REPORT NO. ACNP-62004

PATHFINDER ATOMIC POWER PLANT

BUTTERFLY VALVE

CAVITATION TEST

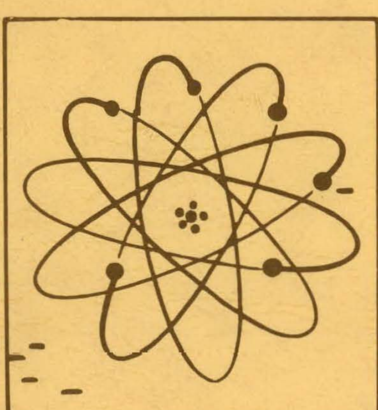
March 20, 1963

Submitted to

U. S. ATOMIC ENERGY COMMISSION
NORTHERN STATES POWER COMPANY
and
CENTRAL UTILITIES ATOMIC POWER ASSOCIATES

by

ALLIS-CHALMERS MANUFACTURING COMPANY
ATOMIC ENERGY DIVISION
Milwaukee 1, Wisconsin



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DISCLAIMER

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BUTTERFLY VALVE CAVITATION TEST

by N. P. Grimm

Submitted to

U. S. ATOMIC ENERGY COMMISSION
NORTHERN STATES POWER COMPANY
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by

ALLIS-CHALMERS MANUFACTURING COMPANY

Under
Agreement dated 2nd Day of May 1957, as Amended
between
Allis-Chalmers Mfg. Co. & Northern States Power Co.
under
AEC Contract No. AT(11-1)-589

March 20, 1963

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Reviewed by [signature]

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ACNP-62004

REPORT

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BUTTERFLY VALVE CAVITATION TEST

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FOREWORD

One of a series of reports on research and development in connection with the design of the Pathfinder Atomic Power Plant, this particular report deals with butterfly valve cavitation tests.

The Pathfinder plant will be located at a site near Sioux Falls, South Dakota, and is scheduled for operation in 1963. Owners and operators of the plant will be the Northern States Power Company of Minneapolis, Minnesota. Allis-Chalmers is performing the research, development, and design as well as being responsible for plant construction.

The U.S. Atomic Energy Commission, through Contract No. AT(11-1)-589 with Northern States Power Company, and Central Utilities Atomic Power Associates (CUAPA) are sponsors of the research and development program. The plant's reactor will be of the Controlled Recirculation Boiling Reactor type with Nuclear Superheater.

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1.0 INTRODUCTION

The reactor for the Pathfinder Atomic Power Plant has three external recirculation loops. A constant-speed recirculation pump (Ref. 1) located in each loop circulates coolant-moderator through the core. Figure 1 shows the arrangement of one of the loops.

A 20-1/2 in. diameter butterfly valve located in the discharge leg of each loop is used to control the recirculation flow. For long periods of operation, essentially cavitation-free operation of the valves is required, because of possible material damage and vibration. Consequently the operating range of the butterfly valves must be limited.

In order to specify the limits of operation for the reactor valves, a dimensionless cavitation number (sigma) was used. This number is related to the flow parameters such that the cavitation condition may be determined by its value. At critical values of sigma, cavitation may be expected.

Although critical values of sigma can be calculated from theory, limited information available on butterfly valve tests showed disagreement with these values. Since experimentally determined critical values are not available for the Pathfinder butterfly valves, a test of such a valve is necessary, so that the operating range of the valves can be specified.

2.0 OBJECTIVE

Tests of an 8-in. diameter butterfly valve were conducted to determine the critical values of sigma at incipient cavitation. The test butterfly valve was similar to the valve used in Pathfinder. The experimentally

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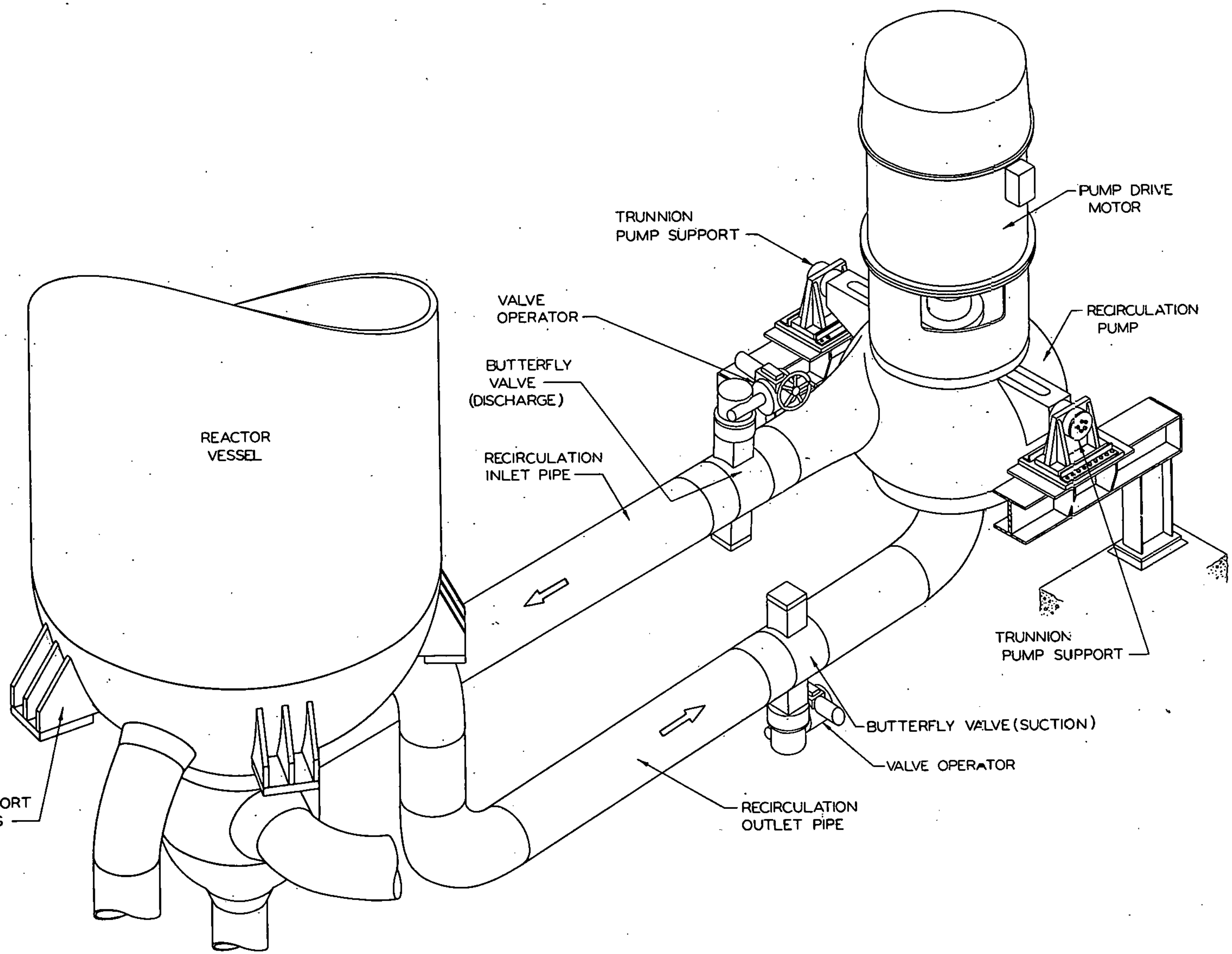

Figure 1 - Reactor Recirculation Pump Loop (43-002-195)

determined values of the cavitation number were then used to determine the cavitation-free control range of the Pathfinder valves.

3.0 SUMMARY AND CONCLUSIONS

The tests showed that both the undissolved and dissolved air content of the water caused cavitation to occur at higher values of sigma. Since the reactor water will be highly deaerated, the air content of the test water was reduced to minimize these effects.

At incipient cavitation, the mean pressure of the flow did not reach the vapor pressure of the water as expected. It appeared that cavitation first occurred in the vortices downstream of the valve disk. By relating the pressure within these vortices to the mean pressure of the flow by a fraction of the velocity head in the valve, an equation was developed to determine, semi-empirically, the critical values of sigma. The calculated critical values of sigma were in close agreement with the values determined experimentally.

Operation of the Pathfinder reactor's recirculation butterfly valves is to be limited to avoid possible cavitation damage. Based on experience gained from the 8-in. butterfly valve test, a limiting cavitation condition was defined for the reactor butterfly valves. Limiting cavitation describes a cavitation condition where no cavitation damage will occur to the valve or to the downstream recirculation piping. The cavitation-free operating limits for the recirculation butterfly valves can be determined for any operating condition by calculating the cavitation constant, sigma, at that condition and by comparing it to the limiting sigma value.

During three pump operation at the normally expected power and recirculation flow conditions, the throttle range for the recirculation butterfly valves will be from 64,300 gpm to 45,000 gpm. Also, at the normal power and recirculation flow conditions, the throttle range will be from 49,500 gpm to 40,000 gpm for two pump operation and from 27,500 gpm to 24,500 gpm for one pump operation.

The limits that have been determined represent the safe operating limits for the butterfly valves for prolonged periods of operation. More severe cavitation conditions can be tolerated for short periods of operation.

4.0 THEORY OF CAVITATION CONSTANT

Cavitation in a flowing liquid is caused by local reductions in pressure to the vapor pressure of the liquid. This condition results in the formation of vapor bubbles, which are carried downstream to regions of higher pressure, where they collapse. This sudden collapsing of bubbles can cause undesirable noise, vibration, and pitting of materials.

Figure 2 shows the flow through a butterfly valve with an inclined valve disk. Flow from station (l) to (j) results in a velocity increase with decrease in static pressure head. Since the increase in velocity is a highly efficient process, the head loss between the two stations due to flow acceleration may be neglected, and the static pressure head at station (j) is evaluated with the Bernoulli equation between the two points thusly,

$$H_l + V_p{}^2/2_g = H_j + V_j{}^2/2_g \qquad (1)$$

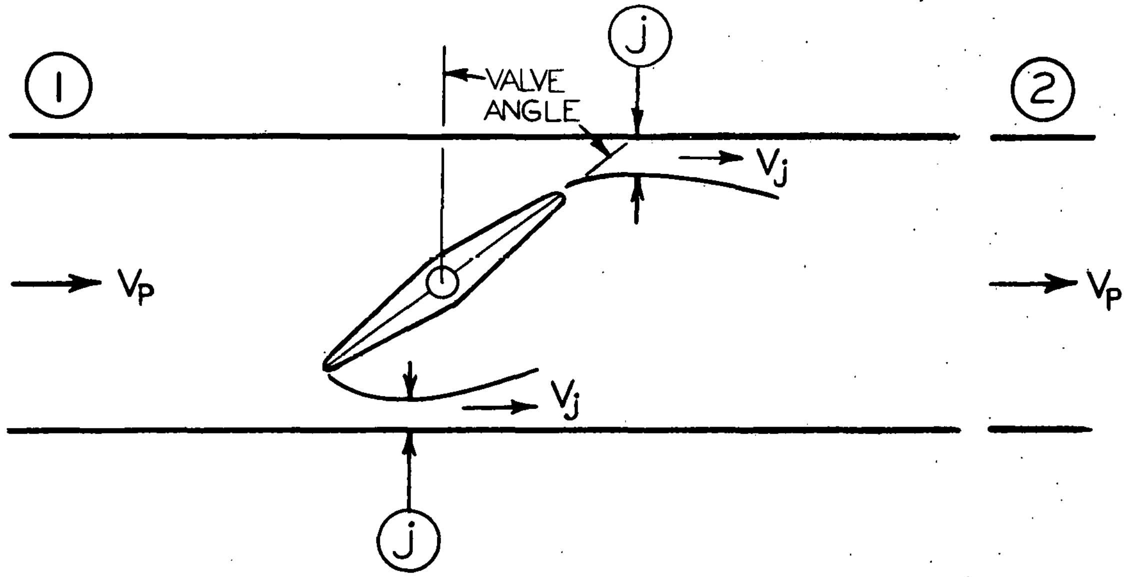

Figure 2 - Flow Through a Butterfly Valve (43-025-357)

where,

V_p - is the pipe velocity

V_j - is the jet velocity

H_1 - is the static pressure head upstream of the valve

H_j - is the static pressure head at the point of maximum jet contraction.

Cavitation occurs when the static pressure head, H_j, is reduced to the liquid's vapor-pressure head, B, i.e., when H_j is equal to B.

In order to describe these conditions for cavitation in terms of quantities that are easily measured and calculated in tests of valves, several additional equations are introduced. Since the velocity in the pipe is the same upstream and downstream from the valve, the head loss across the valve is,

$$\Delta h = H_1 - H_2 \qquad (2)$$

where,

Δh- is the head loss across the valve measured between stations (1) and (2). See figure 2.

H_2- is the static pressure head downstream from the valve.

The abrupt decrease in velocity from station (j) to station (2) caused separation of the flow. The high-intensity of shear between the high-velocity jets on either side of the slow moving flow downstream of the valve disk causes eddies to be formed, which results in a head loss. Since the flow change between stations (j) and (2) is extremely abrupt, the effect of boundary shear stress is comparatively small, and the head loss can be determined by a sudden expansion loss. By writing the momentum, Bernoulli, and continuity equations between stations (j) and (2), the head loss due to the sudden expansion is found to be equal to:

$$\Delta h = \frac{(V_j - V_p)^2}{2g} \tag{3}$$

Noting that cavitation occurs when H_j is equal to the vapor-pressure head (B), and combining Eq. (1), (2), and (3), the following equation results:

$$H_2 - B = \frac{V_p}{g}\sqrt{2g\Delta h} \tag{4}$$

which states the conditions necessary for cavitation.

