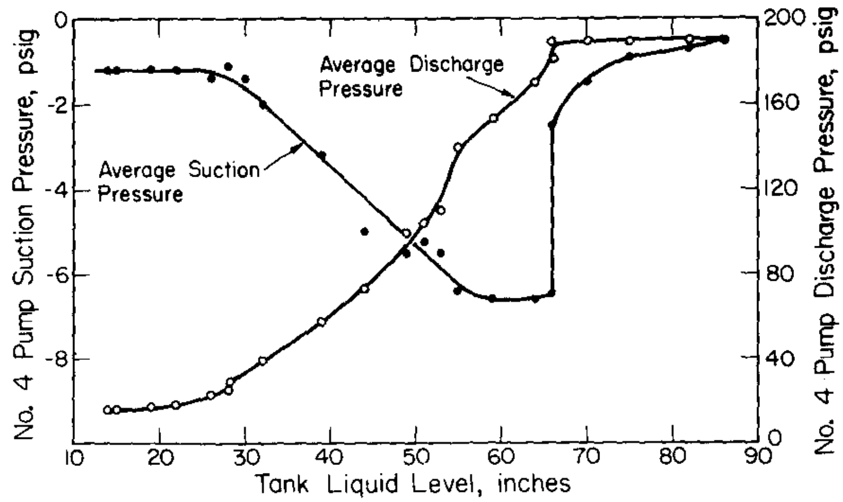


FIGURE 12. Pump Suction and Discharge Pressures (5 AC Test)

trough is propogated across the plenum at a speed which is a function of the flow rate across the plenum and trough depth because it is in water with a free surface. If all pumps were surging, each could produce a wave trough, and the effect of the waves meeting in phase is to increase the depth of the trough. Because the amount of water entering an assembly is a function of water depth in the plenum, the wave troughs reduce coolant flow to the assemblies over some time increment. The applicable time increment is one-half the wave period or one-half the pump surge period (about 1 second in these tests). The effect of plenum waves on assembly flow may be ignored in cases where the fuel and target assemblies have relatively large heat capacities, and the average plenum liquid level can be used to determine assembly flow. In cases where the wave size may be important, the Appendix provides a method of estimating the maximum wave for the inner 10 rows of a Savannah River reactor plenum.

Figures 13 and 14 show the approximate average water level in the plenum for the two monitored positions for both the 5 AC and the 5 DC tests. Both curves show that about the same average water level can be expected in the plenum after starved suction developed regardless of AC or DC pump operation. This is because the flow rate is determined by gravity flow through the pump suction pipe and not by pump operation (surging or uniform flow).

Pump Operation During 5 DC Test

Test results with five pumps operated with DC power (lower pump rpm) were similar in nature to the 5 AC test results. The pumps produced uniform and nearly constant flow rates until the

