**PATHFINDER ATOMIC POWER PLANT
FINAL REPORT
MOISTURE DE-ENTRAINMENT TESTS
IN
TWO-AND FOUR-INCH DIAMETER TEST SECTIONS**

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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by
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and
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I. INTRODUCTION

Complete separation of water from steam is necessary in direct-cycle boiling water reactors since steam laden with droplets of moisture is very erosive and since the droplets of moisture may transfer radioactive corrosion products from the core to the power generating system. As the temperature and pressure at which such reactors operate is increased, moreover, the problem of making the separation would appear to become more difficult.

In the Pathfinder Atomic Power Plant, which is being designed and built by Allis-Chalmers Manufacturing Company, a controlled recirculation boiling water reactor with nuclear superheater is used. The boiler core is designed to operate at a pressure of 600 psig. Steam from the boiler core is separated from the water in two general regions. The largest portion is separated at the two-phase interface while a lesser amount is carried as bubbles with recirculation water into the downcomer region and is removed by centrifugal separators. The steam coming from both regions is then processed by moisture separators located in the steam chamber above the boiler core to reduce the quantity of moisture entrained in the steam to tolerable limits. The dry steam then flows to the superheater.

If an adequate separation of steam and water is not made, the following adverse effects may be expected. Water droplets will tend to transfer radioactive corrosion products from the boiler core to the superheater core. The droplets themselves will tend to erode the surface

of the superheater fuel elements and remove more radioactive material. The accumulated radioactive products will then tend to be transferred from the superheater core to the power generating system.

It is, of course, desirable to use a design that effects as complete a separation as is possible by the natural processes occurring at and above the two-phase interface, since most of the steam for the system comes from this region. If the amount of moisture entrained in this steam is small and predictable, the design requirements of the moisture separators will be more easily met.

A survey of the literature on the natural processes and factors that cause and prevent the entrainment of moisture by rising steam was made to ensure that all available theory and data are being applied to the Pathfinder development program. Tests were then made to determine the amount of entrained moisture occurring in the steam as various design parameters were varied, i.e., as the superficial steam velocity, height above the two-phase interface, system pressure, system temperature, and diameter of the test section were varied.

2. LITERATURE SURVEY

One of the earlier investigators, H. Vorkauf, studied the separation of moisture from steam at relatively low pressures. He concluded that the amount of moisture entrained is a function of the steam release rate and the volume of the steam chamber.⁽¹⁾ The results of his experiments at low pressures are reasonably consistent with the more detailed results obtained by later investigators.

In 1940, R. F. Davis studied the mechanism of droplet formation and entrainment. (2) He found that an upwardly projected droplet results when a steam bubble bursts at the two-phase interface. By considering the energy involved in the bursting of an average sized bubble and the energy required to project an average sized droplet upward to various heights, he calculated the maximum height to which an average sized droplet would rise. By further considering the density and velocity of the rising steam and the gravitational forces exerted on the average sized droplet, he was able to calculate the height to which average sized droplets will rise as a function of steam velocity. He designated the velocities above which all average sized droplets will be entrained as the permissible steam velocities.

Davis also reasoned that smaller bubbles produce smaller droplets, and the smaller droplets would be more easily entrained.

The entrainment of moisture droplets in an air-water system was investigated by D. M. Newitt, et. al. (3) They give excellent photographic and diagrammatic evidence of the mechanism of droplet formation as previously described by Davis. One such diagram is shown in Figure 1.

These investigators conducted tests that indicate a relationship between the bubble diameter and droplet diameter. Their results indicate, as Davis had reasoned, that the larger bubbles produce larger droplets. Results also indicate that bubbles of a given diameter produce droplets of various sizes and that the majority of these droplets rise to a range of heights that are characteristic of a bubble size. They further found that as the height of the droplet size measuring device is raised in the

experimental apparatus, the average size of the droplets measured becomes gradually smaller. This could indicate both that the upward movement of the larger droplets is affected by gravitational forces and that the droplet sizes decrease due to evaporation. A study of the function of baffles in separating moisture from the steam and in preventing it from becoming entrained again is also presented.