To put Eq. (4) in the form of a dimensionless cavitation index that has been used by other investigators, and to evaluate the index, the following equation is used.

$$Q = C_f A_p \sqrt{2g\Delta h} \tag{5}$$

where,

Q - is the volumetric flow

C_f - is the coefficient of discharge

A_p - is the area of the pipe

Continuous pipe tests with a two-dimensional butterfly valve over a wide range of Reynolds numbers indicate that the coefficient of discharge is relatively constant, and no obvious viscous effects are present(Ref. 2). This is entirely logical since the head loss is independent of boundary friction and is due primarily to the abrupt flow expansion from station (j) to (2).

Eq. (5), combined with the continuity equation, $Q = V_p A_p$, reduces to:

$$\frac{V_p}{C_f} = \sqrt{2g\Delta h} \tag{6}$$

Substituting Eq. (6) into Eq. (4) and dividing both sides by the term, $\Delta h + V_p^2/2g$, results in the following equation with dimensionless terms, in which the right side of the equation is only a function of the coefficient of discharge.

$$\sigma = \frac{H2 - B}{\Delta h + V_p^2/2g} = \frac{2C_f}{C_f^2 + 1} \quad (7)$$

where, σ - is the cavitation constant.

Eq. (7) has been used in valve cavitation tests by other investigators (Ref. 3, 4). Other authors have made a similar analysis to predict the conditions necessary to cause cavitation in butterfly valves (Ref. 5, 6).

If the critical value of sigma is evaluated by appropriate values of C_f, it can be seen that sigma approaches a maximum value of 1.0 when C_f is equal to 1.0. This is in sharp disagreement with test data given by Bleuler (Ref. 7) which indicates that the critical value of sigma is 2.5 for the butterfly valve tested.

It is quite obvious, then, that it is not the static pressure in the jet stream which governs the onset of cavitation but rather fluctuations about this mean value. Rapid changes in boundary configuration result in separation of the flow, which causes vortices to be formed. These vortices produce local pressure gradients considerably in excess of the general gradient for the stream (Ref. 8).

It would appear that the major reason for the discrepancy between the cavitation point determined by Eq. (7) and experimental tests, can be explained by the presence of vortex cavitation. To describe this type of cavitation, a distinction will be drawn between two types of cavitation. The first is boundary cavitation which occurs in low pressure regions caused by curvature or irregularities of solid boundaries. The second is vortex cavitation which occurs in the individual vortices of highly turbulent flow found downstream of an abrupt expansion or in the shear zone surrounding a submerged jet (Ref. 9). When separation occurs, as it does downstream of a butterfly valve disk, it is no longer necessary that the mean pressure in the flow approach the vapor pressure of the fluid. It has been found that cavitation initially occurs within the trailing vortices that are formed following a sudden expansion. The local pressure within these vortices may be lower than the mean pressure by 50 per cent or more of the dynamic pressure of the flow (Ref. 10).

Since the pressure within these vortices is less than the mean pressure by a percentage of the velocity head of the flow, the low-pressure point in the flow can be written in terms of the mean pressure head at the point of maximum jet contraction (H_j) and the jet velocity (V_j).

$$H_v = H_j - (X)V_j^2/2g \tag{8}$$

where:

H_v - is the pressure head in the vortices

X - is the fraction of the velocity head

Cavitation occurs when the pressure head in the vortex (H_v) equals the vapor pressure head (B). Rearranging Eq. (8) and noting the condition for cavitation gives:

$$H_j = B + (X)V_j^2/2g \tag{9}$$

Substituting Eq. (9) in Eq. (1) along with Eqs. (2), (3) and (6) results in the same group of variables as Eq. (7).

$$\sigma = \frac{H_2 - B}{\Delta h + \frac{V_p^2}{2g}} = \frac{(X)\, C_f^2 + (2X+2)C_f + X}{C_f^2 + 1} \qquad (10)$$

The same dimensionless grouping of variables appears to be valid for both boundary and vortex cavitation conditions.

Although the low pressure in the vortices is proportional to the velocity head of the flow, the percentage is not known. Because of this, a test appeared to be the only way to find the necessary information.

The dimensionless cavitation constant used in these tests to correlate the cavitation condition is defined below:

$$\sigma = \frac{H_2 - B}{\Delta h + V_p^2/2g} \qquad (11)$$

where:

σ - sigma (cavitation constant)

H_2 - is the absolute static pressure head in pipe 15 pipe diameters downstream from valve (ft. of fluid flowing)

B - is the vapor pressure head of water; absolute pressure at test temperature (ft. of fluid flowing)

Δh - is the differential head across valve less pipe loss, between stations 3 pipe diameters upstream and 15 pipe diameters downstream of the valve (ft. of fluid flowing)

V_p - is the velocity in pipe (ft./sec.)

g - is the acceleration due to gravity (32.2 ft/sec^2)

By using the same index (above) that has been used by other investigators, the results obtained can be compared. The index is convenient because the value of all terms can be easily calculated.

Equal Reynolds numbers are normally required in model tests to obtain complete dynamic similarity. However, in the case of cavitation, where it is not purely a case of frictional phenomena, it is possible to deviate from the theoretical requirement. When the flow separates from the surface and eddies form in the turbulent wake downstream of the valve disk, the resistances and pressures are independent of Reynolds number (Ref. 11).

It was felt that the threshold of incipient cavitation could be satisfactorily represented by the test valve, because the test valve would reproduce the same pressure field that exists at the reactor valve. This means the same boundary and vortex cavitation conditions occur.

The cavitation conditions in two similar butterfly valves will be similar when the model and full size valve operate at the same sigma value. Similar cavitation means the form and extent of the cavitation voids are the same (Ref. 12).

5.0 DESCRIPTION OF BUTTERFLY VALVE TEST LOOP

A combination loop was constructed for testing internal steam separators and the butterfly valve. The test loop is shown in Figures 3 and 4. The vertical standpipe was used primarily to test steam separators in low-

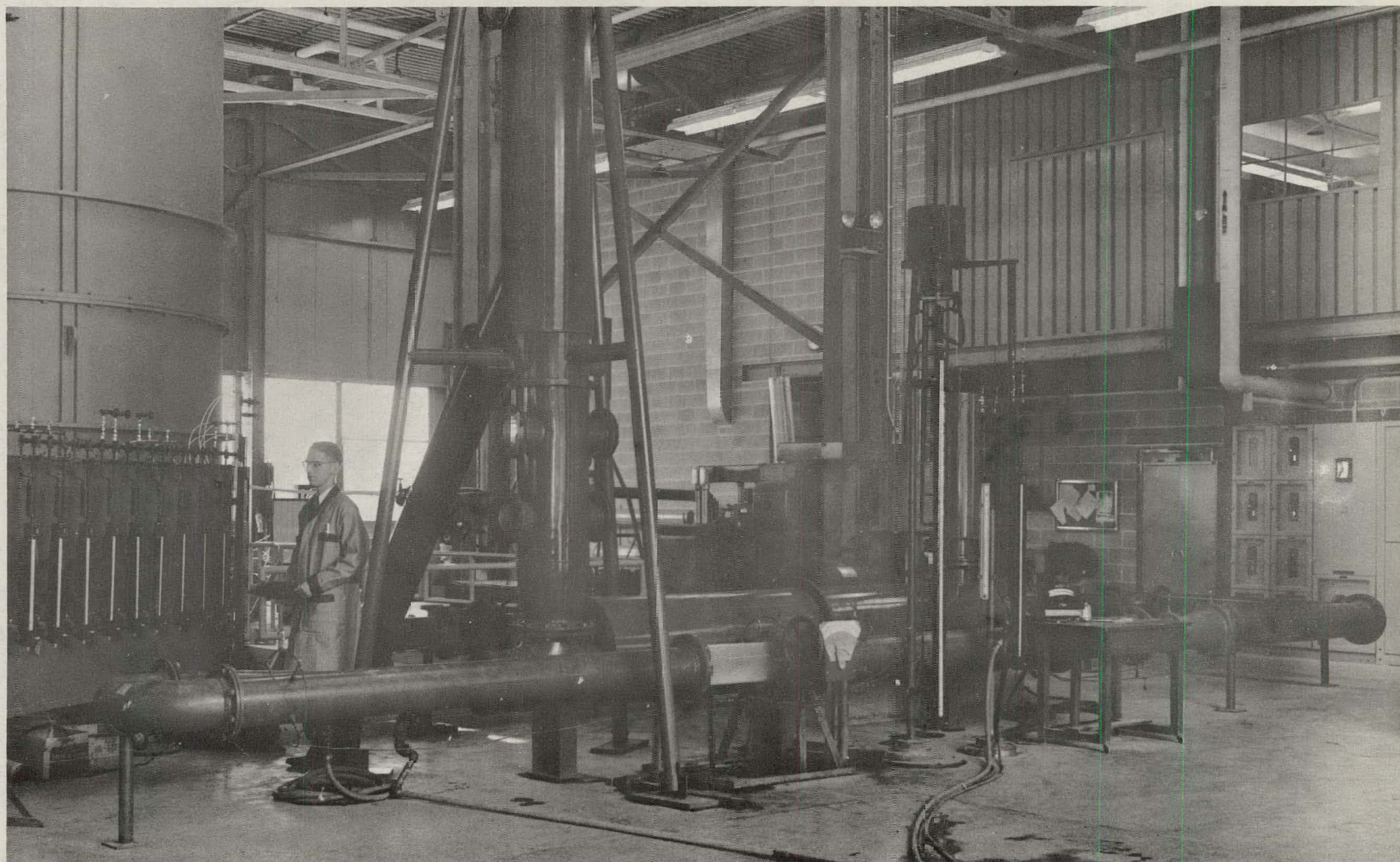

Figure 3 - Butterfly Valve Test Loop (203852-C)

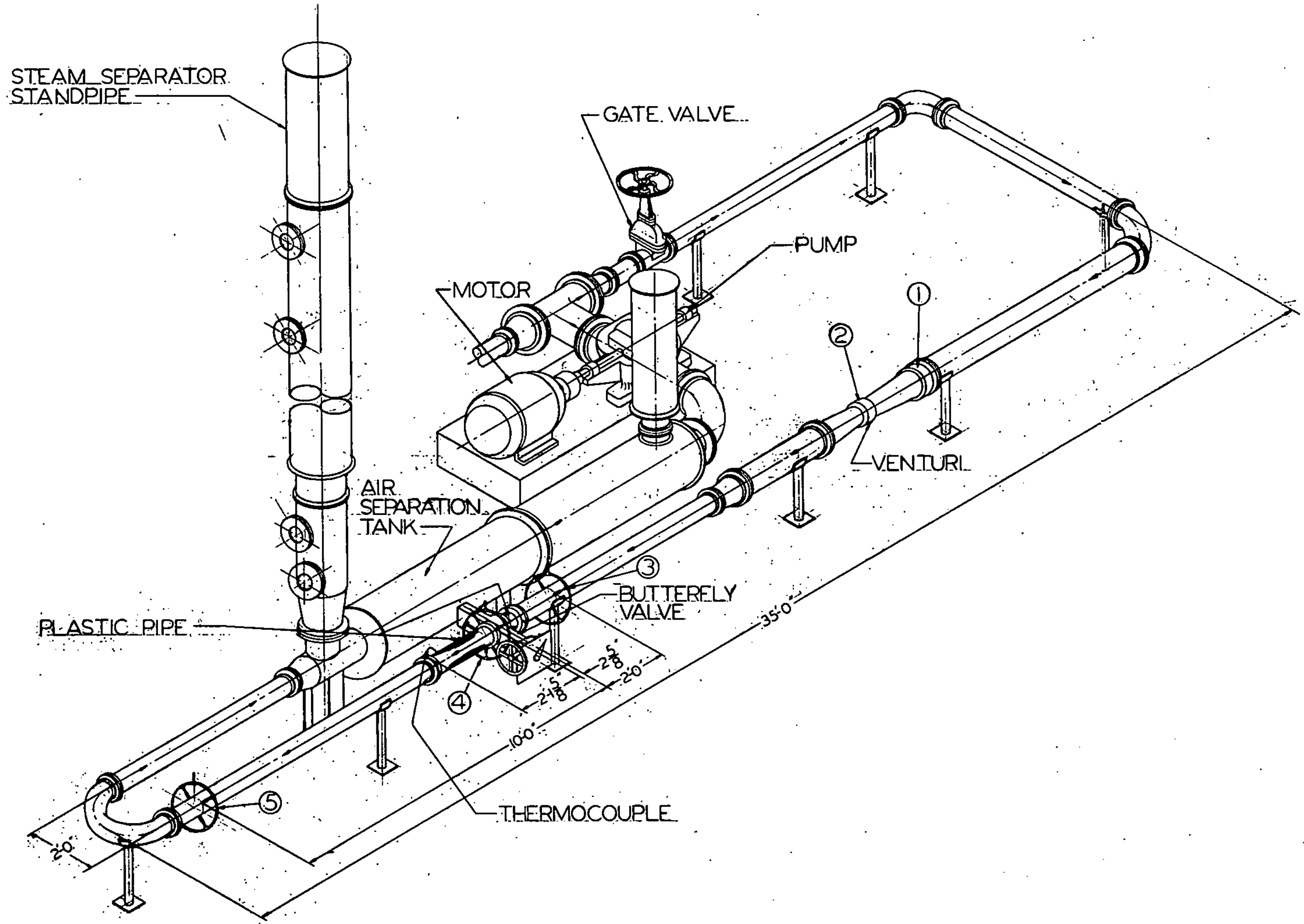

Figure 4 - Isometric View of Butterfly Valve Test Loop (43-401-039)

pressure air-water tests. The horizontal loop was used to test the model 8 in. diameter butterfly valve.