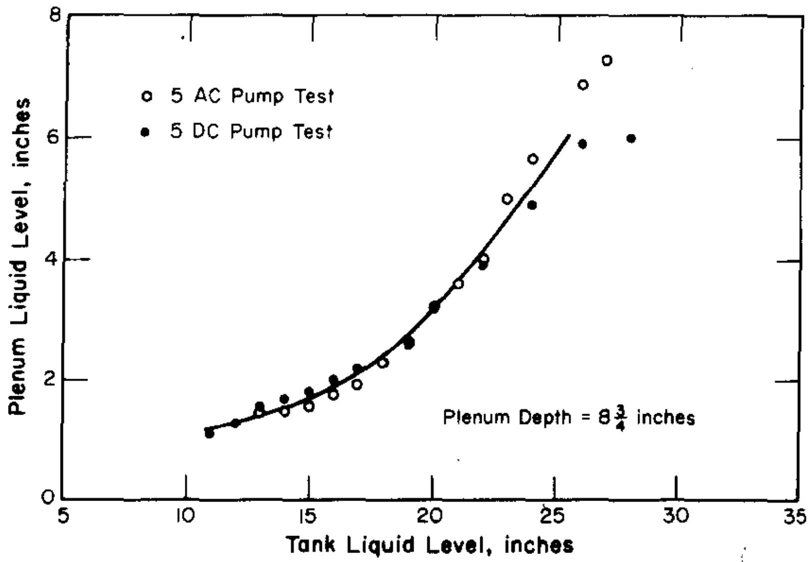


FIGURE 13. Average Plenum Liquid Level at X17-Y33

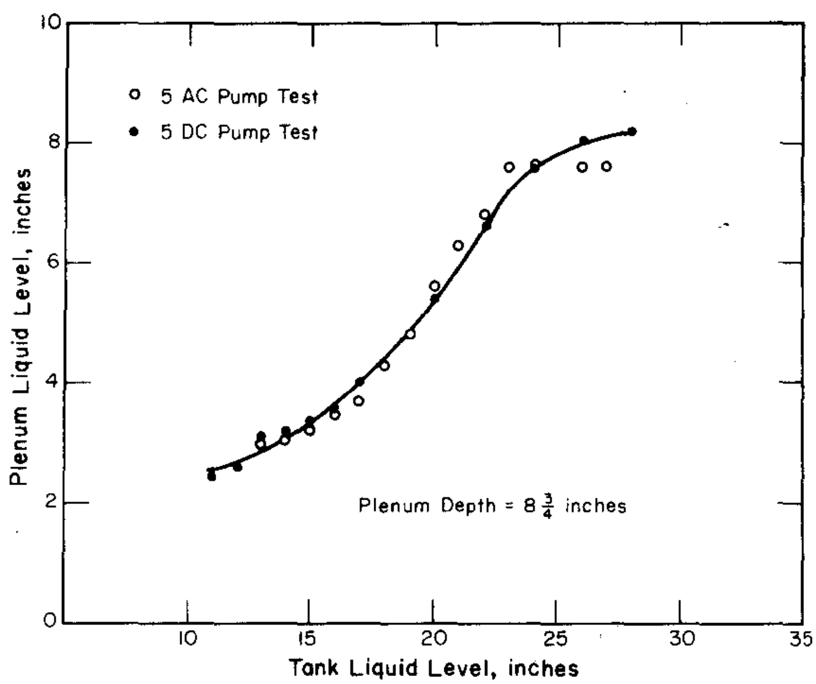


FIGURE 14. Average Plenum Liquid Level at X27-Y45

moderator level was lowered to about 23 inches (Figure 15). At that level, the pump suction pressure decreased sharply (Figure 16) as did the pump flow probably because of air entrainment in the moderator. The effluent nozzle vented with a moderator level of about 18 inches, and minor fluctuations in the pump flow began. The data indicate a discontinuity in the pump flow vs. tank moderator level curve at the 18-inch level, but the change in flow was apparently small and is masked by the system flow noise. After the suction pipe vented, pump flow was limited by gravity flow through the muff. The calculated gravity flow curve is shown in Figure 15. The differences between the curves are attributed to air entrainment because of nearly uniform flow and very small flow signal as opposed to the very large oscillating flow signal for the AC test. The results for the 5 AC test are probably most accurate. In both the 5 AC or 5 DC test, the average flow rates after suction pipe venting are the same because flow to the pumps is limited to gravity flow. This is verified by Figures 13 and 14, which show equal liquid levels in the plenum after the suction was vented for both tests.

All four flow regimes observed in the 5 AC test were also observed in the 5 DC test, except the flow in the 5 DC test varies almost continuously with tank moderator level.

Changes in pump suction pressure with moderator level (Figure 16) correspond well with changes in pump flow. The suction pressure decreased to almost 0 psig after the suction pipe vented (Figure 16).

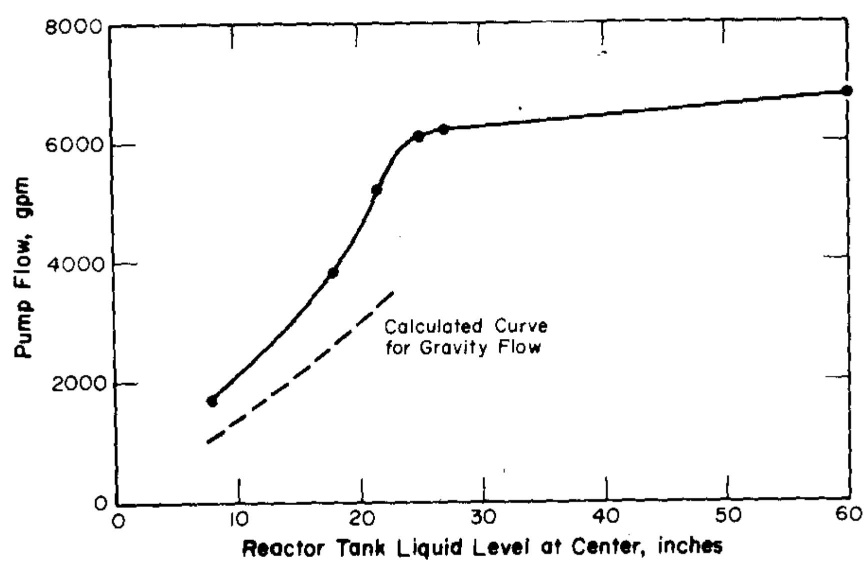


FIGURE 15. Variation in Pump Flow with Liquid Level (5 DC Test)