The size distribution of moisture droplets in the vapor space of an evaporator operated at low pressures (8 to 18.3 psi) was investigated by F. H. Garner, et. al.⁽⁴⁾ They found that over 95 per cent of the droplets measured in the evaporator used are less than 20 μ in diameter, but that their contribution to the total mass of entrained liquid is small...because of their small mass. They further conclude from experiments that the bubble size, surface tension, and viscosity of the liquid are important parameters in determining the diameter and projection of the droplet. Therefore, an increase in the temperature of the liquid will result in the formation of smaller droplets, which are more easily entrained, and the amount of entrainment will decrease as the diameter of the bubbles increases.

A survey of recent Russian literature reveals some significant work which has been done. The work most pertinent to this report is that which is reported by L. S. Sterman.⁽⁵⁾ He uses a system of differential equations describing the energy required to break down the two-phase interface into droplets and predicts that the amount of moisture entrained will be a function of certain variables, i.e.,

$$W = f(G_a, F_r, \frac{r}{r-r''}, \phi) \quad (1)$$

where

$$G_a = \frac{g \left(\sqrt{\frac{\sigma}{\gamma - \gamma''}} \right)^3}{\gamma^2}$$

$$F_r = \frac{W_o''^2}{gH}$$

g = acceleration of gravity (32.2 ft/sec²)

H = height above the two-phase interface (ft)

W = entrained moisture (per cent by weight)

W_o'' = relative steam velocity (ft/sec)

γ = density of water (lb/ft³)

γ'' = density of steam (lb/ft³)

ν = kinematic viscosity of water (ft²/sec)

σ = surface tension (lb/ft)

ϕ = void fraction

He is then able to generalize experimental data and obtains the prediction equation,

$$W = 2.75 (10)^8 \frac{(Fr/\phi)^{2.3}}{G_a^{1.1} \left(\frac{\gamma''}{\gamma - \gamma''} \right)^{0.25}} \quad (2)$$

By considering the case when,

$$\frac{d}{\sqrt{\frac{\sigma}{\gamma - \gamma''}}} \left(\frac{\gamma''}{\gamma - \gamma''} \right)^{-0.2} \gg 260$$

where d is the diameter of the test section, Sterman generalizes

Eq. (2) and obtains the expression,

$$W = 6.1 (10)^9 \frac{F_r^{1.38}}{A_r^{1.1}} \left(\frac{\sqrt{\frac{\sigma}{\gamma - \gamma''}}}{H} \right)^{0.92} \quad (3)$$

where

$$A_r = \frac{g \left(\sqrt{\frac{\sigma}{\gamma - \gamma''}} \right)^3}{\gamma^2} \frac{\gamma - \gamma''}{\gamma''}$$

Both equation (2) and equation (3) are limited by the range of the experimental data from which they are derived. The maximum steam release rate and height of the steam chamber, in particular, are less than that which is proposed for the Pathfinder.

3. MOISTURE ENTRAINMENT TESTS

3.1 Purpose. The review of the literature reveals insufficient data to directly predict the quantity of moisture that is entrained in the steam rising from the two-phase interface above the Pathfinder boiler core. Davis calculates by making certain assumptions a steam velocity above which all average sized droplets are entrained, but experimental data that verifies the calculations is not available for Pathfinder operating conditions. Sterman provides an equation with which the amount of moisture entrained may be predicted, but the equation is applicable only over the range of experimental conditions for which data is taken. These conditions do not include all the operating conditions of the Pathfinder.

What is of interest, then, is to obtain data on the quantity of moisture entrained as the steam velocity, pressure, height of steam chamber above the interface, and diameter of the test section are varied, and to verify the permissible steam velocities. The temperatures and pressures at which information is necessary are those in the range of the Pathfinder.

3.2. Test Apparatus. A schematic diagram of the test apparatus used is shown in Figure 2. The test column is constructed of stainless steel

pipe with welded fittings to accommodate calorimeter taps, sight-glass flanges, and manometer taps. A perforated plate and a fine-mesh screen are supported in the bottom of the test section to distribute the steam bubbles more uniformly across the pipe. Manually regulated throttling valves are located on either side of the test section to adjust the steam flow and pressure. A heat exchanger is located in a line parallel to the steam supply to permit adjustment of the liquid level in the test column. Superheated steam from the Turbine Test Floor of the West Allis Works of Allis-Chalmers was used.