With respect to tests of the butterfly valve, the major components of the loop are as follows:

1. an 8 in. diameter butterfly valve of streamlined profile with clear acrylic-plastic pipe sections 8 and 25 in. long located upstream and downstream from the valve respectively
2. a 12 x 12 in. centrifugal pump rated at 5,000 gpm with a head of 55 ft driven by a 125-hp motor
3. an 8 in. gate valve located on the discharge side of the pump
4. a calibrated 10 x 6-1/2 in. venturi meter for measuring flow.

The piping was acid-cleaned and painted with a rust-resistant paint. A filter for removing rust was installed in a bypass line parallel with the pump. These provisions kept the water clean, so that the valve could be observed through the plastic sections.

A heat exchanger located in the air-separation tank was used to regulate loop temperature. System pressure was controlled by regulating the water level in the standpipe. Flow disturbances were reduced at the pipe joints upstream and downstream from the butterfly valve by filling the small cavity between joints with epoxy resin, so that they were flush with the inside of the pipe.

Temperature was measured with an iron-constantan thermocouple projecting into the flow stream. The thermocouple, which had an accuracy of ± 2 F, was located in the plastic pipe flange downstream from the valve, as shown in Figure 4.

Pressure measurements were made at the five locations shown in Figure 4. Pressure taps 1 and 2 on the venturi were each internally manifolded to measure an average pressure, and were provided with a bleed valve on the top. A 40 in. mercury filled manometer was connected across the taps to measure flow.

Locations 3 and 5 each had four pressure taps spaced at 90 degree intervals. Location 4 had six pressure taps. The pressure taps at each location were connected by rings, and the bottom of the rings were connected to the manometers. Drain cocks were installed at the top of each ring and at high points above each manometer to vent entrapped air.

The pressure taps at location 4 were provided with individual valves. With all valves open, the average pressure at the location was obtained. An indication of pressure distribution around the pipe circumference could be obtained by opening individual valves.

An 80 in. mercury manometer was connected to indicate the differential pressure between pressure taps 3 and 5, or between taps 3 and 4. A U-tube manometer connected to pressure tap 5 at one end and open to the atmosphere at the other end, was used to measure system pressure.

Figure 5 shows the disk profile of the butterfly valve tested. The valve

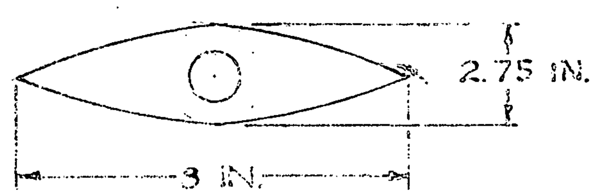

Figure 5 - Valve Disk Profile (43-025-358)

was seated in a position perpendicular to the pipe centerline. The full open and closed positions of the valve were 90 and 0 degrees, respectively.

Downstream pressure head, H_2, was measured 15 pipe diameters downstream from the valve (tap 5), which permits complete pressure regain. Since the length of pipe between pressure taps measuring head loss across the valve (tap 3 to tap 5) was significant (18 pipe diameters), the pipe friction was subtracted from the drop across the valve. The pipe friction was determined by measuring the drop at various flows with the valve disk and shaft removed.

Downstream pressure (H_2) was controlled by regulating the water level in the standpipe. The loop temperature was controlled by an immersion heater located in the standpipe, and by a heat exchanger in the air separation tank. Any air that came out of solution during tests rose in the standpipe or was collected in the upper portion of the air-separation tank, where it was bled off. The flow in the loop was controlled by the gate valve located at the discharge of the pump.

6.0 PRELIMINARY TESTS

6.1 Effect of Cavitation on the Coefficient of Discharge

The cavitation threshold for hydraulic turbines and gate and globe valves is often defined as the point at which performance begins to deteriorate. In the case of valves this would be indicated by a rapid drop in the coefficient of discharge. Therefore, two tests were conducted to determine if a cavitation threshold, so defined, is obtained with the model butterfly valve.

The tests were conducted at a constant temperature at various valve angles. In the first test, the flow through the butterfly valve was increased from a very low value to a point at which advanced cavitation was obtained by regulating the gate valve. In the second test, the flow was held constant at approximately the incipient cavitation condition, and the downstream pressure was decreased to obtain cavitation. Because of the limited range available for the downstream pressure head (0 to 20 ft. gage), severe cavitation was not obtained in this test. The cavitation condition at various points was noted by visual observation and listening. System pressure, temperature, flow, and pressure drop across the valve were recorded at various points, so that sigma and the coefficient of discharge could be calculated. A sample calculation of these quantities is given in Appendix A.

The results of the first test are plotted in Figure 6. The final point to the right of each of these curves represents a condition where the cavitation noise was loud, and was accompanied by vibration of the pipe. The data shows the drop in coefficient of discharge to be too gradual to determine a critical value of sigma. The drop in the coefficient of discharge for the second test was even less.

6.2 Observation of Cavitation

During the tests, cavitation could be detected by listening for noise or by watching for bubbles in the plastic pipe sections. The first indication of cavitation was a slight noise above background noise, which was accompanied by the occasional collapse of

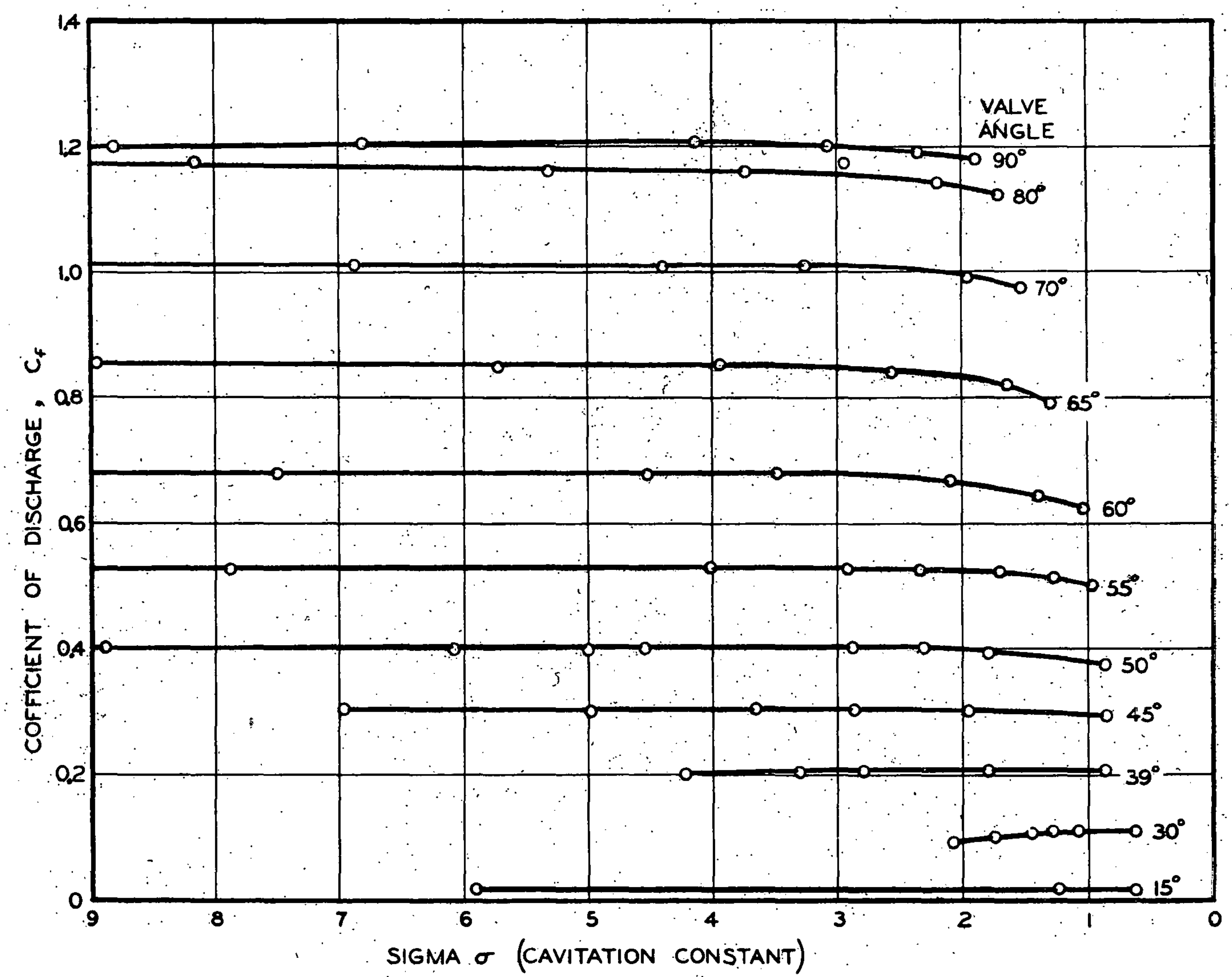

Figure 6 - Drop in Coefficient of Discharge with Cavitation (43-025-359)

vapor bubbles in the downstream plastic pipe. This condition was defined as the incipient cavitation point. Sigma for incipient cavitation varied from 2 to 5 depending on valve angle.

As cavitation was increased beyond the incipient cavitation point, bubbles could be seen (as a cloudy area) in the turbulence downstream of the valve. Figure 7 shows cavitation in the cloudy area and bubbles occurring in the trailing vortices downstream of the valve. The majority of the cavitation bubbles appeared to collapse in the flow stream rather than on the pipe wall. Cavitation was mild at this condition and produced a sound similar to that of sand flowing in a pipe. For this cavitation condition sigma varied from the incipient values to a value of about 1.5.

In a sigma range of 1.5 to 1.0, cavitation appeared as a dense cloudy area immediately downstream from the opening between the valve disk and pipe. The collapse of vapor bubbles was observed on the surface of the downstream plastic pipe. Cavitation in this range of sigma caused pipe vibration, and sounded similar to gravel flowing in a pipe.

When a sigma of 0.5 was reached, a large void appeared downstream of the valve.

6.3 Reproducibility of Sigma Values at Incipient Cavitation

Several tests were conducted to determine the critical values of sigma at incipient cavitation. In these tests the temperature,

← FLOW

Figure 7 - Cavities in Trailing Vortices Sigma = 1.05, valve angle 41°, flow 5.17 ft^3/sec. The black (039-6) object at the right is a stud bolt holding the downstream plastic pipe to the valve body. (039-6)

downstream pressure head, and valve angle were set for each run, and the flow was increased to produce cavitation. Runs were made at temperatures from 106 F to 197 F, at downstream heads of 40 to 60 feet of water, and at valve angles from 90 to 35 degrees. Data was recorded at incipient cavitation so that sigma and coefficient of discharge could be calculated.

The tests showed that the critical values of sigma (incipient cavitation point) varied with valve angle. This is reasonable since Eq. (7) and Eq. (10) show sigma to be a function of the coefficient of discharge (C_f) which is a function of valve angle. The variation in sigma with valve angle obtained in different sets of runs was consistent. However, considerable scatter was obtained in the critical values of sigma for a given valve angle.

To determine if the scatter of cavitation noise was due to the audible detection method, a test was conducted with cavitation detected entirely by visually observing the collapse of vapor bubbles in the downstream plastic pipe. The visual method of cavitation detection showed a more severe cavitation condition than the incipient cavitation point. This is reasonable, since at the incipient cavitation point only an occasional vapor bubble could be seen. The incidence of cavitation determined visually was in close agreement with the incipient cavitation point although about 10 per cent lower. The lower values of sigma were caused by the slightly more severe cavitation condition.

Since the visual cavitation test checked with the cavitation detected audibly, it may be concluded that the noise heard was the incipient cavitation point. This is significant since a gradual clouding of the plastic pipe over the testing period impaired visual detection.

To determine if the scatter in the incipient cavitation data was due to the procedure used (increasing flow with the valve angle held constant), a variation was tried. In this procedure the temperature and pressure were again held constant, but flow was now set at a constant value. The valve was closed until the incipient cavitation condition was reached. The critical values of sigma determined by this procedure agreed with the values determined by changing the flow.

For sigma to be a reliable indication of the cavitation condition, the same value of sigma should be obtained at incipient cavitation regardless of the pressure or temperature at which the test was run. Test data was picked from runs at 45 degrees at various temperatures and pressures to determine if the scatter in the critical value of sigma at incipient cavitation could be due to the test temperature or pressure. Only runs at 45 degrees were used, so that the pressure recovery would be the same. Pressure recovery is that portion of the velocity head through the valve that is converted back into pressure head downstream of the valve.

Sigma at incipient cavitation for these runs varied from 2.05 to 3.04 as shown in Table I.

TABLE I

INCIPIENT CAVITATION AT A VALVE ANGLE OF 45 DEGREES

$$\sigma = \frac{H_2 - B}{\Delta h + V_p^2/2g}$$

SIGMA	Downstream Pressure Head Feet (H_2)	Vapor Press. Head Feet (B)	Valve Head Loss Feet (Δh)	Pipe Velocity Head Feet $V_p^2/2g$
2.68	59.58	2.71	19.64	1.569
2.57	47.68	2.85	16.13	1.308
2.50	59.56	3.99	20.88	1.321
2.68	49.56	5.21	15.28	1.228
2.73	41.13	7.93	11.21	0.910
2.05	51.24	7.93	19.81	1.242
2.22	46.53	8.57	15.77	1.275
2.37	48.72	8.57	15.67	1.252
*3.04	51.13	8.57	12.95	1.047
2.39	49.55	15.85	13.05	1.032
2.07	45.36	18.21	12.34	0.735
*3.03	51.64	25.97	7.84	0.619

*Indicates tests where entrained air was visible in the water.

