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TECHNICAL DATA RECORD

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718-81

TITLE

Dynamic Void Fraction Detector

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PROGRAM

Reactor Safety

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Pressure Transients and Flow Stability

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STATEMENT OF PROBLEM

Prepare a system description of the "Dynamic Void Fraction Detector" which is being used for boiling studies of the Flow Stability Test Loop.

ABSTRACT

Various methods and techniques for measurement of void fraction are discussed. Details of seventeen void fraction detectors are abstracted in Table 1.

A Dynamic "Void Fraction Detector" which measures void fraction and void fraction distribution within a 12 foot long, 1/2" diameter, nickel test section filled with Santowax-R coolant, is described.

Void fraction is determined by measurement of the intensity of a narrow x-ray beam which penetrates the test section. A high intensity, low energy, x-ray generator, scintillation detectors, and a wide band - fast response amplifier, are used for detection of rapid void fraction transients. Major sources of error are cancelled by using two detectors connected in a differential circuit. Serial cooling and heavy magnetic shielding of the detectors further reduces measurement errors. The void fraction detection system is mounted on an elevator assembly which is used for vertical and horizontal scans of the test section.

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INTRODUCTION

Pressure transient and flow stability studies are being conducted as a part of the organic reactor safety program. Some of the objectives of this project are to investigate the heat transfer and hydraulic effects of pressure transients which may result from accidental loss of reactor coolant pressure; and to establish by analytical and experimental means a method of determining coolant flow distribution and flow stability in parallel fuel element channels.

A well instrumented organic test loop was designed and constructed for the purpose of obtaining transient and steady state experimental data.⁽³⁸⁾ A major component of the flow stability test loop is a device which measures void fraction and void fraction distribution along the entire length of the test section.

A survey of void measuring techniques and a system description of the "Dynamic Void Fraction Detector" are presented in this report.

Methods of Measuring Void Fraction

Void fraction determination of a two-phase mixture may be obtained through either of two measurement philosophies:

- a. Direct Measurement (Actual volumetric measurement of the gas phase.)
- b. Indirect Measurement (Measurement of some property of the two-phase mixture from which the void fraction can be inferred.)

For each of these basic measurement philosophies there are a number of techniques which have been suggested or tried.

a. Direct Measurement Techniques

1. Visual Observation

High speed photographs are taken through a transparent test section containing a two-phase mixture. The number and size of the bubbles appearing on the photograph give a direct indication of the void volume and hence the void fraction within the test section.

2. Volumetric Flow

Volumetric flow meters are located at the inlet and outlet of the test section. The inlet flow meter indicates the liquid volumetric flow rate while the outlet meter indicates the liquid plus gas volumetric flow rate. The instantaneous difference in flow meter readings is a direct indication of the volumetric gas flow rate. If this quantity is divided by the inlet flow rate, the result is the average value of void fraction for the entire test section.

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3. Quick Closing Valves

Simultaneously operated quick closing valves located at the inlet and outlet of the test section are used to entrap the boiling liquid. After sufficient separation time the liquid level in the test section is measured. Knowing the total length of the test section, the average void fraction may be easily calculated.

b. Indirect Measurement Techniques

Since density of a two-phase (liquid-vapor) mixture is almost inversely proportional to void fraction, and is relatively easily measured, most investigators have used density measurement techniques. There are many methods for determining density by measurement of various properties of the mixture. Some such properties are; the absorbtivity of vibrational energy, dielectric constant, resistivity, permeability, attenuation of radiant energy, and the absorption of radioactive particles. Various density measurement techniques are discussed in the Literature Survey.

Discussion of Measurement Techniques

Direct measurement of void fraction by mechanical means was not seriously considered for the flow stability test loop because dynamic measurement of void distribution could not be readily accomplished. The successful use of the visual method is limited to low void-fraction situations because of the difficulty of interpreting two-dimensional photographs of a three-dimensional phenomena. In addition, the use of visual observation implies the use of transparent test sections which limit the operating temperature and pressure.

Unfortunately, most density measurement techniques are strongly dependent on the distribution of the vapor phase in the liquid phase, or necessitate the use of some form of signal which affects the phenomena under investigation. For these reasons the use of vibrational energy absorbtivity measurement was discounted. The physical properties of the organic coolant eliminated the possibility of using dielectric constant, resistivity, and permeability measurement techniques. The radiation attenuation method appeared to be the most promising for measurement of void fraction and void fraction distribution, in a forced convection nucleate boiling system, without significantly affecting the phenomena being investigated.

Subsequent calculations indicated that void fraction measurement, within the test loop, could be accomplished with good sensitivity and accuracy, only by radiation attenuation methods.

