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PATHFINDER ATOMIC POWER PLANT

MEASUREMENT OF VOID FRACTIONS IN PARALLEL ROD ARRAYS

January 31, 1963

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

by

ALLIS-CHALMERS MANUFACTURING COMPANY
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MEASUREMENT OF VOID FRACTIONS IN PARALLEL ROD ARRAYS

by R. A. Condon and N. C. Sher

Submitted to

U. S. ATOMIC ENERGY COMMISSION
NORTHERN STATES POWER COMPANY

and

CENTRAL UTILITIES ATOMIC POWER ASSOCIATES

by

ALLIS-CHALMERS MANUFACTURING COMPANY

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under

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Summary Report

PATHFINDER ATOMIC POWER PLANT
MEASUREMENT OF VOID FRACTIONS
IN PARALLEL ROD ARRAYSDistribution

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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 Measurement of Void Fractions in Parallel Rod Arrays.

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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NOMENCLATURE

(In Consistent Units)

- D - outside diameter of pins
- e - naperian base
- N - radiation intensity at detector
- n^* - defined in the text
- N^* - total incident radiation intensity over beam area
- P - center-to-center distance (pitch) between pins
- t - thickness of liquid film in annular flow model
- x - attenuating length
- y - horizontal translation in direction traverse

GREEK

- α - void fraction (volumetric fraction occupied by gas or vapor)
- α' - defined in text
- $\bar{\alpha}$ - overall void fraction
- β - linear attenuation coefficient

SUBSCRIPTS

- L - liquid phase
- MFP - minimum flow path
- S - structure
- TP - two-phase
- v - vapor or gas phase

1.0 OBJECTIVE

To establish the suitability of the gamma attenuation method for measuring void fractions in a parallel rod array.

2.0 CONCLUSIONS

1. The gamma attenuation method can be used for measuring void fractions in a parallel rod array so long as a fine traversing technique is employed.
2. Accuracies of within about 5 per cent absolute void fraction can be expected, although this will depend upon many factors not varied in the present experiments.
3. Measured void fractions in air-water flow among parallel rods agree fairly well with similar results for rectangular channels and round tubes.
4. The density distribution in the air-water flow indicates a tendency for the gas to collect between pins in the square pitch array. (However, the distribution in a boiling flow would be expected to be significantly different from that observed in the present experiment.)

3.0 INTRODUCTION

The extensive heat transfer and fluid flow test programs associated with water reactor development during the past decade have included several studies of void fractions (vapor volume fractions) in boiling flows. Objectives of these studies have been to make available the void data for use in interpreting and analyzing two-phase pressure drop and heat transfer (burnout) data as well as for use in computing moderator densities in nuclear reactors. Naturally, the most serious investigations have been associated with boiling water reactor development and design programs wherein the results have perhaps the most important application.

Similar objectives have stimulated a series of void fraction experiments in conjunction with the heat transfer development for the Pathfinder boiling water integral superheating reactor. The need for this effort was based mainly upon the lack of available information for the flow arrangement of interest -- parallel rod array. While this geometry, which has received wide application in water reactor fuel elements, created the requirement for experimental study, it offered at the same time a new challenge with respect to void measuring technique.

Of the various void measuring techniques employed previously, including dissolved radioactive tracers, X-ray attenuation, and β -ray attenuation, none has been so widely used as the external source detector, gamma attenuation technique. This was the method selected for the present experiments in recognition of at least some of the potential sources of measuring error - particularly for the parallel rod array geometry. However, a preliminary set of experiments was undertaken to establish the

accuracy of this measuring technique, using a Lucite mockup, and to subsequently apply the technique to a relatively simple, air-water, parallel flow rod array. Results from this study were used to guide the execution of the 600 psia boiling water void experiments which were part of the heat transfer development for the Pathfinder Boiling Water Integral Superheating Reactor and were reported in ACNP-63002.

4.0 HISTORICAL BACKGROUND

Although several good literature surveys concerning two-phase void fractions have been published (Ref. 1, 2, and 3), the scope of problems included in this area has continually broadened to the extent that such surveys may be really more comprehensive than desired. The references discussed in the following are restricted to those considered by the authors to be most pertinent to:

1. void measuring technique
2. voids in unheated two-phase systems
3. voids in boiling water systems

4.1 Void Measuring Techniques

A survey of the available techniques for measuring void fractions is contained in Reference 4. A detailed discussion of the external source, gamma ray attenuation method was presented in Reference 5 and the results from an extensive experimental evaluation of this technique were presented in Reference 6 for rectangular channel geometry.