Although this spread was large, no relationship between sigma and the relative magnitudes of B and H_2 was detectable within the limited range of pressure and temperature of the test loop. If only test data from runs that contained no entrained air were used, sigma would be reduced to the range of 2.05 to 2.73. Entrained air is revealed by undissolved or visible air bubbles in the water.

From these test results it may be concluded that the variation of sigma depends primarily upon the air content of the water.

6.4 Effect of Air Content on Incipient Cavitation

6.4.1 Objective

To determine the effect of air content on cavitation data, tests were conducted with water of reduced air content. These tests are to be compared with the preceding tests which were conducted with aerated water.

6.4.2 Procedure

The incipient cavitation test procedure described in Section 6.3 was used.

The air content of the water was reduced by the following methods. First, air bleed off points located on the high sections of the piping were opened to remove any undissolved air that might collect in these pockets. These bleed off points were left open to remove air that came out of solution as the temperature was raised. The largest portion of air was removed in the steam separator standpipe where the air bubbles were free to rise (Fig. 4). Any air collected in the air separation tank could also be bled off. The air content was further decreased by cycling the water temperature until all entrained air was removed. Temperature cycling consists of raising the temperature about 10 degrees above the test temperature for approximately 2 hours and then reducing it to the test level again. The temperature reduction was accomplished with the heat exchanger in the air separation tank. It was also found that by leaving the water in the test loop for several days of testing the water became more deaerated.

6.4.3 Results

The effect of air content on test data can be seen in Figure 8. Curve A was plotted from data taken from water that contained entrained air. Curve B was developed from data taken with water that was temperature cycled before the test data was taken. No entrained air was visible in this water. Curve C represents data taken with water that had been temperature cycled several times and had remained in the test loop for over a week. As shown by Figure 8, the air content of the water has an appreciable effect on cavitation inception. With reduced dissolved and entrained air, the critical value of sigma was reduced. Also, less scatter in the test data was noted. The more consistent data was due to the sharp collapse or distinct crackling noise that is characteristic of cavitation in deaerated water. In contrast, cavitation noise in water that contained entrained air was found to be muffled. The incipient cavitation point was difficult to detect in aerated water because of muffled

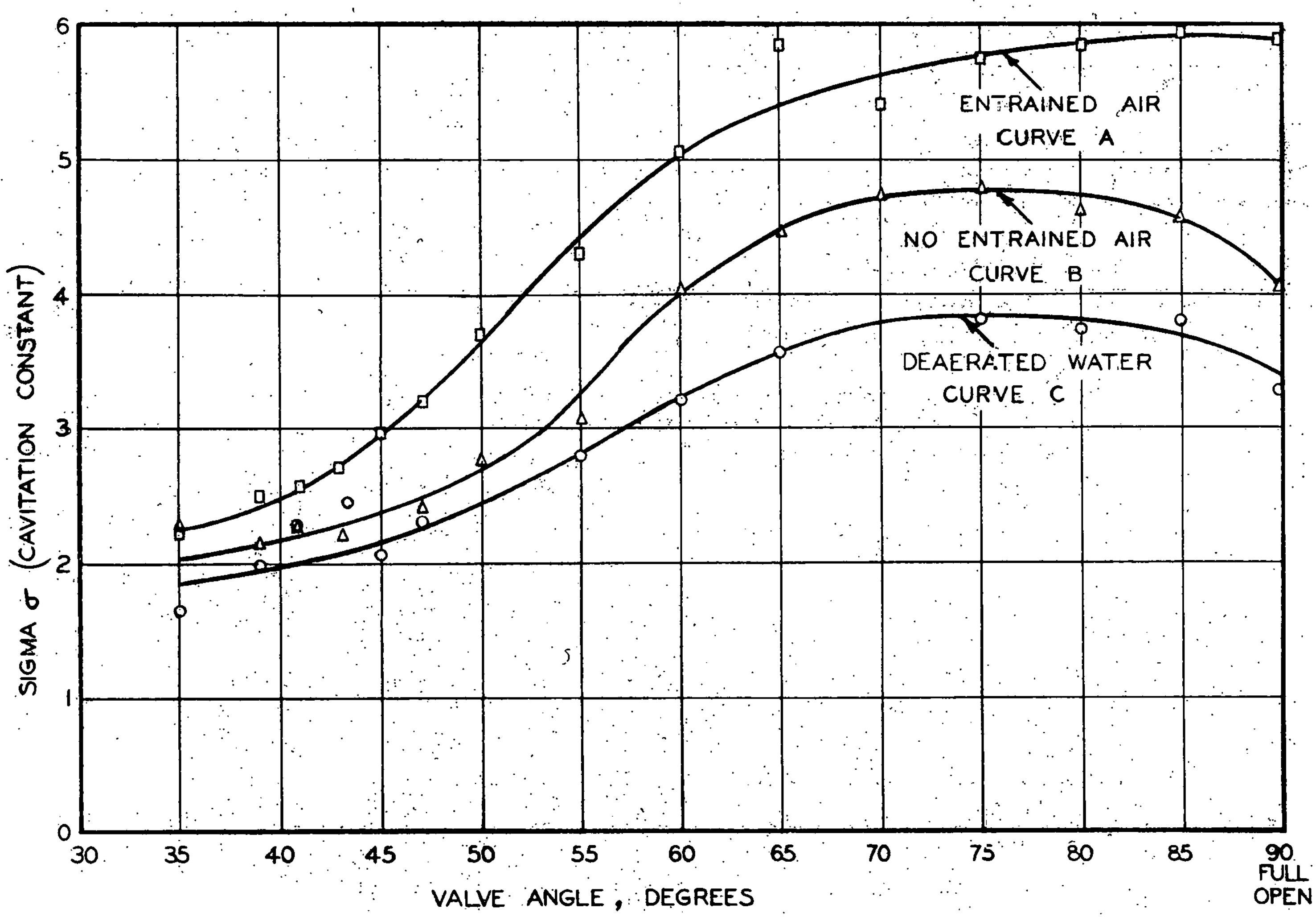

Figure 8 - Sigma at Incipient Cavitation Versus Valve Angle with Water of Differing Air Content (43-025-360)

cavitation. This was reflected in a wide scattering of data with aerated water. It was also noted that as cavitation was increased beyond the incipient point with aerated water, the violence was considerably less than that with deaerated water.

These observed differences are understandable when a distinction between two types of cavitation is made. Vaporous cavitation is the sudden expansion of a vapor bubble due to vaporization of the liquid at the bubble wall. Gaseous cavitation is the relatively slow expansion of a gas bubble due to diffusion. Vaporous cavitation occurs when the low pressure point reaches the vapor pressure. However, gaseous cavitation can occur at pressures greater than the vapor pressure (Ref. 13). This accounts for the larger values of sigma with water that contains air. Downstream of the valve where the pressure is greater, the vapor bubbles collapse violently, whereas the gaseous bubbles are compressed. Thus, the compression of the gaseous bubble cushions and muffles vaporous cavitation noise.

Curve B of Figure 8 shows that even though there is no entrained air visible in the water, the critical values of sigma were higher than the deaerated Curve C. The values of sigma may be affected by dissolved air or minute air bubbles that adhere to particles of dirt in the water which were too small to be seen.

7.0 TESTS TO DETERMINE THE CRITICAL VALUES OF SIGMA

7.1 Tests with Deaerated Water

7.1.1 Objective

Tests were conducted to determine the value of sigma at incipient cavitation with deaerated water. This is necessary because the reactor water will be highly deaerated.

7.1.2 Procedure

Incipient cavitation data was not recorded until the air content of the water was reduced by the methods described in Section 6.4. In these tests the temperature and downstream pressure were held constant. The valve angle was set in each run and the flow increased from a low value to the point of incipient cavitation by control of the gate valve located upstream. The data recorded at incipient cavitation was system pressure, temperature, flow, and pressure drop across the valve. This procedure was followed for 15 intermediate valve angles between 90 degrees and 35 degrees to complete a test.

7.1.3 Results

The results of these tests are shown in Table II. Even though the procedures of Section 6.4 were used to reduce the air content of the water, small amounts of entrained air were visible in Tests 4 and 5. The air content of these tests is reflected in the higher values of sigma at incipient cavitation.

TABLE II

CRITICAL VALUES OF SIGMA AT INCIPIENT CAVITATION

Test Number	1	2	3	4	5	6	7	8	9	10
Test Temp (°F)	108	150	175	114	150	125	151	132	147	120
Downstream Pressure Head (Ft.)	47.5	48.6	49.5	51.0	51.1	45.4	46.5	49.6	51.2	59.5
Valve Angle (degrees)										
90	4.28	5.21	4.25	5.88	5.49	3.48	4.08	5.35	3.31	6.50
85	4.85	5.07	4.98	5.95	6.06	4.46	4.58	5.72	3.82	5.74
80	4.69	4.63	4.47	5.86	5.45	4.58	4.67	5.84	3.75	5.38
75	4.16	4.68	5.07	5.74	5.20	5.69	4.81	5.97	3.82	6.50
70	4.67	4.91	5.19	5.40	5.30	6.22	4.62	----	2.92	7.39
65	4.20	5.08	4.28	5.80	4.76	5.48	4.47	----	3.57	6.67
60	4.20	4.20	3.53	5.04	4.72	4.76	4.08	4.26	3.22	4.12
55	3.91	2.97	3.25	4.30	4.41	3.86	3.09	3.28	2.80	2.89
50	2.62	2.60	2.88	3.71	3.42	3.20	2.78	2.64	----	2.39
47	----	2.42	2.58	3.34	3.20	3.08	2.43	2.68	2.31	2.60
45	2.57	2.37	2.39	2.98	3.04	3.02	2.22	2.67	2.05	2.50
43	2.66	2.21	2.25	2.68	3.05	2.59	2.27	2.44	2.46	2.39
41	2.12	2.25	2.01	2.56	2.72	2.28	2.40	2.28	2.32	2.43
39	2.16	2.11	1.90	2.49	2.64	2.17	2.19	2.31	2.01	2.54
35	1.70	1.92	1.79	2.24	2.35	1.95	2.30	1.92	1.64	2.03

(Test runs 603 to 707, 714 to 742 and 799 to 813)

All other tests in Table II were conducted with water that contained no visible air.

7.1.4 Discussion

To aid in discussing the test results, the data from test 3 has been represented graphically in Figures 9 and 10. This test is typical of those in Table II. With the test procedure used the water temperature and downstream pressure were held constant. Thus, the values of B and H_2 are constant for all valve angles in Figure 9. The pressure head upstream of the valve (H_1) was obtained by adding the head drop across the valve (Δh), at incipient cavitation to the downstream pressure head (H_2). The velocity head of the pipe was calculated and added to H_1 to give the total head upstream of the valve. With these values of H_2, B, Δh, and $V_p^2/2g$ for various angles at incipient cavitation, sigma, was calculated, and is shown in Figure 10. As seen from Figure 10, there is scatter in the value of sigma at large valve angles. This scatter at large valve openings was also noted in the other tests. It can be attributed to the fact that at large valve angles the value of $\Delta h + V_p^2/2g$ is small compared with the value of H_2-B. Very small changes in $\Delta h + V_p^2/2g$ as shown in Figure 9 result in erratic