Literature Survey of Void Fraction Detection Methods

Extent of Survey

The literature search on methods of void-fraction measurement covers the period from 1951 to date and includes work done in England, Germany, and New Zealand as well as the U.S.A. Twenty-six references are listed in the bibliography; of these twenty-one have been reviewed, and of those reviewed seventeen are abstracted in Table I. Those references reviewed but not abstracted in Table I duplicate information already in the Table. References 1, 9, 18, 20, 21, and 26 were not available for review but it is believed that information contained in those references would not change the conclusions of this literature survey.

Table I is a tabular summary of the results of previously published attempts to measure void-fraction in various types of two-phase flow systems. The references are entered in chronological order.

It is immediately apparent from Table I that the most commonly used method of measuring void-fraction is by means of γ -ray attenuation (14 references) and the least used method is the use of a radioactive tracer (1 reference). Gamma-ray attenuation has been tried by investigators at Tulane (3), Battelle Memorial Institute (1), University of Minnesota (7), MIT (12), and principally at Argonne National Laboratory (5, 11, 6, 13, 2, 14, 10, 4). Photographic techniques have been used at MIT (25) and the Jet Propulsion Lab (24) while x-ray attenuation has been tried at the University of California (15, 16), the General Electric Company (17), and currently at Ramo-Wooldridge (18). Beta particle absorption has been used at the General Electric Company (20), the University of Washington (23), in New Zealand (21), and in England (22).

On the basis of void-fractions actually reported as measured, it appears that the various methods in order of decreasing sensitivity are: photographic, x-ray attenuation, β absorption, γ attenuation, and radioactive tracer. It is not possible to determine what the actual accuracies were in most of the reviewed references.

Discussion of Published Results According to Method

1. Photographic

The use of high speed photography is perhaps the most informative, and most sensitive method of measuring void-fraction. However, the process of taking high speed photographs and then counting and measuring bubbles is tedious and time consuming. The successful use of a visual method is, of course, limited to an apparatus with some transparent wall area, usually glass. The use of glass imposes serious limits on the allowable operating

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temperature and pressure levels. Finally, the methods can be accurately employed only in low void-fraction situations; i.e., 0.2 or less, because of the difficulty encountered in interpreting two-dimensional photographs of a three-dimensional phenomena.

In spite of the difficulties mentioned above, Griffith (25) measured void-fraction as low as 0.0002. Gunther (24) did not actually measure void-fractions, but such information can be extracted from his data. Much of the analytical work in the literature is based on these two visual studies as they have provided the analyst with a model of the flow phenomena investigated; namely, forced convection nucleate boiling.

2. γ -Ray Attenuation

The most commonly used source of γ -rays has been the 0.084 mev peak of Thulium 170 (1, 2, 4-6, 8-14) with Selenium 75 (7) and Iridium 192 (3), each being used once. All investigators have used Thallium activated Na-I scintillation crystals in conjunction with some type of photomultiplier tube as a detector system. Various source geometries and types of source collimation have been tried. Best results are obtained when a beam of parallel monoenergetic particles is employed.

The lowest void fraction actually reported as measured (but with unknown accuracy) is 0.01 by Richardson (14).

3. X-Ray Attenuation Method

In principle, the x-ray attenuation method is identical to the γ -ray attenuation method; the only differences being the nature of the source of photons and their relative energy; x-rays generally being a softer radiation. An x-ray system is identical to a γ -ray system with the additional complication that the x-ray tube which serves as a source of radioactive particles must be cooled. If the void-fraction measuring apparatus is to traverse the length of a test section, then flexible electrical leads and cooling water supply lines to the x-ray tube must be used.

The smallest value of void-fraction reported as measured (with unknown accuracy) was reported by Buchberg, et al (15), and is 0.01.

4. β -Particle Absorption

A statistical analysis of the absorption of beta particles is complicated by the fact that they are emitted with a continuous spectrum and that a beta particle can lose a large fraction of its energy in one collision. However, it has been shown that an exponential absorption law combined with a maximum range is approximately valid.

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If Strontium 90 (β energies to 2.2 mev) is used as a source, then the total weight per unit area of absorbing material between the source and detector should not exceed 1.2 gms/cm². This implies that only thin walled small diameter tubes or thin wall closely spaced channels can be used as a test section.

Even though the β -absorption method is limited to use in thin cross sections, it has the advantage that there is almost no scattering of β particles, and hence it is possible to obtain a well defined beam for use in making local measurements of void-fraction.