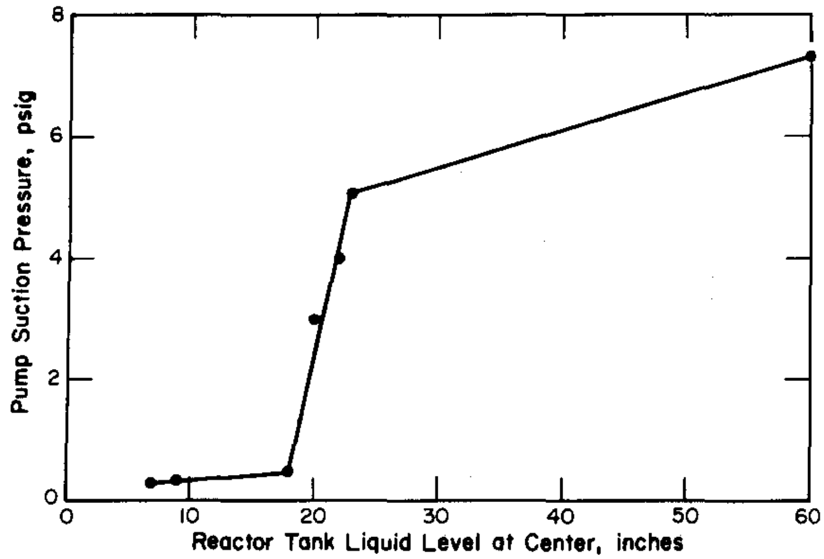


FIGURE 16. Variation in Pump Suction Pressure with Liquid Level (5 DC Test)

ACKNOWLEDGMENTS

The tests described in this report were a joint effort involving the Reactor Technology and Engineering Assistance Sections of the Savannah River Plant and the Reactor Engineering Division of of the Savannah River Laboratory.

APPENDIX A — ANALYSIS OF PLENUM WAVES

PLENUM WAVE BEHAVIOR

Inspection of the starved pump test data showed the plenum wave form at positions X17-Y33 and X27-Y45 to be a "negative surge wave" or trough traveling across the plenum as opposed to the more conventional wave form of a trough and crest. The negative surge wave originates from each plenum nozzle, with a surging pump, and propogates and decays across the plenum.

The wave trough causes only a decrease in level below the mean. However, when several trough waves meet at a point and combine out of phase, the net result is a wave form that oscillates in both directions (of amplitude) about the mean. Such a case will also produce an apparent higher frequency. This is exactly the situation observed at positions X17-Y33 and X27-Y45 (Figure A-1). For the data shown in Figure A-1, pumps 2 and 4 were the primary sources of waves. The wave form at X17-Y33 (halfway between nozzle 4 and plenum center) consists of wave troughs that are at the same frequency as pump 4. Pump 2 was also surging at about the same frequency, but the level oscillations at X27-Y45 (plenum center) were at about twice the frequency observed on either of pumps 2 or 4. Thus, the level oscillations at X27-Y45 are a combined wave form for two waves consisting of troughs only. The reasoning is further supported by the fact that the waves had to arrive at X27-Y45 at 180° out of phase. Since the position is equidistant from both nozzles, pumps 2 and 4 should have been