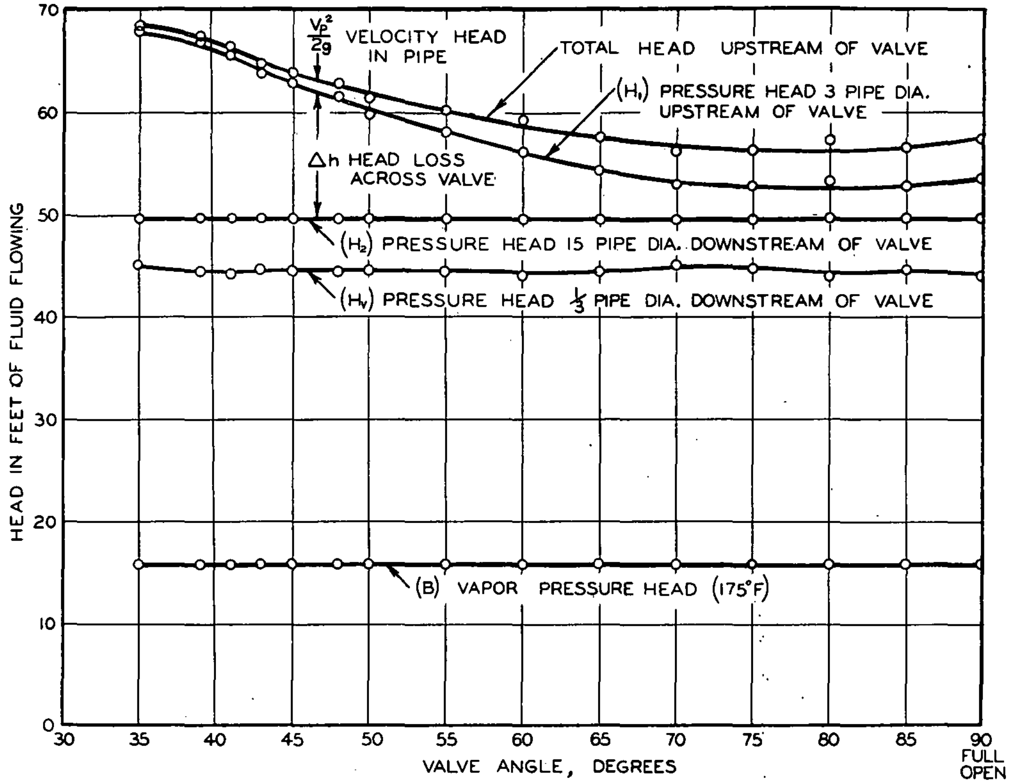

Figure 9 - Graphical Representation of Data from Test 3

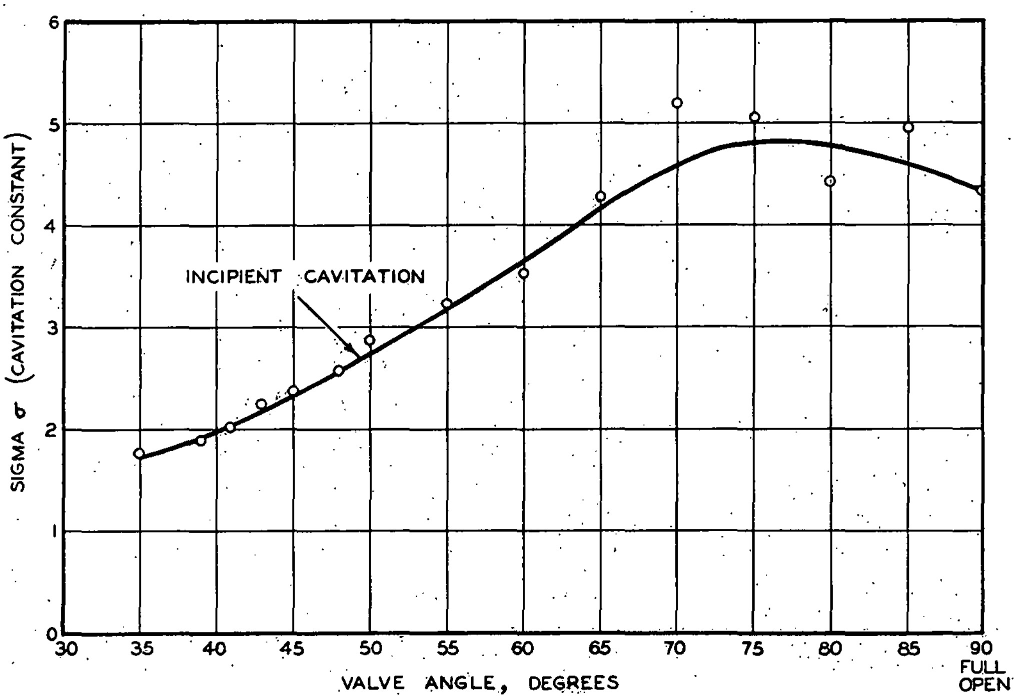

Figure 10 - Sigma at Incipient Cavitation Versus Valve Angle for Test 3 (43-025-362)

changes in the values of sigma in Figure 10. Thus, small errors in reading the flow, the drop across the valve, or in judging the exact incipient cavitation condition, result in a substantial variation in the critical value of sigma.

In two of the cavitation tests, the pressure distribution around the pipe near the valve was measured to determine if there was a sufficient variation in pressure at this point to cause the vapor pressure to be reached. To measure the low pressure point in this region, six pressure taps were located around the pipe circumference 2-5/8 in. downstream from the valve (approximately 1/3 pipe dia.) This pressure connection is shown in Figure 4 as pressure tap 4. The six pressure taps were provided with individual valves so that average or individual pressures could be measured. The average pressure head at this point for various valve angles is shown in Figure 9 as line Hv. While this pressure head (Hv), is less than the downstream pressure head (H_2), it is not near the vapor pressure head (line B). Also reading of the individual pressure points revealed only a $\pm$ 5 ft variation from the average value.

It is significant to note that while the head loss across the valve (Δh) varied with valve angle at incipient cavitation, the pressure head Hv remained essentially a constant distance from the vapor pressure head for all valve angles tested (Figure 9). This would indicate that the same incipient cavitation condition or pressure existed in the vicinity of the valve at all valve angles.

The low pressure point of the flow is not at the surface of the pipe where the pressure taps are located. For this reason, the velocity of the flow between the valve disk and pipe was calculated to determine if there were sufficiently large velocities in this area to cause the vapor pressure to be reached. The velocity in this area was calculated by dividing the pipe flow, as determined by the test, by the projected free flow valve area with a contraction coefficient applied. The magnitude of this average velocity resulted in a pressure that was only slightly less than that measured (1/3 pipe dia.) downstream from the valve. Since the velocity in this area is not large enough to cause the vapor pressure to be reached, there must have been localized regions of low pressure. As noted in Section 4.0, local pressures can equal the vapor pressure immediately downstream of the valve because of vortex cavitation. This can occur even though the mean pressure is above vapor pressure.

Although all but two tests included in Table II were conducted with water that contained no visible air, there is enough scatter in the data to indicate that the dissolved air content of the water may be a factor. To determine the effect of dissolved air, the following test was conducted.

7.2 Effect of Dissolved Air on Incipient Cavitation

7.2.1 Objective

Tests were run to determine the effect of dissolved air on incipient cavitation data.

7.2.2 Procedure

The temperature of the loop was raised to the boiling point to drive out the dissolved air. Heat was obtained from strip heaters placed on the outside of the test loop piping in addition to the heat supplied by the pump and the immersion heater located in the steam separator portion of the loop. After heating for almost five hours, boiling was observed through the portholes in the steam separator stand-pipe. The water was held near the boiling point for three hours to drive off the free and dissolved air. Because of the time required to boil the water, no test could be run at that time, and the water was allowed to cool overnight. The following day, the temperature was raised to 180 F and incipient cavitation data was taken following the procedure used in Section 7.1.

After the loop temperature had cooled to 104 F, a sample of the test water was taken and was found to contain no visible air. Another sample in an open beaker was heated from room temperature to boiling. The first bubbles were driven off at 180 F, which indicates that the water contained very little air even after cooling to room temperature. If the water was saturated with air at 180 F, it would have a dissolved air content of 6.4 cc/liter, whereas air saturated water at 70 F has an air content of 18 cc/liter. It is evident from this that a large portion of the dissolved air was removed due to the temperatures of the tests.

Because the water was boiled the day before the test, and the loop was closed except for a small area exposed to air at the surface of the water in the standpipe, it is believed that the dissolved air was below the saturation point, but no chemical analysis was made to determine the dissolved air content.

For a comparison, additional tests were made with water that was just saturated with air at the same temperature and pressure. Tap water was continuously introduced to the loop to maintain traces of visible air in the water. This was thought to be the saturated air condition for the water.

7.2.3 Results

The results of these tests are shown in Table III.

TABLE III

THE EFFECT OF DISSOLVED AIR ON THE CRITICAL VALUE OF SIGMA AT INCIPIENT CAVITATION

	Deaerated Water				Dissolved Air in Water			
Test Number	11	12	13	Average	14	15	16	Aver.
Temperature (^{o}F)	180	180	158		179	181	180	
Press. (H_2 in ft)	45.0	44.9	43.8		45.7	45.5	45.0	
(Valve Angle (degrees)								
90	4.38	3.34	3.88	3.87	4.45	4.87	3.87	4.40
85	3.65	3.16	3.68	3.50	4.00	3.83	3.36	3.73
80	3.40	2.97	3.65	3.34	3.45	3.83	2.93	3.40
75	2.91	2.96	3.42	3.10	3.88	3.62	2.69	3.40
70	2.92	2.57	3.15	2.88	4.56	3.34	2.90	3.60
65	2.81	2.90	3.06	2.92	3.34	3.48	2.88	3.23
60	2.46	2.87	2.68	2.67	3.57	2.75	2.79	3.04
55	2.28	2.38	2.49	2.38	2.90	2.74	2.42	2.69
50	1.91	1.92	2.15	1.99	2.18	2.24	2.48	2.30
47	1.68	1.74	2.06	1.83	2.02	2.14	2.00	2.05
45	1.53	1.62	1.99	1.71	1.91	2.07	1.89	1.96
43	1.47	1.56	1.79	1.61	1.86	2.10	2.12	2.02
41	1.42	1.56	1.70	1.56	1.77	1.87	1.96	1.87
35	1.33	1.33	1.53	1.40	1.68	1.63	1.97	1.76

(Test runs 822 to 849 and 859 to 914)

A comparison between the tests with dissolved air in the water and deaerated water is made in Figure 11 by using the average values from Table III. From Figure 11 it can be seen that the critical values of sigma were affected by the dissolved air content of the water.

When the loop was disassembled, the upstream edge of the plastic pipe was found to be peeled back, so that it projected into the flow stream. (Fig. 12).

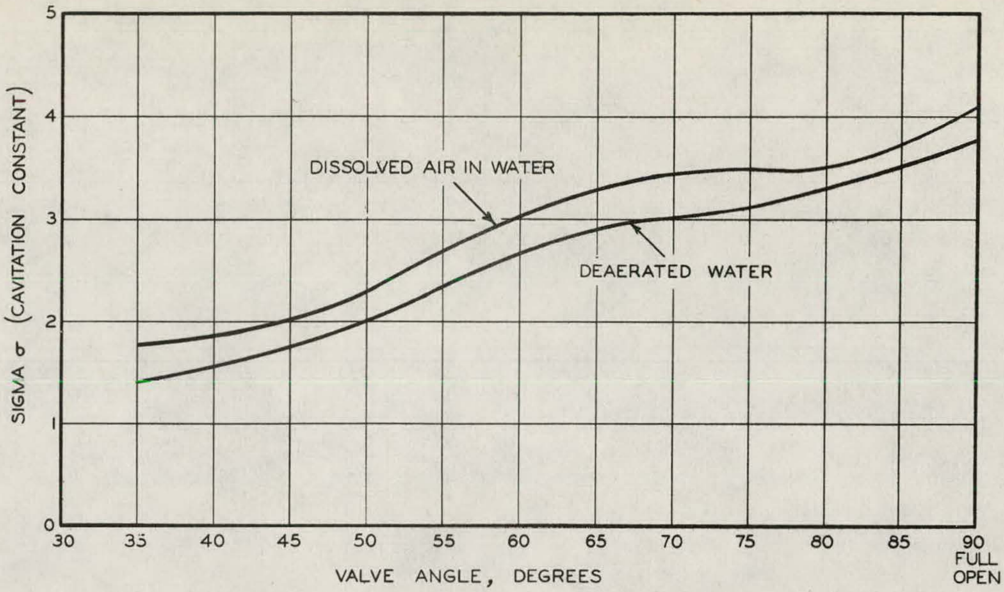

Figure 11 - Sigma at Incipient Cavitation as Affected by the Dissolved Air Content of the Water (43-025-363)

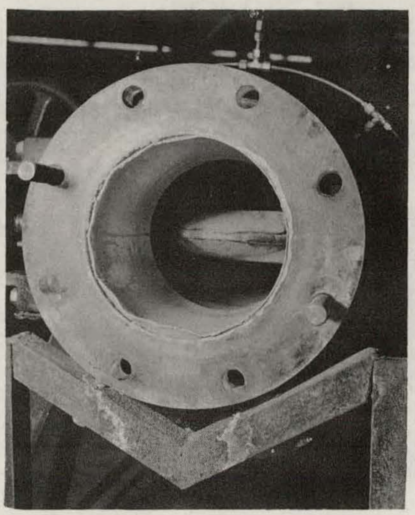

Figure 12 - Plastic Pipe Damage (206867)

Since a drop in coefficient of discharge was noted only after the water was boiled, it is reasonable to assume that the deformation was not present during previous tests. This deformation was probably due to overheating the plastic.

The values of sigma obtained from the concluding tests were about 30 per cent lower than the corresponding sigma values of Table II. Since the deformation of the plastic pipe increased the head drop across the valve only slightly and since test 9 of Table II is in close agreement with the data of Table III, apparently the reduction in the value of sigma at incipient cavitation is due to the reduced air content of the water.

8.0 TEST RESULTS AND DISCUSSION OF RESULTS

To determine a final curve of sigma versus valve angle at incipient cavitation the results from several tests were averaged. The method used to select the tests to be averaged was to eliminate any tests that were conducted with water that contained visible air. Of the remaining tests, only tests that indicated the lowest value of sigma at incipient cavitation were averaged to give the curve in Figure 13. The tests averaged were tests 1, 2, 3, 7 and 9 from Table II and tests 11, 12 and 13 from Table III.