Costello (23) has reported void-fraction of 0.03 ± 0.013 with Strontium 90 as the β -particle source. He employed an annular test section with a cylindrical source inside the inner stainless steel tube and the detector outside the outer glass tube. Water was the test medium.

5. Radioactive Tracer

Only one investigator, Dengler (26), has reported using this technique. It is essentially a γ -ray attenuation technique with the source distributed in the test fluid. This technique offers no advantages over the previously discussed methods. In fact, serious safety problems are introduced by the use of this method.

Type of Void-Fraction Measurement

In examining Table I one will see the following expressions:

1. One shot
2. Local traverse
3. Longitudinal traverse

These expressions are defined below:

1. One Shot

At a given cross-section along the length of a test section, the attenuation of a beam of radioactive particles is measured and the void-fraction inferred. In some cases, the beam dimensions are such that only a portion of the flow through the cross section of the test section is scanned. In other cases, the beam is wider than the test section, and the entire flow through the cross section is scanned.

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2. Local Traverse

In this case, at a given cross-section along the length of the test section, a well defined beam of radioactive particles and an equally well collimated detector are simultaneously traversed across a cross-section of the test section. In this case, the dimension of the beam of radioactive particles in the direction of traverse is much less than the corresponding dimension of the test section being scanned.

3. Longitudinal Traverse

Usually a one shot local measurement is used here with the source and detector simultaneously traversing the length of the test section giving information as to the distribution of void-fraction along the length of the test section.

The most informative type of measurement would be a combination of local and longitudinal traversing. This, however, would not be possible in transient situations as such a measuring procedure would be time consuming. The one shot method used alone assumes that the voids are distributed uniformly both along and across the test section.

TABLE I

SUMMARY OF METHODS AND RESULTS OF VOID FRACTION MEASUREMENT

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 γ -Ray Attenuation

REF. & DATE	FLOW DIRECTION & TEST FLUIDS	TEST SECTION MATERIAL AND GEOMETRY	TEST CONDITIONS	SOURCE-TYPE -GEOMETRY -STRENGTH -COLLIMATION	DETECTION EQUIPMENT BEAM COLLIMATION	CALIBRATION	TYPE OF MEASUREMENTS MADE	MINIMUM MEASURED VOID FRACTION REPORTED
2 4/15/55	No flow - only stationary lucite models and layers of water, steel, and brass	No Data	Ambient	Thulium 170 No Collimation	No Data	No Data	One shot of Lucite models and water air models	Lucite model 0.136+60% -100% H ₂ O Layers 0.044+15%
3 12/21/55	Vertical, no liquid throughput air - water air - methanol air - glycerine	2" std steel pipe 6', 10' & 20' long 6" glass pipe 10' long 6" & 12" std steel pipe, 10' & 20' long 24" std steel pipe 5' long	Gas velocity to 5.7 fps Liquid velocity to 10 fps	Iridium 192 $\frac{1}{2}$ " diameter beam	Thallium activated NaI crystal	Test section full & empty	Radial traverse, source inside pipe, moved along diameter in 24" pipe	0.09
4 12/55	Vertical upflow steam-water	$\frac{1}{4}$ " x 4" x 60" stainless steel	Pressure, 600 psia Mass flux, 3.10^5 lb/hr ft ²	Thulium 170 $\frac{1}{2}$ r/hr @ 1 ft.	Dumont photo multiplier tube, & Scintillation Crystal	No Data	No Data	0.05
5 2/56	Vertical upflow steam-water	5 parallel channels 2- $\frac{7}{32}$ " x 3 $\frac{5}{8}$ x 48" outer 3- $\frac{7}{16}$ " x 3 $\frac{5}{8}$ x 48" inner 304 stainless steel	Pressure, 114.7 to 615 psia Inlet velocity 1.52 to 1.83 ft/sec Exit quality 1.9% to 8.2%	Thulium 170 (.085 mev γ) $\frac{1}{2}$ r/hr @ 1 ft.	Dumont photo multiplier tube, Hewlett Packard Current Amplifier Esterline Angus Recorder	Interpolation between full liquid and full vapor	One shot traverse longitudinal	0.1
6 11/56	Vertical upflow steam-water	$\frac{7}{16}$ " x 3 $\frac{11}{16}$ " x 2' $\frac{7}{16}$ " x 3 $\frac{11}{16}$ " x 4' stainless steel	Pressure 164.7 to 614.7 psia Inlet subcooling to 20 F Exit quality to .15	Thulium 170 (.085 mev γ) 2 r/hr at 1 ft	Dumont photo multiplier tube, Hewlett Packard Current Amplifier Esterline Angus Recorder	Lucite mockups water-air layers	One shot traverse longitudinal	0.006
7 3/57	Vertical upflow of steam-water mixtures	.872" I.D. x 16' long	Mass flow rates used .347, .526 & .702 #/sec, maximum quality 4%	Selenium 75 10 mcurie. Collimated by 1" diameter $\frac{1}{16}$ aperture	Model DS-1, Nuclear Instrument and Chemical Corp. Scintillation Counter	No Data	Longitudinal traverse. Local traverse. Rotation around test section to sample various diameters at a given station.	0.1