Two test sections were used in the test, one being a section of nominal 4-inch diameter pipe and the other being a section of 2-inch diameter pipe. The test columns were fabricated so that they could be interchangeably used.

Steam flow through the test column was measured by a flange-tap orifice plate flow meter. Steam quality at various heights above the two-phase interface was measured by a throttling calorimeter. The pressures above the orifice plate and in the test section were measured with Bourdon-tube pressure gauges that were calibrated periodically. Temperature measurements were obtained with thermocouples.

A one half-inch diameter sight glass was provided with which both visual observations and motion pictures of the condition of the interface were made.

3.3. Test Method. The flow regulating valves on either side of the test section were adjusted so that the pressure and steam flow rate reached

the values desired. The water level in the test column was then adjusted so that the two-phase interface was located in the sight glasses. Measurement of steam quality was made at the various calorimeter taps with the throttling calorimeter. The steam flow rate was measured with the orifice plate flow meter. Test measurements were made for a series of selected flow rates and pressures. The procedure was then repeated with the second test section.

The steam quality measurements made with the throttling calorimeter were verified with the sodium carryover method. In this method, a very dilute solution of sodium sulfate is placed in the water in the test column (approx. 100 ppm). Test samples are then withdrawn simultaneously from the water in the test column and from the calorimeter taps. The ratio of the amount of sodium in the sample from the steam chamber to the amount in a sample of the water provides a measure of the amount of moisture carried from the interface to a particular height in the steam space. (The incoming steam contained no detectable sodium). A flame photometer is used to measure the sodium content of the samples.

3.4. Test Results. Typical results of steam quality measurements on the 4-inch diameter test section are plotted as a function of the steam release rate in Figure 3. The change in moisture content from 1 to 7 per cent or greater in the experiment was very abrupt. It was extremely difficult to reach a stable calorimeter temperature in this region, and the quality of the steam, therefore, could not be read with an accuracy greater than 1 per cent. In some cases, the quality of the steam varied

from 1 to 7 per cent while all conditions apparently remained stable. The locations of these transition points were verified by the sodium carryover method.

The transition points for the 2-inch diameter test section were also evident, but were not as sharply defined as they were for the 4-inch section.

The heights above the interface at which transition points occur in the 4-inch section are plotted as a function of the steam velocity in Figure 4 where the velocity at the transition point is defined as the permissible velocity.

The permissible steam release rates in the 4-inch section are plotted as a function of pressure in Figure 5. Curves for various heights above the interface are given. All data are plotted in terms of Pathfinder operating parameters.

Data from the two test sections are correlated in Figure 6, i.e., the permissible steam velocity 15 inches above the interface is plotted as a function of the reciprocal of the diameter of the test section. The curves are extrapolated to a 9-inch section.

Since only a one-half inch sight glass was used, the entire interface could not be observed. In such observations as were made, however, no steam vortex through the liquid was detected, and the vapor appeared to exit uniformly from the interface. An interface between the bubbling mixture and the steam could be seen, and in the range of the tests, the interface appeared to become more stable as the vessel pressure increased.

4. DISCUSSION

The transition point where the steam quality becomes unstable is referred to as the break off point (Figure 3). These points define a steam release rate above which the amount of moisture entrained abruptly increases. It defines, therefore, a limiting steam velocity similar to the permissible steam velocities calculated by Davis.

The permissible steam velocities calculated by Davis for 300 and 600 psig are included in Figure 4 for comparison. The curves plotted by Davis define a permissible steam velocity which is independent of height whereas curves obtained experimentally do not; this may be explained as follows.

Davis assumed an average size bubble. He assumed that when this given bubble bursts, a droplet of a given size is projected upward with a given initial velocity. When the force exerted on the droplet by the rising steam becomes great enough to overcome the gravitational force acting on the droplet, all droplets will become entrained. This phenomenon should have become obvious experimentally as a permissible steam velocity.

In making calculations for this velocity, Davis assumed a solid mass of water surrounded the bubble.