The curve shown in Figure 13 can be used to predict the incipient cavitation point for butterfly valves. Knowing the conditions under which a valve operates, the cavitation constant sigma can be calculated. If the value of sigma lies above the incipient curve in Figure 13 the valve operation will be cavitation free. However, if the value of sigma lies below the

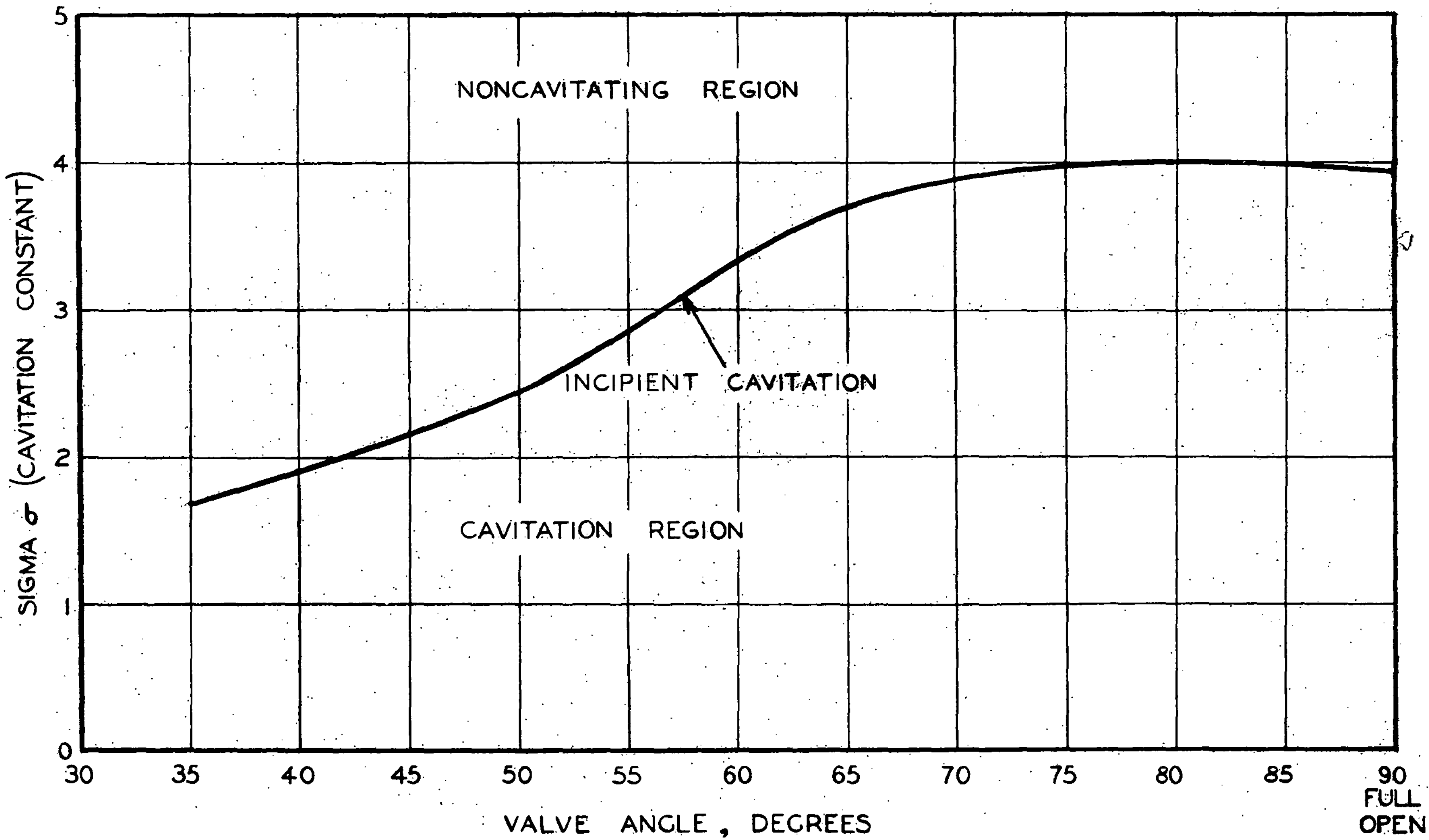

Figure 13 - Final Curve of Sigma at Incipient Cavitation Versus Valve Angle (43-025-364)

incipient curve, the valve operation will be in the cavitation zone. The further the value of sigma is below the incipient cavitation point the more severe the cavitation will be.

The errors in Figure 13 are estimated as follows: First, the thermocouple measuring loop temperature had an accuracy of ± 2 degrees F. The system pressure, the pressure drop across the valve, and the flow were measured with manometers with an accuracy of ± 0.1 in. Hg. This results in an accuracy of sigma of ± 5 per cent. It is obvious that variations in test data exceed this. As discussed before, the air content of the water is probably the most significant factor for these variations. Although the only tests used to construct this curve were conducted with water that contained no visible air, the water did contain some amount of dissolved air. Based on Tests 11, 12 and 13 shown in Table III, the value of sigma at incipient cavitation is about 20 per cent less than that shown in Figure 13. This indicates the degree of conservatism in this final curve.

A factor which is difficult to evaluate is the judgment of the observer as to the exact point of incipient cavitation for each run. Since the same incipient cavitation point was reproduced for two procedures in Section 6.3, it would appear that only small errors are introduced by this detection method.

The test data is to be compared with the vortex cavitation theory presented in Section 4.0 of the report. To determine the critical values of sigma at incipient cavitation, Eq. (10) is used. This equation was developed by considering that the onset of cavitation is governed not by the mean pressure of the flow but by the fluctuations about this mean value. These pressure fluctuations occur in vortices produced downstream of the valve disk. It has been found that cavitation initially occurs within these trailing vortices following a sudden expansion. Appel has reported that the pressure within these vortices may be lower than the mean pressure by 50 per cent or more of the dynamic head of the flow(Ref. 14).

The coefficient of discharge as determined by the test of the 8 in. valve is shown in Figure 14.

Choosing velocity head fractions of 0.5 and 1.0, which appears to be reasonable from Appel's report, and with the coefficient of discharge from Figure 14, Eq. (10) can be evaluated. The resulting critical values of sigma are plotted in Figure 15 along with the incipient cavitation test results from Figure 13.

In Figure 15 the calculated critical values of sigma from Eq. (10) at X = 1.0 are in close agreement with the test results for valve openings between 60 degrees and 35 degrees. It appears that there is some departure between the values of sigma from the 60 degree position to the full open position. However, the region of primary interest for setting of valve control limits is in the range of valve angles of 60 degrees to 35 degrees.

The incipient cavitation curve in Figure 15 was obtained by averaging the results from tests conducted with water with some dissolved air content. If tests were conducted in completely deaerated water the true value for X in Eq. (10) would be approximately 0.75.

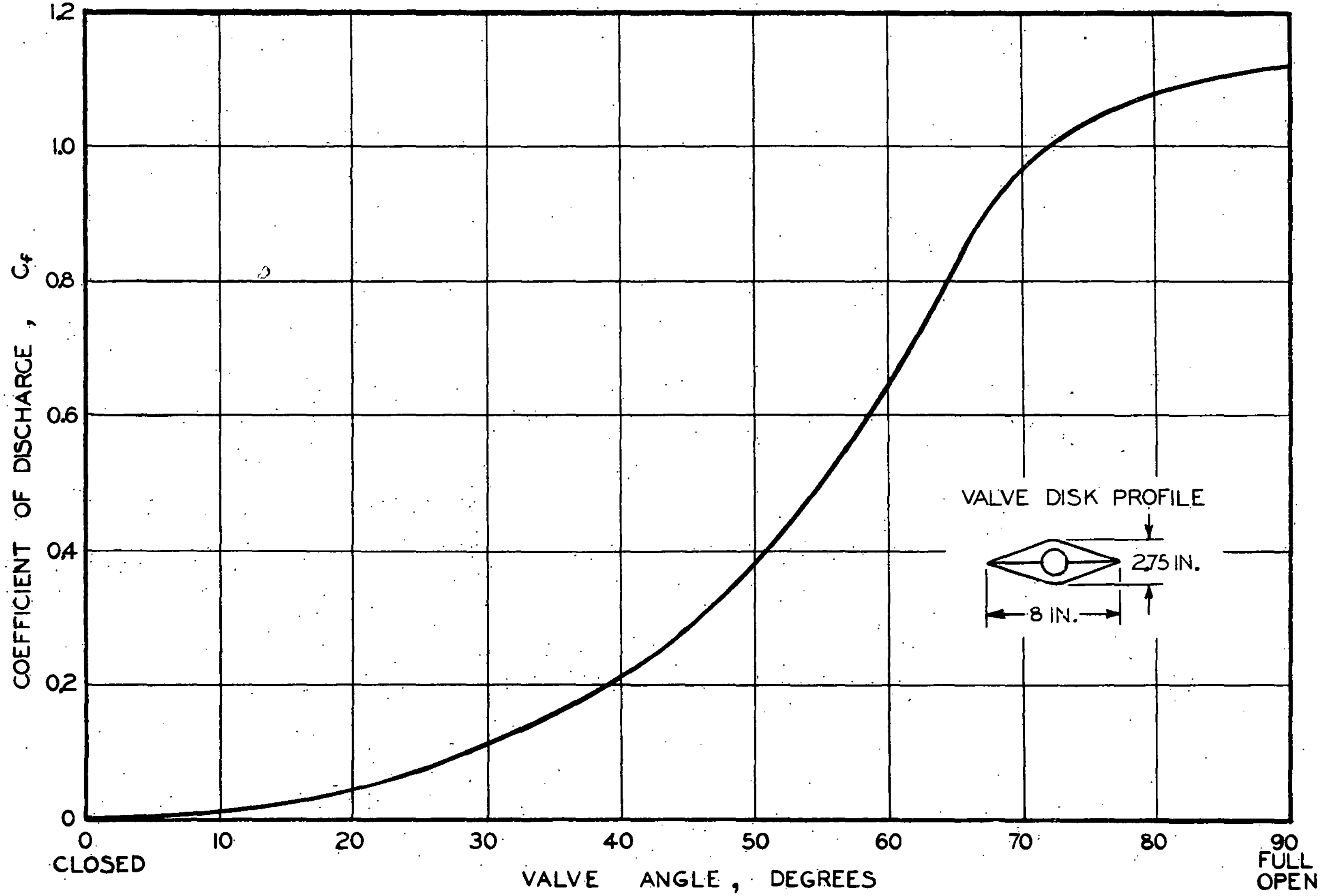

Figure 14 - Coefficient of Discharge for Test Valve (43-025-365)

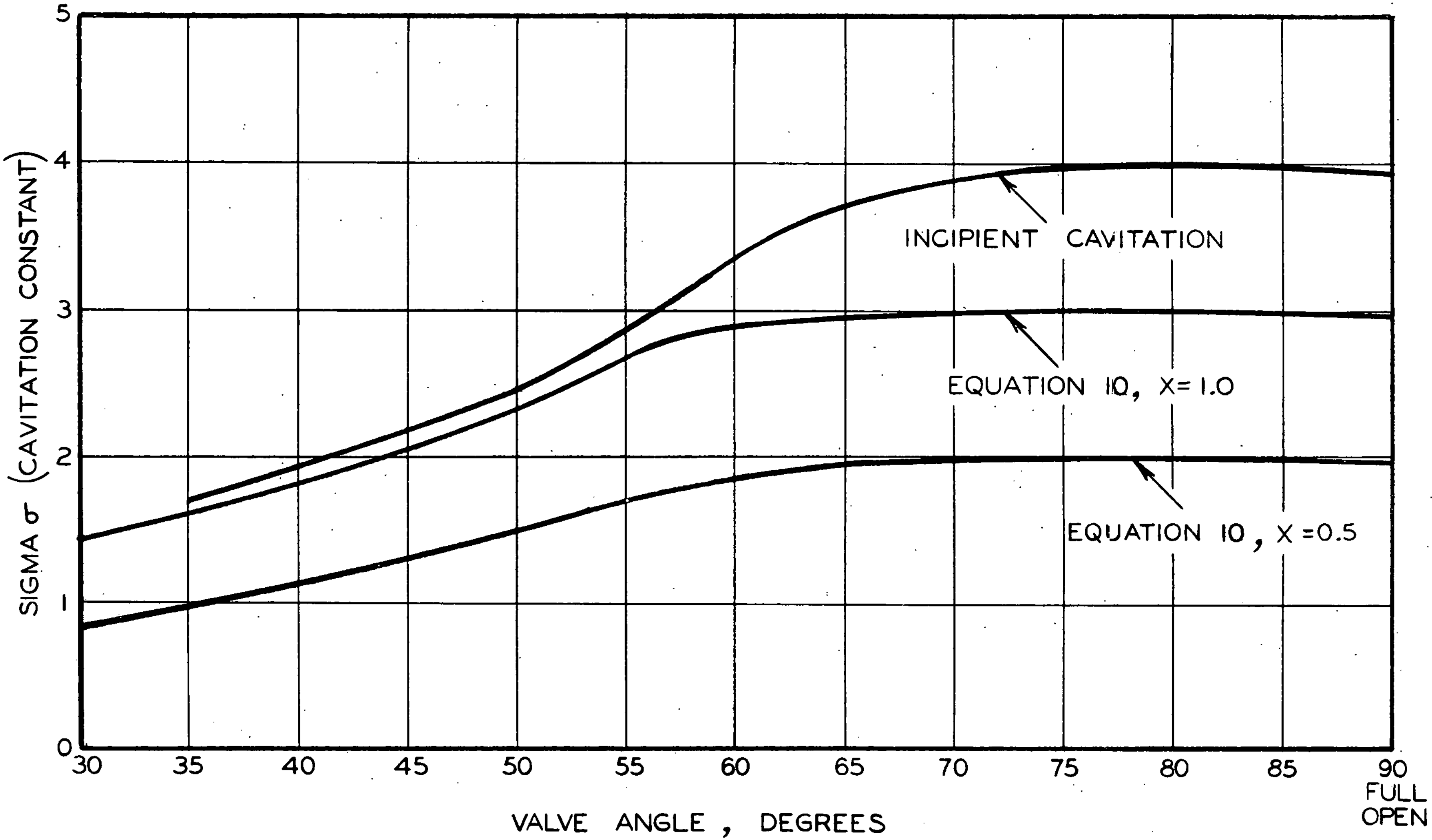

Figure 15 - Experimental and Calculated Critical Values of Sigma (43-025-366)

Since there is good agreement between the calculated and test critical values of sigma, it would appear that a good approximation of the critical value of sigma can be obtained for a similar butterfly valve if its coefficient of discharge is known.