The results from a study of liquid holdup in a vertical round tube using a traversing technique with gamma attenuation instrumentation

were reported by H. S. Isbin (Ref. 1).

It was apparent from these references that while the external source, gamma attenuation technique for measuring voids has associated with it certain serious disadvantages, it is by far the most widely applied and has been the most thoroughly evaluated of any of the other known techniques.

4.2 Voids in Unheated Two-Phase Systems

Experiments at the University of Minnesota yielded void data for the atmospheric pressure flow of steam-water mixtures in horizontal and vertical tubes (Ref. 1). These data fall slightly higher than the Lockhart-Martinelli correlation based upon horizontal air-water and oil-air flows (Ref. 7). Subsequent data from Minnesota for higher pressure steam-water flows (400 to 1000 psia, Ref. 8) fall below the Martinelli-Nelson curves at low steam qualities (about 10 per cent and less) but appear higher than the curves at higher qualities.

Argonne National Laboratory has reported data for horizontal and vertical air-water flows in rectangular ducts with sudden contractions and expansions (Ref. 6 and 9).

Results for vertical air-water flows in a round glass pipe at atmospheric pressure have been reported by Anderson (Ref. 10). Void fractions were measured by isolating a section of the duct and determining the volume of trapped liquid.

Air-water flows were also studied by Govier (Ref. 11) at 36 psia in a horizontal tube. Again the void fractions were measured by the isolation technique.

4.3 Voids in Boiling Water Systems

Most investigators interested in boiling flows have recognized the presence of voids in the so-called "sub-cooled" region under certain conditions (Ref. 3). This situation is not of prime importance in the present development effort and references pertaining to this situation are not included.

The results from an extensive series of experiments performed at Argonne with boiling water in vertical rectangular channels have been summarized in Reference 12.

These results indicated that the void fraction is dependent upon superficial vapor velocity, quality, and pressure with appreciable interaction between effects.

5.0 GAMMA ATTENUATION THEORY

The theoretical basis for the gamma attenuation void measuring technique has been treated in considerable detail by Petrick (Ref. 9) and by Hooker and Popper (Ref. 5), and only a brief review will be presented. The principal assumptions used are as follows:

1. The gamma beam consists of parallel rays and is very thin.
2. The beam is monoenergetic.
3. The attenuation is exponential with thickness and density.

The attenuation of the gamma beam is given by:

$$N/N^* = e^{-\beta X} \quad (1)$$

where N/N^* is the fraction of incident radiation penetrating a distance X in the attenuating material. The linear attenuation coefficient, β , is assumed to be dependent only upon the nature of the material, its density,

and the radiation energy.

If the radiation intensity is measured from a duct containing a given permanent structure and completely filled with vapor, equation 1 becomes

$$N_V/N^* = e^{-\beta_V X_V} e^{-\beta_S X_S} \quad (2)$$

A similar measurement obtained at the same position with the duct filled with liquid would be represented by

$$N_L/N^* = e^{-\beta_L X_L} e^{-\beta_S X_S} \quad (3)$$

Finally, a measurement obtained with the duct filled partly with liquid and partly with vapor would be represented by

$$N_{TP}/N^* = e^{-\beta_L X_L} e^{-\beta_V X_V} e^{-\beta_S X_S} \quad (4)$$

Thus, the fraction of fluid present in the infinitely thin beam as liquid becomes

$$\frac{X_L}{X} = \frac{\ln(N_{TP}/N^*) - \ln(N_V/N^*)}{\ln(N_{TP}/N^*) - \ln(N_L/N^*)} = \frac{\ln(N_V/N_{TP})}{\ln(N_V/N_L)} \quad (5)$$

if the attenuation coefficients are assumed to be the same in the completely filled and partially filled conditions (and the decay of the source is neglected). Note that with this assumption (and those preceding) it is possible to measure a local liquid fraction (and/or void fraction, since $X_V = 1 - X_L/X$) by performing three radiation measurements at the location of interest without ever being committed to a certain value or set of values for the attenuation coefficients. The value of performing all three measurements at each position will be apparent from later discussion.