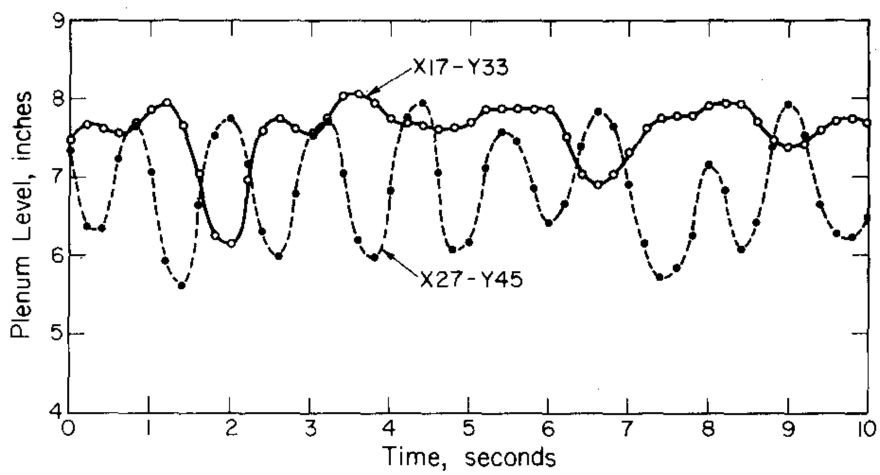


FIGURE A-1. Plenum Level Oscillations

approximately 180° out of phase. Figure A-2 shows that pump flows from pumps 2 and 4 were indeed 180° out of phase (heat exchanger ΔP indicates pump flow).

Average pump flow during surging was determined by integration of the flow-ΔP signal using Simpson's rule. Time increments as small as 0.1 second were used when the flow (ΔP) was varying rapidly. Auto-correlation and cross-correlation were also used to unveil relationships masked because of noisy signals or complexity.* The results of this analysis confirmed the dominate frequencies and phase relations discussed above and further supported the negative surge wave theory.

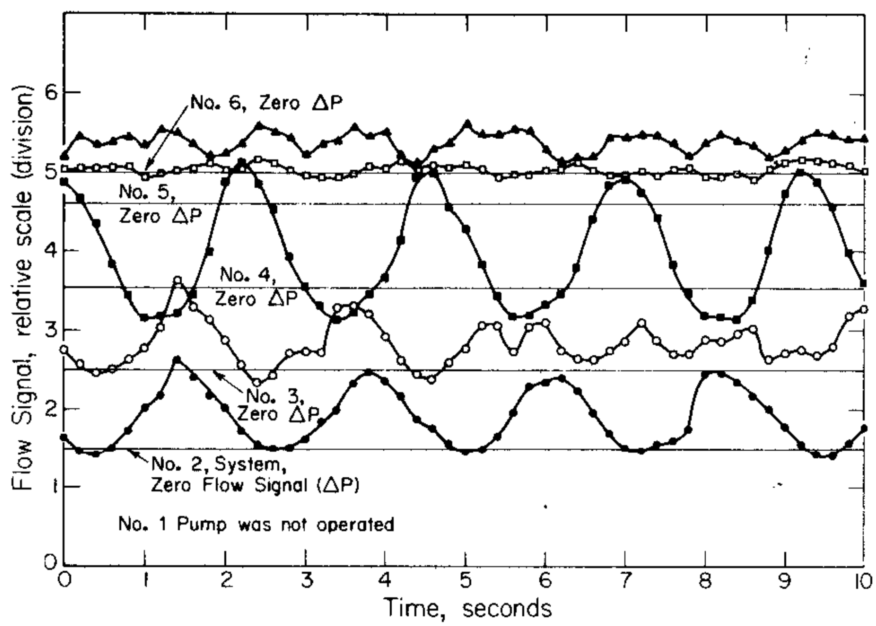


FIGURE A-2. Comparison of Pump Flow Signals

*Auto-correlation and cross-correlation are mathematical procedures for analysis of signals by use of Fourier transforms. Fourier transform theory assumes that any signal can be represented in the limit as a sum of an infinite number of sinusoids at various frequencies. A computer program[2] was used for analysis. This program required finite frequency increments to approximate the signal. The analytical results are presented as a frequency spectrum which shows the variance (or standard deviation) of the frequency component of the signal.

MODEL DEVELOPMENT

Because of the complexity of wave motion in a circular tank and very limited data, a mathematical model was developed to better describe the effects of the plenum waves on plenum levels. The model was developed based on observed behavior of waves traveling across a circular tank and on data from the starved pump test. It was observed that waves generated at the edges of a circular tank do not travel as concentric rings about the origin, but the waves at the tank wall travel faster than the waves moving diagonally across the tank. Because wave speed is a function of wave amplitude, this means the waves at the edge of the tank are larger than the waves at the center after traveling the same distance from the point of origin. Stated in another manner, the waves traveling along the tank wall do not decay as rapidly as the waves traveling diagonally. A model of this type is further supported by plenum geometry because waves traveling at the plenum edge are not subject to decay provided by friction from plenum tubes. The cross-correlation analysis provided additional evidence that wave amplitude decayed more rapidly traveling diagonally than circumferentially. Thus, a three-dimensional plot of the wave amplitude would appear "dished" with the minimum deflection near the center of the tank. The extent of the "dished" effect is not known accurately, but it was estimated from the data. A mathematical model that approximates the "dished" shape was developed based on the following reasoning and assumptions.