9.0 TEST CONCLUSIONS

Test confirmed that cavitation could be detected by the visual and accoustical effects of cavitation. However, cavitation could not be detected by noting the point at which the coefficient of discharge dropped off because of the gradual drop off with cavitation. It was found that both the undissolved and dissolved air content of the water caused cavitation to occur at higher values of sigma. The final values of sigma at incipient cavitation were obtained by averaging the results of several tests conducted with water of reduced air content. It is significant to note that at incipient cavitation the mean pressure of the flow did not reach the vapor pressure of the water. At incipient cavitation it appeared that cavitation occurred in the vortices downstream of the butterfly valve disk. By relating the pressure within these vortices to the mean pressure of the flow by a fraction of the velocity head in the valve, Eq. (10) was developed to determine semi-empirically the critical values of sigma. By using a value of 1.0 for the fraction of the velocity head in the valve, and by using the coefficient of discharge for the test valve, the calculated critical values of sigma were in close agreement with the experimentally determined values.

A good approximation of the critical values of sigma for a similar butterfly valve can be obtained by the use of Eq. (10).

10.0 CONTROL LIMITS OF BUTTERFLY VALVES IN THE RECIRCULATION SYSTEM OF THE PATHFINDER REACTOR

10.1 Description of Reactor Valves

The 20-1/2 in. reactor butterfly valves have a 4 in. thick valve disk of streamlined profile. The head loss coefficient for the reactor valve is shown in Figure 16. The coefficient of discharge for the reactor valves can be obtained from the head loss coefficient with the relationship:

$$C_f = \sqrt{1/K} \tag{12}$$

where,

C_f - is the coefficient of discharge

K - is the head loss coefficient

The reactor valves are of the angle-seat type. When seated the valve disks are 12-1/2 degrees from a perpendicular to the pipe centerline. To conform to the valve angle convention used by the valve supplier, the full open position is considered to be 77-1/2 degrees, and the closed position, zero degrees.

10.2 Limiting Values of Sigma for Reactor Butterly Valves

Using the point of incipient cavitation, as determined by this test program, for specifying the control limits of the Pathfinder reactor valve, will undoubtedly lead to safely conservative valve operation. Naturally, it is desirable to determine a limiting cavitation condition for the reactor valves where little or no cavitation will be present.

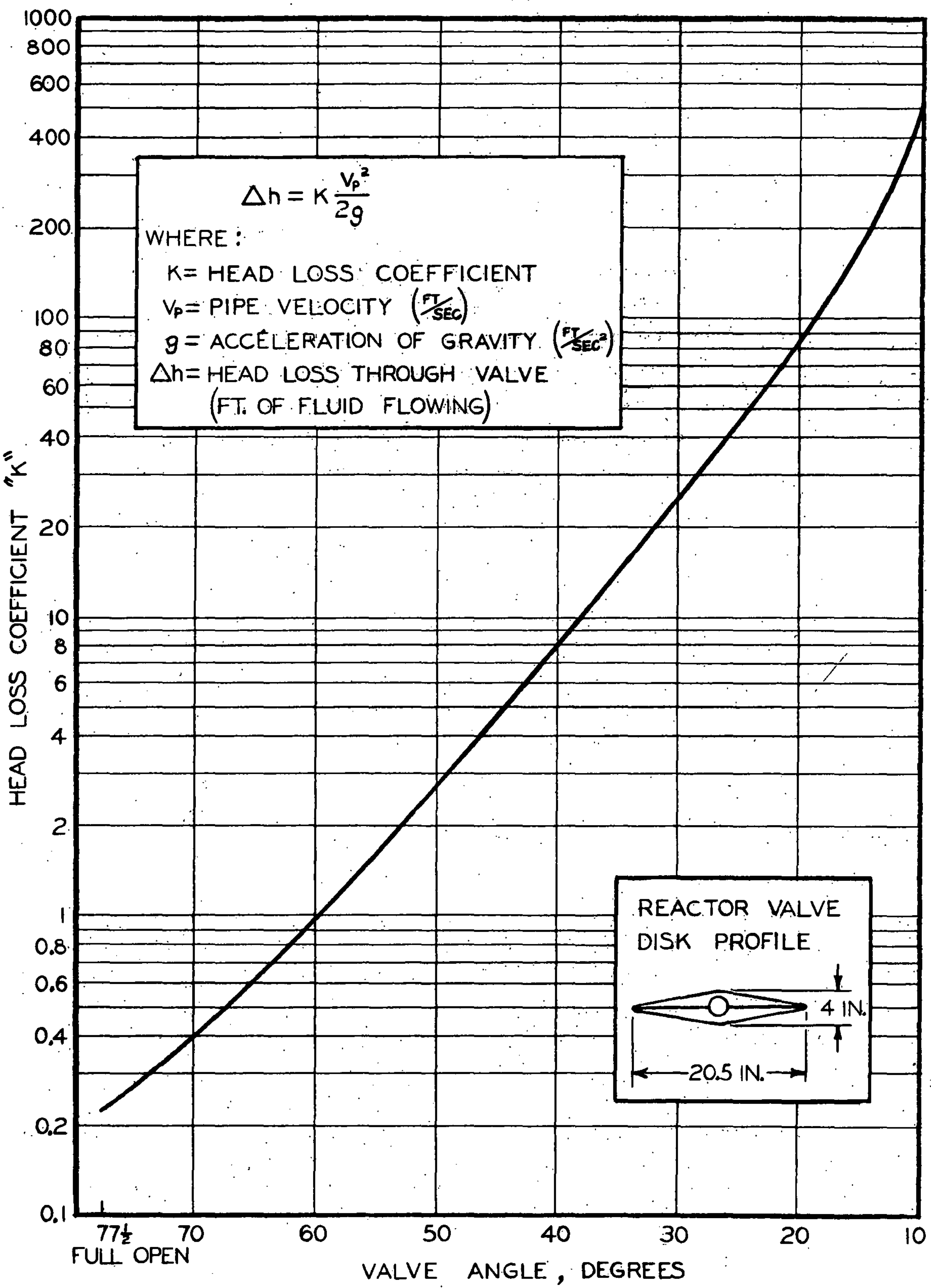

Figure 16 - Head Loss Coefficient for Reactor Valves (43-025-367)

There are three reasons why the incipient cavitation point as determined by the 8 in. test valve is considered conservative.

First, cavitation was found from test experience to be very mild from the incipient cavitation point to a sigma of about 1.5. In this range the cavitation appeared to occur in the vortices downstream from the valve disk. Although cavitation does occur in this range of sigma, damage to the pipe wall will probably not occur because of the layer of water between the collapsing vortex cavities and the pipe wall.

Secondly, the test results were obtained with water that contained some degree of aeration, which causes the experimental value of sigma (Fig. 13) to be higher than that which would be required in deaerated reactor water. Thus, the reactor valve can be throttled further than indicated by the tests.

Finally, cavitation tests conducted by others have indicated that less NPSH (net positive suction head) is required for hot water than is indicated by cold water tests. It was also found that at higher pressures and temperatures the effects of cavitation operation, noise, and vibration are reduced(Ref. 15). This reduction of cavitation at elevated temperatures can be attributed to the properties of the vapor and liquid phases of water becoming more nearly the same as the temperature increases. Since most of the cavitation tests were run at about 175 F and the reactor water will be at 486 F, the critical sigma values required by the valves at reactor conditions will be less than those indicated by the low temperature water tests.

Taking these factors into consideration, the limiting values of sigma for the reactor valves were determined by using Eq. (10). The coefficient of discharge for the reactor valve can be obtained from its head loss coefficient(Fig. 16). With these values for the coefficient of discharge and using a value of 0.75 for the fraction of the velocity head, the limiting cavitation line in Figure 17 was constructed. Using a value of 0.75 for the fraction of the velocity head is reasonable based on the results from the 8 in. valve test.

The critical values of sigma at incipient cavitation from the test results has been placed on Figure 17 for a comparison with the calculated values. The incipient cavitation data was obtained from the final incipient cavitation test curve in Figure 13. Since the coefficient of discharge is essentially the same for the test valve and the reactor valve in the flow control range of 57 to 30 degrees, the incipient cavitation sigma values were transferred to the reactor valve angle convention by plotting the values at the same coefficient of discharge.

Figure 17 shows that in general the incipient and limiting cavitation lines have the same shape. Because the incipient cavitation

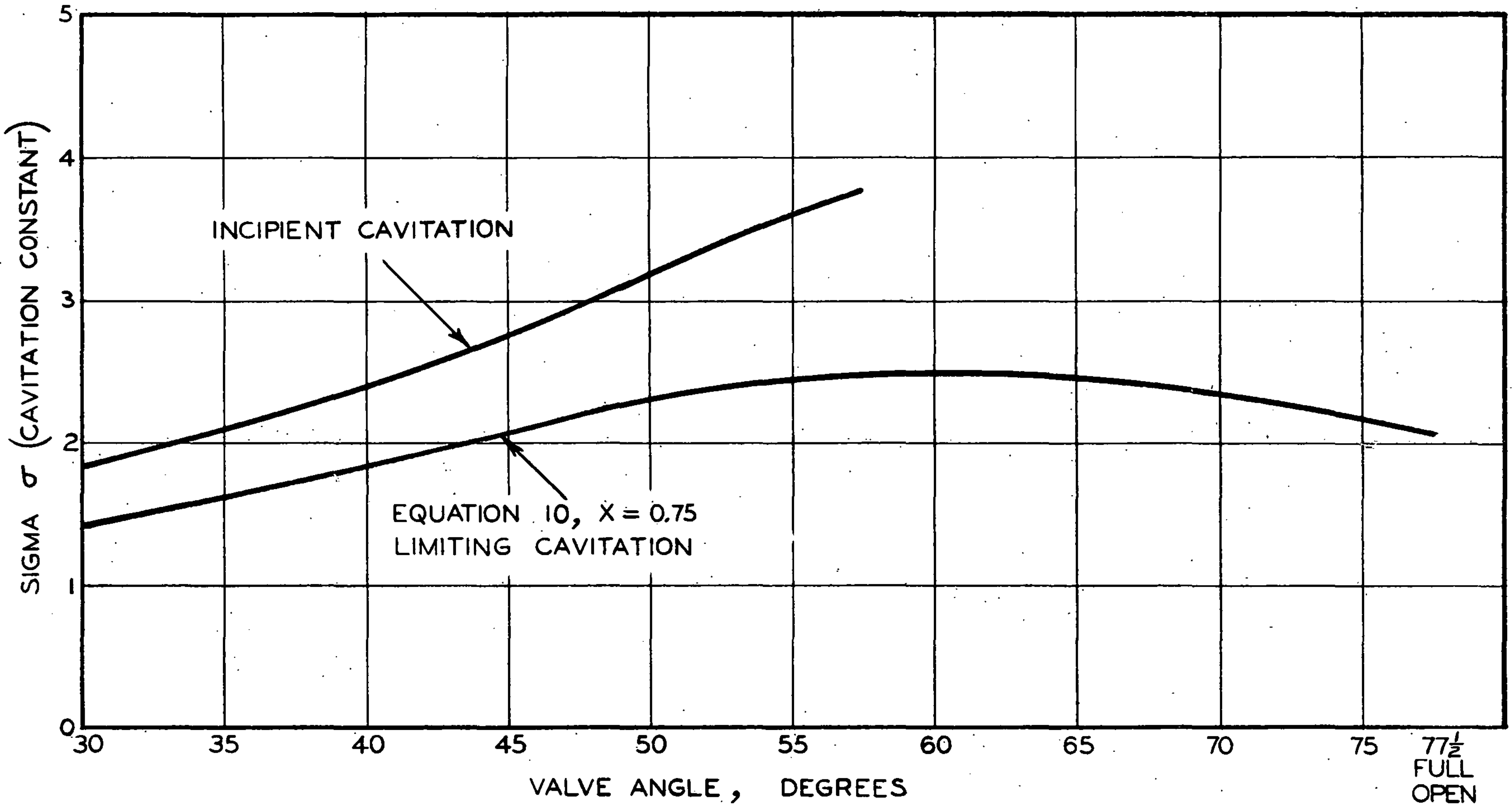

Figure 17 - Limiting Values of Sigma for Reactor Valves (43-025-368)

line is very conservative, the limiting cavitation line for the reactor valves is believed to describe a cavitation condition where little or more likely no cavitation will occur in the valves.

The limiting cavitation line in Figure 17 can be used to indicate the safe throttling limit for prolonged periods of operation. The value of sigma can be calculated for any operating condition of the reactor valves. If the calculated value of sigma lies above the limiting cavitation condition, the valve operation will be cavitation free. However, if the value of sigma lies below the limiting cavitation line, the valve operation will be in the cavitation region. In order to avoid this, the operating range of the valve must be limited.

10.3 Calculated Cavitation Limits for the Pathfinder Butterfly Valves

To calculate the values of sigma for the Pathfinder valves at normal throttle conditions, the maximum recirculation flow and the full power steam flow (100 per cent power) are taken as rated conditions for the reactor. At 100 per cent reactor power the reactor valves operate under these conditions when full open: 636 psia, 486 F and 21,433 gpm. The reactor power is assumed to drop off directly with a reduction in recirculation flow. This assumption is expected to be in close agreement with actual operating conditions. This drop in steam flow (or power) with recirculation flow is important in calculating sigma because it has a direct effect on the subcooling of the water. The recirculation flow for various valve angles was obtained from the head loss coefficient for the reactor butterfly valves, Figure 18 shows the recirculation flow control for three, two and one pump operation plotted versus valve angle. The butterfly valves are in the ganged position for the two and three pump operating conditions.

At each valve angle, the value of sigma can be calculated. Since the flow is known for each valve angle, the head drop across the valve and the pipe velocity head can be calculated. The pressure and temperature conditions can be calculated from the reactor power condition. A sample calculation of sigma for the recirculation valve is included in Appendix B for three, two and one pump operation. The calculated values of sigma at various angles are plotted in Figure 19. The intersection of these sigma lines for three, two, and one pump operation with the limiting cavitation line represent the control limit for the recirculation valves. As seen from Figure 19, the limiting throttled condition for three, two, and one pump operation is 34, 42, and 51 degrees, respectively.