With respect to the ultimate application of the void data, it is desirable

to determine the mean void fraction in the duct cross section. This can be accomplished by performing a series of local measurements at different positions and then numerically integrating the results over the width of the duct. i.e.,

$$\bar{\alpha} = \frac{\int \alpha X dy}{\int X dy} \approx \frac{\sum (\alpha_i x_i) \Delta y}{\sum X_i \Delta y} \quad (6)$$

One of the more important assumptions in the foregoing discussion is that of a very narrow beam. It is worthwhile at this point to consider how the theory might have to be modified if this assumption were eliminated, but all other assumptions were retained. The basic attenuation equation would then be given by

$$N = \iint_a n^* e^{-\beta X} da$$

where a is the area of the beam, n^* is the incident radiation per unit area, N is the total radiation intensity over the beam area, and variations in β and X within the beam area are taken into account. If, however, variations in these parameters in the height of the beam are neglected, the equation becomes

$$N = \int n^* e^{-\beta X} dy \quad (7)$$

where n^* is the incident radiation per unit beam width and y is the beam width. First consider attenuation in the duct structure only

$$N = \int n^* e^{-\beta_S X} dy \quad (8)$$

Thus, with the duct full of vapor

$$N_V = \int n^* e^{-\beta_S X} e^{-\beta_V X} dy \quad (9)$$

and full of liquid

$$N_L = \int n^* e^{-\beta_S X} e^{-\beta_L X} dy \quad (10)$$

It is unnecessary to proceed further to realize that a simplified expression comparable to (Eq. 5) is now impossible to derive. However, if n^* is assumed to be constant, and all the attenuation coefficients are assumed to be constant, certain mean values can be defined, i.e.,

$$e^{-\beta_s \bar{X}_s} e^{-\beta_x \bar{X}_x} = 1/y \int e^{-\beta_s X_s} e^{-\beta_v X_v} dy \quad (11)$$

$$e^{-\beta_s \bar{X}_s} e^{-\beta_L \bar{X}_L} = 1/y \int e^{-\beta_s X_s} e^{-\beta_L X_L} dy \quad (12)$$

Thus, even the identification of proper mean values for the attenuating thicknesses would be quite difficult.

6.0 EXPERIMENTS

6.1 Equipment

A block diagram showing the equipment layout used for measuring void fractions in a parallel rod array is shown in Figure 1. The test sections consisted of hollow rectangular aluminum boxes containing 36 hollow aluminum pins (Fig. 2) which were closed at both ends in the air-water tests so that the mixture had to flow around and not through the simulated fuel pins.

The gamma source consisted of encapsulated thulium 170 housed in a lead pig, 4.5 in. in dia. and 7.0 in. long. The source strength initially had been specified at 10 curies but had decayed by 3 to 4 half lives at the time of the present tests. Collimation at the source was effected by a 0.0625 x 0.5312 in. slot, 2 in. long, formed in one end of the lead pig.

Collimation of the gamma beam on the detector side was obtained by

Figure 1 - Gamma Attenuation Equipment Block Diagram

using 2.5 in. long lead cylinder with a 0.035 in. x 0.625 in. slot. The detector had a 1.25 in. dia. sodium iodide crystal which was located just behind the collimator slot.

The assumption of a monoenergetic beam of photons was considered of sufficient importance to warrant special steps to assure its achievement. This is due largely to the relatively long attenuation path length of interest (up to five inches). The distinguishing features of the Greendale Laboratory's void measurement program lay in the method of obtaining a monoenergetic beam, and in obtaining measurements by counting individual pulses with an electronic scaler.

The beam of photons passes from the source through the test section and collimator slot. The photons then enter the detector, where they are converted to light flashes in the thallium activated sodium iodide crystal. The light flashes are converted to avalanches of electron pulses by the photomultiplier tube, and are increased with a net gain of two by the preamplifier. Leaving the detector preamplifier the pulses pass to the amplifier where they are further amplified. The pulses from the amplifier then pass to the pulse height analyzer where they are sorted. See Figure 1. With this equipment an energy band of pulses can be selected to be saved and subsequently used in the scaler. In order to properly use the pulse height analyzer it was calibrated with a known source, (Co-57 and Cs-137), and then used with the thulium 170 (10% gamma peak at 84 KEV). In the monoenergetic beam portion of the experiments, photons in a band of energy from 79 to 89 KEV were used.