Wave amplitude is assumed to decrease (decay) with distance from origin according to the function exp(-cx), where c is a decay constant and x is the distance from the wave origin to the point of interest. Also, the wave amplitude at a point in the plenum is assumed to be the average of a contribution from two sources. One source is the wave traveling in a straight line from the point of origin (nozzle) to the point in question and decaying at the rate c_1. The second source is the wave traveling around the edge of the plenum (outside the tube bank), decaying by the rate c_2, and then traveling by the shortest distance to the point in the plenum. The decay rate on the second source coming from the edge of the plenum is the same as the first source because it too travels past the plenum tubes. This explanation does not mean that two waves reach a point for every wave generated, but it is intended to be a partial explanation of how the model works and why it produces the "dished" shape on wave amplitude. With reference to Figure A-3, the equation is:

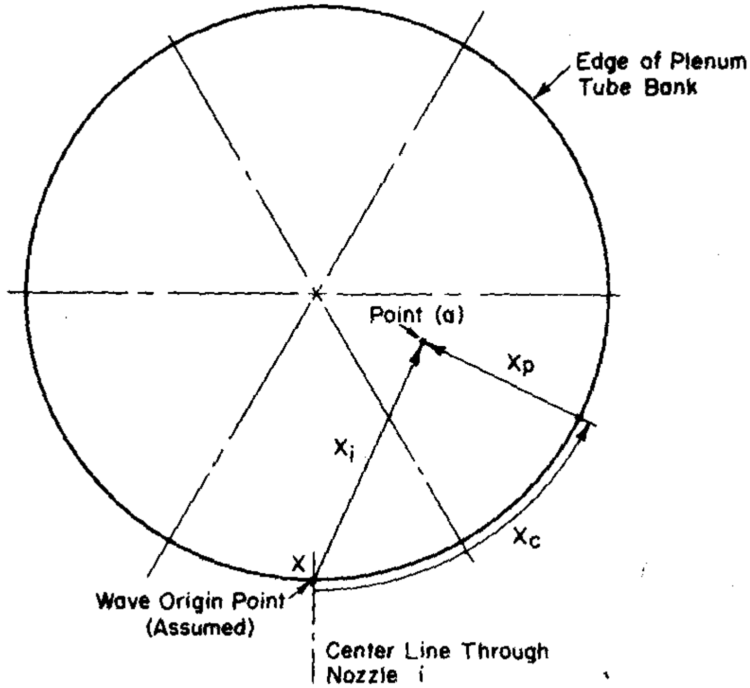


FIGURE A-3. Measurement of Plenum Variables for Mathematical Model

$$\Delta Y_a = A_i \frac{\exp(-c_1 x_i) + \exp(-c_2 x_c - c_1 x_p)}{2} \qquad (1)$$

where:

ΔY_a = wave amplitude at point a, inches

A_i = initial wave amplitude at nozzle i, inches (see Figure A-4)

c_1 = decay constant for waves traveling past plenum tubes, inches^{-1}

c_2 = decay constant for waves traveling along edge of plenum, inches^{-1}

x_i = straight line distance from wave origin (nozzle i) to point a, inches

x_p = shortest distance from point a to edge of plenum, inches

x_c = circumferential distance from wave origin to point from which x_p is measured, inches

The starved pump test data were used to calculate the value of c_1 and c_2. c_2 was calculated to be very nearly zero. The value of c_1 varied with pump flow, primarily because of changes in the average moderator flow velocity across the plenum. The initial decay constant immediately following start of surging was about 0.008 in.$^{-1}$, but rates as high as 0.02 in.$^{-1}$ were observed. A satisfactory average value for c_1 was found to be about 0.013 in^{-1}. These values are a function of plenum geometry.