These valve angles correspond to recirculation flows of 45,000 gpm for three pump operation, 40,000 gpm for two pump operation, and 24,500 gpm for one pump operation. These values were obtained from Figure 18. From these calculations, the safe throttling

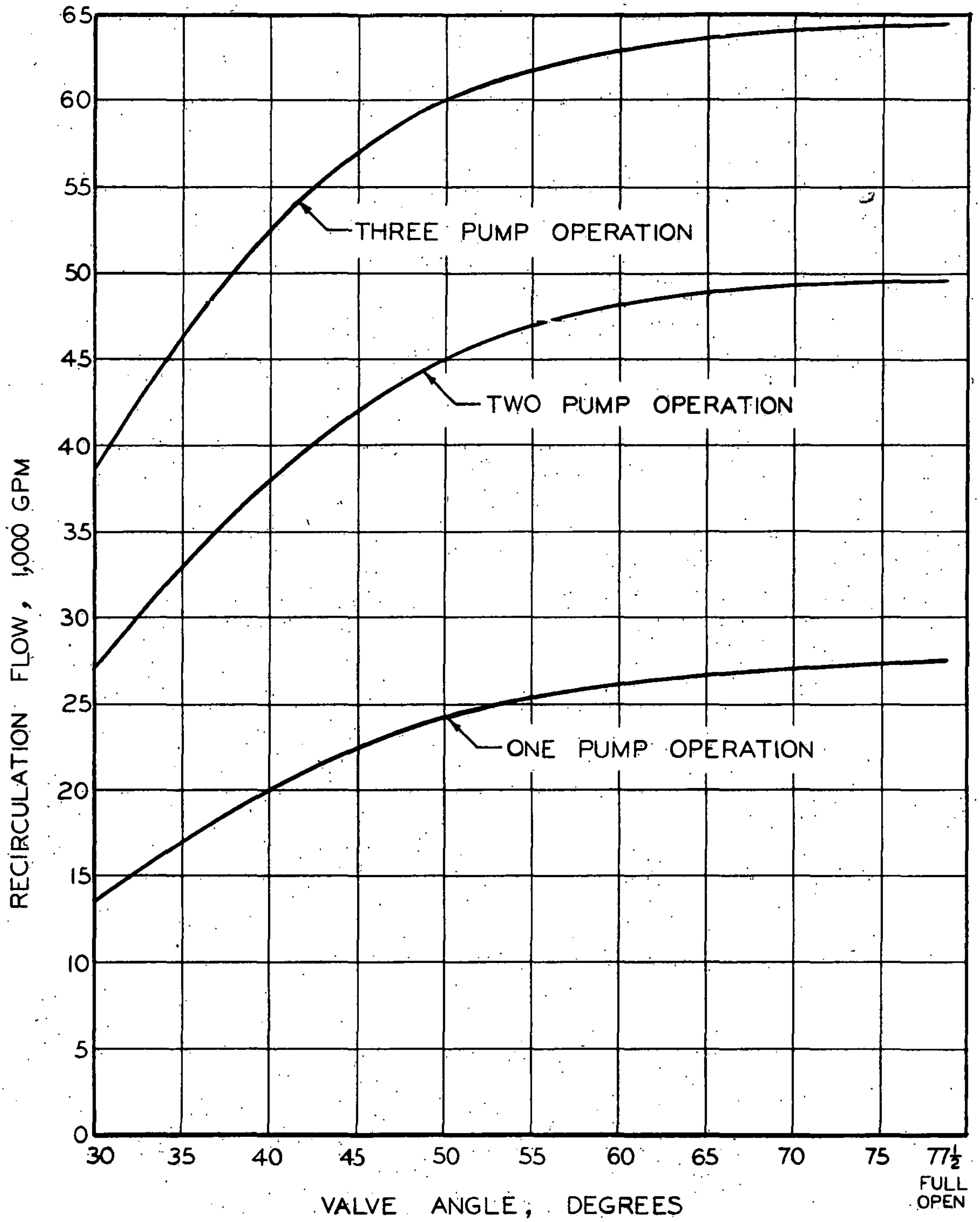

Figure 18 - Recirculation Flow Versus Valve Angle for One, Two, and Three Pump Operation (43-025-369)

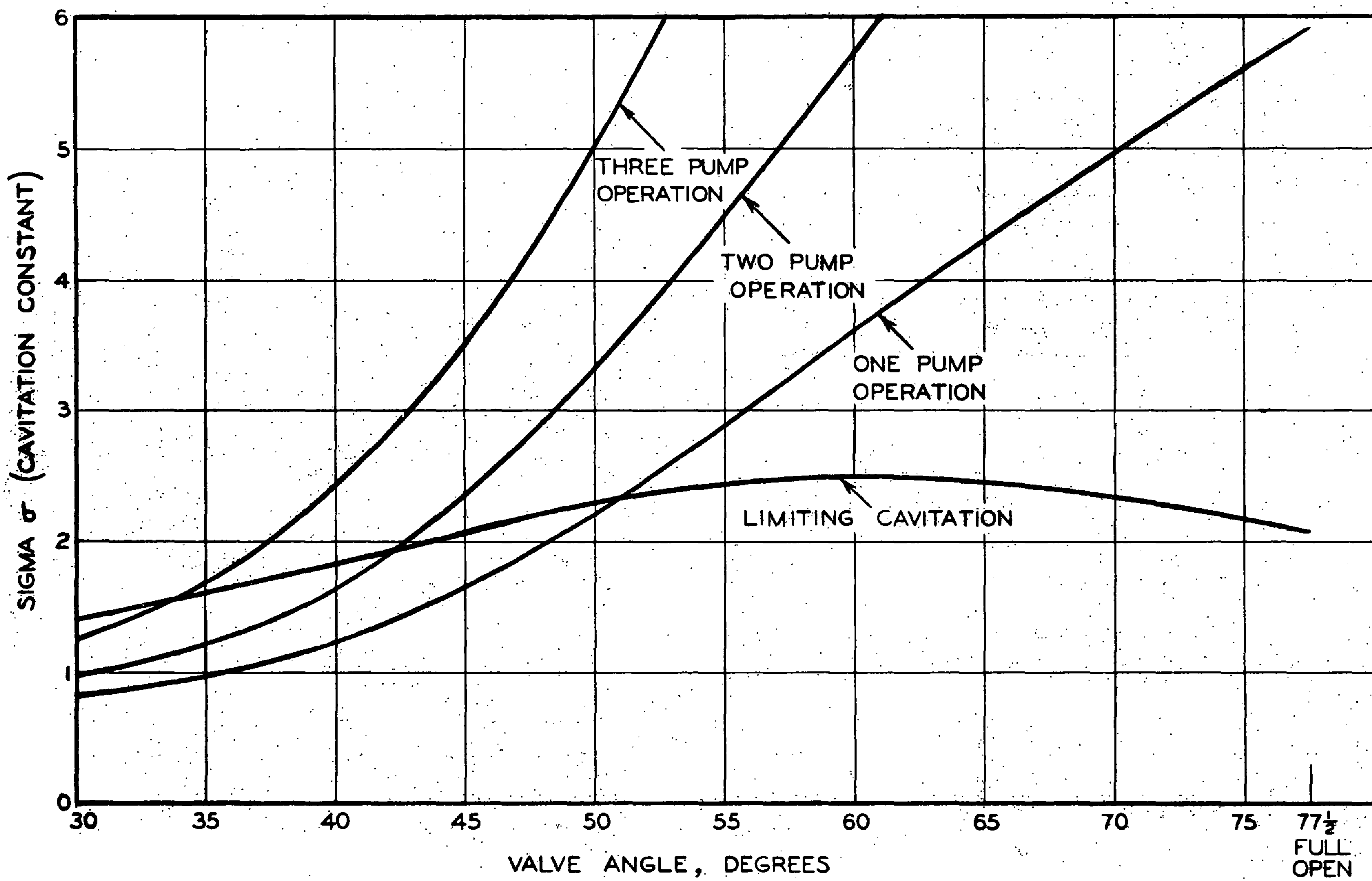

Figure 19 - Intersection of Calculated and Limiting Values of Sigma for Reactor Valves (43-025-370)

limits for prolonged periods of operation can be determined. The recirculation flow control range available with three pump operation is approximately from 64,300 gpm to 45,000 gpm. Since changes in recirculation flow can be used to change the reactor power level, the range of recirculation flow control available at three pump operation can be used to control reactor power from 100 per cent to 70 per cent of full power.

The recirculation flow control for two pump operation is from 49,500 gpm to 40,000 gpm. The recirculation flow control for one pump operation is from 27,500 gpm to 24,500 gpm.

10.4 Conclusions

Based on experience gained from the 8 in. butterfly valve test, a limiting cavitation condition was defined for the reactor butterfly valves. Limiting cavitation describes a cavitation condition where no cavitation damage will occur to the valve or to the downstream recirculation piping. The cavitation free operating limits for the recirculation butterfly valves can be determined for any operating condition by calculating the cavitation constant sigma at that condition and by comparing it to the limiting sigma value.

During the three pump operation at the normally expected power and recirculation flow conditions, the throttle range for the recirculation butterfly valves will be from 64,300 gpm to 45,000 gpm.

Also at the normal power and recirculation flow conditions, the throttle range will be from 49,500 gpm to 40,000 for two pump operation and from 27,500 gpm to 24,500 gpm for one pump operation.

The limits that have been determined represent the safe operating limits for the butterfly valves for prolonged periods of operation. More severe cavitation conditions can be tolerated for short periods of operation.

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APPENDIX A

Sample calculation of sigma and coefficient of discharge from test data.

Test Data:

Run 643

Venturi differential (A)	= 2.25 in. Hg.
Valve Angle	= 45°
Downstream manometer (C)	= 10.00 in. Hg.
Differential across valve (D)	= 12.40 in. Hg.
Temperature	= 175 F
Atmospheric pressure (ATM)	= 29.33 in. Hg.

Calculated Data:

1. Specific gravity of flow (S) calculation:

$$S = \frac{\text{Sp. volume @ 68 F}}{\text{Sp. volume @ 175 F}}$$

$$S = \frac{0.01605}{0.01648} = 0.974$$

2. Vapor pressure (B) calculation:

from steam table @ 175 F; abs. press. = 13.67 in. Hg.

$$B = \frac{(\text{abs. press})\ (1.131)}{S}$$

$$B = \frac{(13.67)\ (1.131)}{0.974} = 15.87 \text{ ft. of fluid flowing}$$

3. Downstream pressure head (H_2) calculation:

elevation correction for manometer = 4.75 ft.

$$H_2 = \frac{(\text{ATM})\ (1.131) + (\text{C})(1.048) + 4.75}{S}$$

$$H_2 = \frac{(29.33)(1.131) + (10.00)(1.048) + (4.75)}{0.974}$$

$$H_2 = 49.69 \text{ ft. of fluid flowing}$$

4. Pipe velocity head ($V_p^2/2g$) calculation:

venturi calibration equation $Q\ (ft^3/sec) = 6.4971 \sqrt{(A)/12(S)}$

$$Q = 6.4971 \sqrt{\frac{2.25}{(12)(0.974)}} = 2.85\ ft^3/sec$$

$$\text{pipe velocity } (V_p) = \frac{Q}{Ap} = \frac{2.846}{0.3491} = 8.164$$

$$V_p^2/2g = \frac{(8.164)^2}{2(32.2)} = 1.035 \text{ ft. of fluid flowing}$$

5. Head loss across valve (Δh) calculation:

$$\Delta h + \text{pipe friction} = \frac{(C)(1.048)}{S} = \frac{(12.40)(1.048)}{0.974} = 13.34 \text{ ft.}$$

$$\text{pipe friction} = 0.0315\ Q^2 = 0.0315(2.85)^2 = 0.26$$

$$\Delta h = 13.34 - 0.26 = 13.08 \text{ ft of fluid flowing.}$$

6. Sigma cavitation constant (σ) calculation:

$$\sigma = \frac{H_2 - B}{\Delta h + V_p^2/2g} = \frac{49.69-15.87}{13.08+1.035} = 2.39$$

7. Coefficient of discharge (C_f) calculation:

$$C_f = \frac{Q}{Ap\sqrt{2g\Delta h}} = \frac{2.85}{(0.3491)\sqrt{(2)(32.2)(13.08)}} = 0.281$$

APPENDIX B SAMPLE CALCULATION OF SIGMA FOR PATHFINDER RECIRCULATION BUTTERFLY VALVES

Three-Pump Operation

a) All three valves at 45°

b) Total recirculation flow 57,000 gpm

c) Reactor power 89 per cent

d) Recirculation flow in one loop 19,000 gpm

$$\sigma = \frac{H_2 - B}{\Delta h + (V_p^2/2g} = \frac{107.1}{25.0 + 5.27} = 3.54$$

Two-Pump Operation

a) Two valves at 45°

The down-loop valve closed to 5°

b) Total recirculation flow 42,000 gpm

c) Reactor power 66 per cent

d) Recirculation flow in one loop 21,400 gpm

$$\sigma = \frac{H_2 - B}{\Delta h + (V_p^2/2g)} = \frac{89.3}{31.9 + 6.74} = 2.31$$

One-Pump Operation

a) One valve at 45°

The down-loop valves closed to 5°

b) Total recirculation flow 23,340 gpm

c) Reactor power 35 per cent

d) Recirculation flow in loop 22,500 gpm

$$\sigma = \frac{H_2 - B}{\Delta h + (V_p^2/2g)} = \frac{74.5}{38.0 + 8.0} = 1.62$$