The count rate measured by this system is assumed to be directly proportional to the incident radiation intensity reaching the detector. Thus, the efficiency and calibration of the instrumentation are unimportant so long as only ratios of count rates are used. The assumption of proportionality is acceptable so long as the count rate does not exceed the "linear" capacity of the equipment.

Analysis here and elsewhere indicated a sensitivity of void measurements both to small changes in high voltage applied to the various stages of the photomultiplier tube and also to changes in temperature. These effects became very important to the Greendale program since a single traverse of a test section required one and one-half hours. Thus, the fundamental accuracy of the measurements was limited by the drift which occurs in that time.

The entire detector was surrounded by copper cooling coils. The water supply and exhaust temperatures were experimentally found to be essentially constant.

The manufacturer's specifications indicated relative insensitivity to changes in incoming line voltage and a ± 0.05 per cent long term stability. The incoming line voltage was varied between 100 and 125 volts using a variac, and no significant effect on counting rate was observed.

The complexity of the test sections used and the manner of obtaining data made exacting demands on precise and reproducible positioning of

the source and detector. Thus, a special rack was designed and built. This rack provides 12 ft of vertical travel and 8 in. of horizontal travel. Horizontal position can be determined and reproduced to within 0.005 in. Test sections up to 10 in. wide can be accommodated between the source and the detector platform. When in use, the rack was jacked up off the floor on four screws to maintain its position.

The air-water loop consisted of a pump, an air supply, an open receiver for separation of air and water, and an instrumentated test section mounted vertically in the loop. The test section consisted of a 2.5 in. x 5.0 in. aluminum box containing 36 closed hollow cylinders (0.436 in. o.d. with a 0.101 in. wall) in a 4x9 array. The pin-to-pin spacing was 0.560 in.

The Aluminum-Lucite model, shown in Figure 2, consisted of a 4x9 array of aluminum tubes enclosed in an aluminum box. The aluminum tubes were 0.423 in. o.d. and 0.340 in. i.d. Lucite blocks 1 in. thick, 2.5 in. x 5 in. were drilled through for 0.423 in. dia. holes arranged on a 0.560 in. square pitch. The assembly clearance between the blocks and the aluminum tubes was found by inspection to be less than 0.001 in. diametral. The Lucite blocks were used to simulate the "full of water" condition.

Two two-phase conditions were simulated by inserting the aluminum tubes into hollow Lucite tubes, again with less than 0.001 in. diametral clearance. The Lucite tubes were 6 in. long with a step change in o.d.

Figure 2 - Mockup of Boiler Fuel Section with Lucite Simulating Water

at the mid-plane. The upper o.d. was 0.527 in. and the lower o.d. was 0.550 in. The two regions formed by the stepped tubes represented void fractions of 53.7 per cent and 41.7 per cent respectively. The region where no Lucite was present among the aluminum tubes represented the "empty" condition.

6.2 Procedure

The air-water mixture data were taken at one location 2 in. upstream from the set of aluminum spacers located 36 in. from the test section inlet. The void data were taken through the long side of the test section. In taking measurements this way, measurements taken through a row of pins had enough available path length so the results would be meaningful. The beam path length available for flow varied from 1.2 in. through the pin rows to 5 in. between rows of pins. The corresponding ratios of empty to full count rate readings varied from about 1.5 to 8.5.

A counting period of 40 sec. was used for each measurement. Counts measured on the scaler varied from 2,300 to 56,000 for the monoenergetic beam tests and from 52,200 to 550,000 for the integral spectrum experiment. The corresponding most probable statistical errors varied from 0.09 to 1.4 per cent.

A discriminator was used to eliminate the "noise" for the integral spectrum data, and the background count was found to be negligible for both measuring methods.