TABLE I (CON'T)

REF. & DATE	FLOW DIRECTION & TEST FLUIDS	TEST SECTION MATERIAL AND GEOMETRY	TEST CONDITIONS	SOURCE-TYPE -GEOMETRY -STRENGTH -COLLIMATION	DETECTION EQUIPMENT BEAM COLLIMATION	CALIBRATION	TYPE OF MEASUREMENTS MADE	MINIMUM MEASURED VOID FRACTION REPORTED
8 2/57	Vertical upflow of steam-water mixtures	304 SS rectangular 1" x .103" x 27" electrically heated	Pressure, 2000 psia, heat flux .04x10 ⁶ to .50x10 ⁶ Btu/hr ft ² , mass flux, 0.7x10 ⁶ to .9x10 ⁶ lb/hr ft ² . Inlet temperature 500, 575, & 625 F.	Thulium 170 (.085 mev & .053 mev peaks) Collimated by .2" x .2" hole.	NaI crystal water cooled magnetic shielding	Test section full and empty with interpola- tion. Lucite void models	One shot measurements	0.01
10 & 11 3/58	Vertical upflow of air-water mixtures	Lucite, rectangular cross-sections 2"x1/8", 1/4", 1/2", 3/4", 1" all 4' long	Ambient temp. Atmospheric pressure Water velocity, 1 to 10 fps. Mass flux, 2.5x10 ⁵ to 20x10 ⁵ lb/hr ft ²	Thulium 170 (.085 mev peak) Pellet .19" dia. 9 r/h @ 6"	NaI thallium activated scintillation crystal, RCA 5819 photo- multiplier tube, Lucite light pipe between crystal and tube. Linear current amplifier, Brown 0-10 mv recorder, Beam collimated at tube by Pb window 1" thick with slot 1" x 1/32". NaI crystal cooled by water coils.	Lucite mockups of 2 phase flow patterns, annular flow, local boiling, parabolic distribution of voids in liquid, homogeneous flow.	One shot, local traverse, longitudinal traverse	0.1
12 8/58	Vertical upflow of air-water mixtures	.724" I.D. glass tube 5' long	Ambient pressure & temperature	Thulium 170 .01" dia x 1 1/8" long, .9 mcurie	Baird Atomic 8125 scintillation probe Baird Atomic 131 scaler	Test section full & empty interpola- te in between. Check against quick closing valves to trap flowing mixture.	One shot and local traverse	
13 11/58	Vertical upflow of steam-water	SS, rectangular 1/2" x 2". 1/8" thick wall, elec- trically heated	No Data	Thulium 170 (.085 mev peak) Pellet .19" dia. 9 r/h @ 6" collimated by 1/2" dia. hole	NaI thallium activated crystal, 1 1/4" dia. x 1" thick. RCA 5819 or Dumont 6292 photo multiplier tube detector shielded by MU-metal against mag field & Pb shield against background & scatter, water cooled detector, beam colli- mated at crystal by 1/2" x 5/8" Pb window.	Lucite mockups and interpolation based on full & empty reading of test section	One shot and longitudinal traverse	No Data

TABLE I (CON'T)