Equation 1 characterizes only the decay in wave amplitude and not the wave form. The wave form may be approximated by the cosine curve as a function of pump surge frequency and time. With more than one pump surging, the level change at a point is determined by the combined wave forms of all waves reaching a point (one from each system with surging flow). Thus

$$\Delta Y_a = \sum A_i \; (\cos \alpha_i t) \left[\frac{\exp(-cx_i) + \exp(-cx_p)}{2} \right] \qquad (2)$$

where:

α_i = surge frequency of pump i, rad/sec

t = time, sec

The phase relationship between pumps is not included in Equation 2. However, all waves are assumed to be nearly in phase at some point nearly all the time to calculate the minimum plenum level. The level is calculated by setting $\cos \alpha_i t$ equal to 1 and calculating the amplitude decay at a point with all waves in phase. The resulting equation predicts the maximum level change at point (a) caused by waves generated from surging pump flow:

$$\Delta Y_{max(a)} = \sum A_i \left[\frac{\exp(-cx_i) + \exp(-cx_p)}{2} \right] \qquad (3)$$

The calculated initial wave amplitude A_i was determined from the starved pump test data to be a function of flow with a maximum value of about 3.5 inches at about 4,000 gpm. Figure A-4 shows the calculated initial wave amplitude versus pump flow. As flow was reduced below 4,000 gpm, initial wave amplitude decreased apparently because of the operating characteristics of the pump system. That is, the pump surge frequency did not change significantly with flow (see Table II). Thus, at the lower flow rates, the quantity of water pumped in each surge decreased, and the size of the wave that could be generated in the plenum decreased. The value of A_1 is applicable to the Savannah River reactor system only. The maximum size of the surface wave trough is limited by the plenum tube sheets to 8-3/4 inches. Thus, the calculated maximum of 3.5 inches is within the expected value.

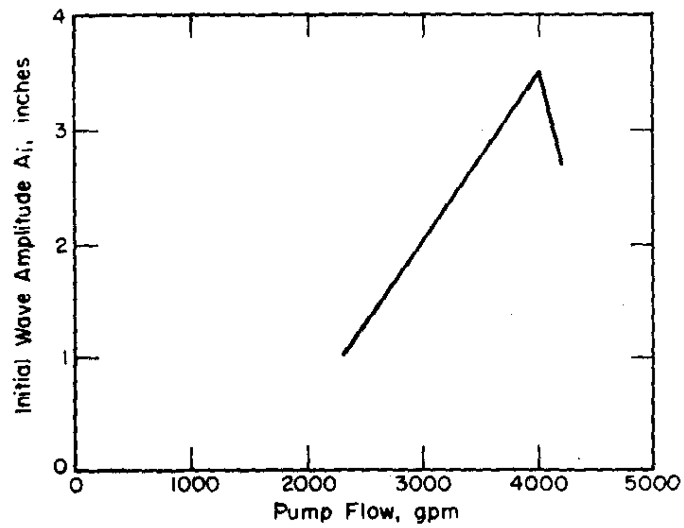


FIGURE A-4. Variation in Initial Wave Amplitute with Pump Flow

The mathematical model given by Equation 3 is considered valid only for about the first ten rows from the center of the plenum (for a full charge), although it may be applicable wherever a free surface exists. However, the center of the plenum is of most interest because the calculated assembly flows are lowest and, therefore, assembly damage is more likely in accident calculations. The model was developed from limited data available only from two locations within the first eight rows. Other data taken from a high-pressure transducer located in front of nozzle 4 where the plenum was full indicated the value of the initial pressure wave (due to flow surge) was significantly greater than that calculated from the surface wave data. Hence, the model is not applicable in the outer rows. Also, there may be significant wave decay in the transformation from a pressure to surface wave.

The duration of level changes in the plenum is one-half of the pump surge period or about one second for Savannah River reactor systems. For reactor assemblies with relatively slow heating rates, flow reductions of one second duration are insignificant and can be ignored in the accident analysis. For low heat capacity assemblies, the surge frequency of the pumps with starved suction must be considered in an analysis of the effect on assembly coolant flow.

REFERENCES

1. J. L. Crandall, ed. *The Savannah River High Flux Demonstration.* USAEC REPORT DP-999, Savannah River Laboratory, E. I. du Pont de Nemours & Co., Aiken, S.C. (1965).

2. S. D. Harris. *Computer Program for Correlation and Spectral Analyses of Reactor Flow Data.* USAEC Report DP-1244, Savannah River Laboratory, E. I. du Pont de Nemours & Co., Aiken, S.C. (1971).