A void measurement was obtained by taking appropriate ratios between the all-air, all-water, and the mixture count rates (measured with the

scaler) at a fixed location through the test section. An all-water reference and an empty reference consisted of taking a series of count rates at physical locations 0.020 in. to 0.040 in. apart. Thus, 80 separate count rate readings which took one and one-half hours were necessary for each run. Once the air and the water reference were established, the count rate readings for air-water mixtures were taken at the same physical locations as for the references for the all-air and all-water data. (The attenuation in air is negligible compared to water at the pressures of interest).

The count rates were taken at a schedule such that no adjustment for source decay (half life is 129 days) was required.

The overall void fraction was found by numerically integrating the local void fractions over the flow area (Eq. 6). Detailed examination of the air-water mixture data suggested that an annular type flow distribution correlation could be used to represent the data.

In considering the Lucite and aluminum model of the air-water test section (with Lucite simulating water), it was desired to simulate the air-water mixtures and at the same time to make as extreme demands on the measuring techniques as would be expected in actual void measurement programs. The limiting case of an annular flow model was chosen, namely that of an all-liquid cylinder around the pins and all-gas elsewhere.

The Lucite model (Fig. 2) incorporated these ideas and provided two mixtures. The data were obtained and reduced in the manner similar to

that used in the air-water studies. However, in these experiments, the "empty", "full" and "two-phase" traverses were actually made through different sections of the model. Variations in the metal components from one section to another were found to be small compared to the positioning uncertainty.

The thulium 170 source used had appreciable bremsstrahlung up to about 250 KEV. Thus, hopefully using all the photons available from the thulium source, one could obtain sufficient photon density to use this source on the pressurized steam-water experiments in which the beam must penetrate 1.5 in. of steel in the pressure walls. The magnitude of the effect of multi-energetic photons on the void measurements (compared to the monoenergetic measurements) would determine the usefulness of pursuing this approach. With this in mind, another complete set of data was obtained on the Lucite model using all the photons available from the thulium source, regardless of energy, to attempt to evaluate the error introduced by failing to use a monoenergetic beam.

6.3 Results and Discussion

6.3.1 Lucite-Aluminum Model

The local void data obtained from the Lucite mock-up are presented in Figures 3 through 6. The values for the local voids determined from (Eq. 5) were obtained from a partial traverse of the test section. Data from geometrically similar positions are shown as a function of distance from a pin centerline. (Symbols 1S, 2N, and 2S refer to these positions and are equivalent to run numbers.)

Data obtained using a monoenergetic beam are shown in Figures 3 and 4 for two different Lucite arrangements. The agreement between the data and the actual void fractions is in general within 5 to 10 per cent absolute void fraction. This, of course, is equivalent to a relative agreement of only 50 to 100 per cent at the low void levels. The poorest agreement appears to exist at locations where the geometry is changing most rapidly in the beam width, i.e., at the edge of the aluminum pins and at the edge of the lucite annuli.

A similar set of data is presented for the integral spectrum technique in Figures 5 and 6. These data agree in general with the actual voids also to within about 5 to 10 per cent absolute void fraction. However, there does appear to be appreciably less scatter in these data than in the monoenergetic beam data and the accuracy appears to be somewhat better.

There does appear in both sets of data a tendency for the experimental values to be slightly higher than the true voids. This is also illustrated in Table I, wherein integrated mean void fractions are compared with the actual values. The measuring accuracy was within 13 per cent for the monoenergetic beam and within 7 per cent for the integral spectrum.

In considering inaccuracies in the measuring method, the two sources of error should be considered. One source is the assumptions used in interpreting the results, and the other is uncertainties in the measurements themselves.

AVERAGE VOID FRACTION = 41.7 %

Figure 3 - Local Void Fraction for Lucite Model with Monoenergetic Beam (43-024-699)

AVERAGE VOID FRACTION = 53.7%

Figure 4 - Local Void Fraction for Lucite Model with Monoenergetic Beam (43-024-701)

AVERAGE VOID FRACTION = 41.7 %

Figure 5 - Local Void Fraction for Lucite Model with Integral Spectrum Beam (43-024-700)

AVERAGE VOID FRACTION = 53.7%

Figure 6 - Local Void Fraction for Lucite Model with Integral Spectrum Beam (43-024-702)

One of the weaker assumptions used was that of an infinitely narrow beam when the beam actually used had a width of 0.035 in. This width is significant compared to the geometry tested as shown in Figures 3 through 6, where the actual void is seen to change by as much as 100 per cent (relative) over a single beam width.