In a boiler region such as is in the Pathfinder or in the test sections, the assumptions made by Davis are not entirely applicable. The void fraction increases sharply near the interface at high steam release rates, and a solid mass of water is therefore not present beneath the bubble. Moreover, the energy released by a bursting bubble could be expended in other ways than projecting a droplet upward, notably in causing turbulence at the interface and in the steam. What may be expected

then is a broad spectrum of droplet sizes that are projected at varying velocities. A permissible steam velocity that is independent of height would therefore not exist, since the actual conditions involved are inherently different than the conditions Davis assumes. The test results show this to be true.

Other factors that would cause a discrepancy in the curves presented by Davis and those obtained in the experiment are as follows: turbulence at and above the interface would cause small droplets to combine and form larger droplets that would be removed by gravitational force; droplets would collect on the side of the vessel; and evaporation would occur at the surface of the entrained droplets.

In a practical application, the variation in steam quality with height becomes an important consideration. In the Pathfinder, for instance, the moisture separators should be placed at an optimum but practical height above the interface. Sterman's equations show the relationship of steam release rate, moisture content, steam pressure, and height of steam chamber above the interface, but his equations are limited to cases where the moisture content is low. His data and data reported by Styrikovich⁽⁶⁾ show a sharp increase in the amount of moisture entrained as the steam velocity increases, but the equations themselves do not attempt to predict either a permissible steam velocity or a break off point.

In tests conducted at a pressure of 600 psig and at a height of 15 inches above the interface, the break off points occur very near the point where the amount of moisture entrained is one-half per cent

(Figure 3). Sterman's equation (3) was evaluated for the case where the moisture content is one-half per cent. The predicted height to which this amount of moisture will be carried over as a function of steam velocity is shown in Figure 7. The curve is compared to results obtained in the tests, and there is a reasonable agreement with the break off points in the Pathfinder range. This agreement is not necessarily true for other pressures. At lower pressures, for instance, the break off points do not occur until the moisture carryover reaches a value greater than one-half per cent.

Figure 6 indicates that the limiting steam velocity is proportional to $D^{-0.4}$ in the region tested where D is the diameter of the test section. Sterman reports, however, that at 600 psig, the influence of the diameter is negligible for diameters greater than 9 inches. If this is true, the limiting steam release rates for large diameter vessels are as shown in Figure 8. Before this figure can be applied, however, the influence of forced or natural circulation below the interface and the effect of increasing or decreasing the velocity of the steam above the interface would require consideration.

5. CONCLUSIONS

In designing a boiler or a boiling water reactor, the height of the moisture separator and the velocity of the steam should be adjusted so that the permissible steam velocity for the particular height is not exceeded. If this is done, the amount of moisture entering the separator should be less than one per cent, an amount of moisture that should not be difficult to remove with moisture separators.

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Schematic Diagram of Entrainment Test

Fig. 2

NOTE:
 R = STEAM RELEASE RATE IN TEST SECTION (LB/HR-FT²)
 P = PATHFINDER DESIGN STEAM RELEASE RATE (LB/HR-FT²)

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NOTE:

r = STEAM VELOCITY IN TEST SECTION (FT/SEC)

p = PATHFINDER DESIGN STEAM VELOCITY (FT/SEC)

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NOTE:

R = STEAM RELEASE RATE IN TEST SECTION (LB/HR-FT²)
P = PATHFINDER DESIGN STEAM RELEASE RATE (LB/HR-FT²)

Fig. 5

FIGURE 6

DIAMETER EFFECT ON CARRYOVER 15 INCHES
ABOVE INTERFACE

r = STEAM VELOCITY IN TEST SECTION (FT/SEC)
 p = PATHFINDER DESIGN STEAM VELOCITY (FT/SEC)

FIGURE 7

EXTRAPOLATED VALUES FOR PERMISSIBLE STEAM
VELOCITY IN LARGE DIAMETER VESSEL AT 600 PSIG

r = STEAM VELOCITY IN TEST SECTION (FT/SEC)
 p = PATHFINDER DESIGN STEAM VELOCITY (FT/SEC)

NOTE:

R = STEAM RELEASE RATE IN TEST SECTION (LB/HR-FT²)

P = PATHFINDER DESIGN STEAM RELEASE RATE (LB/HR-FT²)

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