In order better to understand the importance of this phenomenon, solution of Equations 9 and 10 plus a similar equation for a two-phase system were carried out using an IBM-704 computer. These calculations utilized the geometry of the aluminum-Lucite model, together with the assumption of parallel rays and estimates of the linear attenuation coefficients for aluminum and Lucite based upon the experimental, monoenergetic beam results. The coefficients were assumed to be constant throughout the model cross section, whereas the experimental results for the "empty" and "full" regions indicated some (as much as 5 per cent) variation in the Lucite attenuation coefficient as a function of geometric position. (This is undoubtedly caused by changes in the gamma scattering.) Nevertheless, the computations are believed to be reasonably precise with respect to the effect of parametric variation.

The attenuation integrals were evaluated for various beam widths at different positions in the array. The results, in the form of continuous curves, are shown in Figure 7 for one of the simulated two-phase regions. The curve for a "very thin" beam is identical to the curves in Figures 3 and 5. The "errors" shown in Figure 7

Figure 7 - Computation of Mean Values for Void Fraction over Various Effective Beam Widths (43-025-055)

are qualitatively similar to the errors observed in Figure 3, with the data being reasonably well explained by an "effective" beam width between 0.034 in. and 0.068 in. in the region between pin rows, and by an "effective" width of 0.136 in. in the region of the pin row centerline. Integration of these calculated curves over the model cross section was also qualitatively consistent with the overall void data (shown in Table I) in that the apparent void was found to be 2 per cent (relative) too high for the 0.068 in. beam and nearly 8 per cent (relative) too high for the 0.136 in. beam.

TABLE I
MEASURED MEAN VOID FRACTIONS

	<u>Beam Energy Spectrum</u>		
	Monoenergetic	Integral (15 KEV and up)	Position
Mixture 1 Actual $\alpha = 53.7\%$	60.5%	56.3%	1S
	58.2	57.1	2N
	59.2	55.3	2S
Mixture 2 Actual $\alpha = 41.7\%$	47.2%	44.7%	1S
	44.9	44.4	2N
	46.3	44.5	2S

The geometric arrangement of the collimators indicated that the "effective" beam width would be somewhere between 0.035 in. and 0.0625 in., although the influence of scattering on the "effective" beam width was not established. It is interesting to note that the data from Figure 4 are also in qualitative agreement with the curves in Figure 7, indicating that restricting the counting energy band

does not have a marked influence on errors from the "finite beam" considerations.

Computations of the type shown in Figure 7 were also performed for a 4x4 pin steel test section with a similar Lucite arrangement and a cesium 137 source. For this situation, errors of the type shown in Figure 7 virtually disappeared even for beam widths up to 0.136 in. This was attributed to relative changes in the attenuation coefficients because of the steel and the higher energy gammas from the cesium. Subsequent computations were unsuccessful in predicting significant errors for the cesium-steel situation for a wide variety of Lucite geometric arrangements.

At first glance, the effort to obtain a monoenergetic beam would appear to have been unnecessary since the integral spectrum data appear as accurate, if not more so. However, this is felt to be a fortuitous result for the following reasons:

1. Both experiments were performed by counting photon pulses for the same period of time (40 sec.) The reduced count rates available with the monoenergetic scheme, therefore, introduced a larger statistical counting error than those for the integral spectrum data. This effect is believed to account for the reduced scatter in the integral spectrum data.
2. A series of slab experiments performed with Lucite and an integral spectrum beam demonstrated that appreciable "hardening" occurs in passing through absorber thicknesses

of as little as 1 in. (thicknesses as long as 5 in. were present in the aluminum-Lucite mock-up). This "hardening" invalidates the use of (Eq. 5) since the linear absorption coefficient for the "filled with liquid case" is not the same as (lower than) the coefficient in the "partially filled" case. The net result is that the use of (Eq. 5) for the integral spectrum case tends to underestimate the void fraction. This effect is believed to account for the lower void fractions measured with the integral spectrum beam.

It was concluded from the Lucite results that the error in void fraction measurement by the gamma attenuation method was about 5 per cent absolute void fraction. The results may be expected to run somewhat on the high side particularly for density distributions of the type represented on the Lucite cylinders. The results of the air-water experiments presented in the following must be interpreted in recognition of this error.

6.3.2 Air-Water

The three count rates required for application of (Eq. 5) are shown for a typical traverse in Figure 8. A definite tendency for the gas to collect near the center of the test section is observed, as well as an even more definite tendency for the gas to collect in the "open" areas of the square pitch array.

The local void measurements were integrated over the five typical flow channel regions between pin centerlines shown in Figure 9, and

Figure 8 - Data Run Obtained with Gamma Attenuation Equipment (typical) (43-202-007)

Figure 9 - Air-Water Test Section Diagram (43-024-707)

the mean values for each region are shown in Figure 10 for several different air qualities (weight fraction air flowing). While gross gas distribution is believed to be a natural phenomenon, it is barely conceivable that it could have been caused by the method of injecting air. The latter cause is considered unlikely, since the air was injected from a perforated probe located upstream from the test section inlet more than 60 equivalent dia. from the axial measuring station.

The overall void fraction data are compared to the homogeneous curve, the Lockhart and Martinelli correlation, and some results from air-water tests in other geometries in Figure 11. The data are seen to fall significantly below the homogeneous curve; the agreement to be associated with the other comparisons is difficult to assess quantitatively because of the uncertain effect of differences in flow rate. (It is impossible to establish the importance of flow rate from the limited data herein presented.) Considering all factors, it can be concluded that the overall void fractions for parallel rod arrays are not significantly different from similar results for other geometries although the rod data may be slightly lower.

Similar comparisons with respect to the mean void fraction for the unit cell located between the centerlines of the two centermost rows of pins are shown in Figure 12. Considering the data in this fashion, and referring to the average quality over the whole array,

Figure 10 - Region-wise Void Distribution Superficial Liquid Velocity of 3.2 ft/sec (43-024-705)

Figure 11 - Overall Void Fraction with Air-Water Flow (43-024-628)

Figure 12 - Region "C" Average Void Fraction with Air-Water Flow (43-024-703)

the data seem to be in fairly good agreement with the Argonne data. The data are presented in this form only in order to appreciate the possible significance of larger arrays.

The effect of velocity on slip ratio (ratio of mean linear gas velocity to mean linear liquid velocity) was examined in Figure 13. The data seem to follow the same qualitative trends as predicted by the Argonne rectangular channel correlating lines with respect to superficial liquid velocity (assumes all fluid flowing as liquid in entire duct cross section); however, the effect of quality on the rod array data seems to be quantitatively different.

In an attempt to gain some insight into the flow pattern in the rod array, the data were compared with an annular flow model.

In this model the fluid is assumed to be divided into two regions:

1. All liquid annulus of thickness, t , around each rod.
2. External region of void fraction, α' (The void fraction which would be measured at the position midway between pin rows.) The minimum flow path void fraction (in a plane containing the centerlines of all the pins in a given row) would then be given by:

$$\alpha_{MFP} = \alpha' \frac{(P-D-2t)}{P-D}$$

where P is the pitch for the square array and D is the pin dia.

The average void fraction is given by:

$$\bar{\alpha} = \frac{[P^2 - \pi/4 (D+2t)^2]}{[P^2 - \pi/4 D^2]} \alpha'$$

Figure 13 - Comparison of Experimental Results with Argonne Correlation (ANL-5787)
(43-024-704)

Thus, it is possible to establish a relationship between α_{MFP}/α' and $\bar{\alpha}/\alpha'$ as a function of P and D. This was done for the present geometry and is compared with the data for region C in Figure 14. The agreement is better than ± 10 per cent, and most of the scatter is believed to be caused by uncertainties in measuring the void fraction at the pin row centerline (minimum flow path) because of the small total path length available at this position. Another manner of illustrating the distribution of density in the array is shown in Figure 15. Here the void fractions measured between pin rows are compared to the average void fractions at this region. The between-pins-voids are seen to fall about 10 per cent absolute void fraction higher than the average over most of the void levels tested.

D

Figure 14 - Comparison of Air-Water Data for Region "C" Monoenergetic Beam with Annular Flow Model (43-024-706)

Figure 15 - Region "C" Space Centerline Void Fraction for Air-Water Data with Monoenergetic Beam (43-024-708)

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