REF. & DATE	FLOW DIRECTION & TEST FLUIDS	TEST SECTION MATERIAL AND GEOMETRY	TEST CONDITIONS	SOURCE-TYPE -GEOMETRY -STRENGTH -COLLIMATION	DETECTION EQUIPMENT BEAM COLLIMATION	CALIBRATION	TYPE OF MEASUREMENTS MADE	MINIMUM MEASURED VOID FRACTION REPORTED
14 12/58	Horizontal flow of air-water mixtures	Lucite, rectangular cross-sections, 2" x 1/8", 1/4", 1/2", 3/4", 1". Test section length 10 feet.	Ambient temperature, atm. pressure, quality .0005 to .0517 W _{H₂O} , .3 to 3.66 #/sec, W _{air} , .001 to .06 #/sec.	Thulium 170 (.085 mev peak) Pellet .2" dia. 9 r/h @ 2"	Same as 10. Beam collimated at crystal by 1/2" x 5/8" window or 1/32" x 1/2" window large window for one shot, small window for traversing	9 different Lucite mockups	One shot and local traverse across a given cross-section. Longitudinal traverse along length of test section.	.09 local traverse, 0.01, one shot 0.09
15 3/51	Vertical upflow of water subcooled and bulk boiling	X-Rays 1/4" I.D. x 25" long stainless steel	Pressure 100 to 2500 psia. Sub- cooling 0 to 236°F. Heat flux to 3.8x10 ⁶ Btu/hr ft ² . Mass flow .96x10 ⁶ to 7.7x10 ⁶ #/hr.	250 Kv, 10 ma. Westinghouse X-ray unit	Cadmium-tungstate crystals, lucite light pipe, photo multiplier tube	No Data	One shot	.01 g/cc @ 0 cps, .04 g/cc @ 100 cps.
16 10/54	No flow water-steam	Pyrex battery jar 6 1/2" x 8 1/2" x 11 1/2" electric resistance bulk heating of liquid	Pressure 14.7 and 135 psia	Westinghouse 250,000 volt Quadroconex Therapy unit operated at 10 ma. no external reg- ulation or filtra- tion of power supply	ECA 5819 photo multi- plier calcium tung- state scintillation crystal	full - empty readings and interpolation	One shot	.05
19 2/29/60	Vertical upflow water-steam	1060 aluminum 24.625" long x .830" x .116". Electrically heated	No Data	Gen. Elec. CA -7 Mo target x-ray tube in G.E. XRD-5 diffraction x-ray machine line voltage & tube current stabilization, 30 Kv potential, 23 Ma tube current. Converted to constant potential machine.	Ba SO ₄ screen on RCA 931A photo multiplier converted to NaI crystal & Dumont 6292 photo multiplier.	full - empty and interpolation	One shot sample of cross-section vertical traverse.	No Data

TABLE I (CON'T)

REF. & DATE	FLOW DIRECTION & TEST FLUIDS	TEST SECTION MATERIAL AND GEOMETRY	TEST CONDITIONS	SOURCE-TYPE -GEOMETRY -STRENGTH -COLLIMATION	DETECTION EQUIPMENT BEAM COLLIMATION	CALIBRATION	TYPE OF MEASUREMENTS MADE	MINIMUM MEASURED VOID FRACTION REPORTED
22 2/55	Vertical upflow of water subcooled boiling	<u>β Attenuation</u> Rectangular channel .177" x .80" x 60 cm., oval channel .177" x .80" x 60 cm. Heated length, 60 cm. Stain- less steel with .010" wall thickness.	Exit pressure 30" H ₂ O. Inlet velocity 12'/sec, inlet temp. 44.3°C. Heat flux to 550 watts/cm.	Praseodymium 144 & daughter cerium 144. 20 mc, $\frac{1}{2}$ " dia. beam.	End window Geiger tube with 2 minute counting time. Ionization chamber $\frac{1}{2}$ " dia. hole in detector shield.	Full - empty with various liquids and interpolation	One shot longitudinal traverse	No Data
23 8/59	Vertical upflow of water subcooled boiling	Flow in annulus .190" O.D. inner heater tube, 304 SS .516" I.D. outer tube SS or glass	Pressure, 34" Hg. Inlet velocity 1.5, 3, & 4 fps. Heat flux, to 8.21x10 ⁵ Btu/hr ft ²	Strontium 90 (β up to 2.2 mev) no collimation	Geiger tube & Tracerlab sealer, model SC-51	Lucite mockup with 3 different source strengths	One shot longitudinal traverse	0.03 $\pm$.013
25 8/58	Vertical upflow of water subcooled boiling	<u>Photographic</u> Rectangular 2 sides glass 1 side heater strip .378" wide x 3" long .5, .18, or .09 inches to opposite wall from heater	Pressure, 500, 1,000, 1,500 psia. Water velocity 20 & 30 fps. Heat flux .25x10 ⁶ to 2.7x10 ⁶ Btu/ hr ft ²	Bubble counting and measurement		None required		0.0002

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General Description of the Dynamic Void Fraction Detector

The void fraction detector consists of an x-ray tube photon source, collimators, water-cooled scintillation detectors, and position transducers; all mounted on an elevator assembly which permits scanning the test section either vertically or horizontally. Located outside of the test section enclosure are: the x-ray control console and high voltage power supply, the elevator control panel, the detector control panel, detector power supply, differential amplifier, X-Y recorder, and a line voltage regulator.

The x-ray beam is split into two narrowly collimated beams. One beam is transmitted through a dummy or reference test section filled with Santowax-R, at room temperature. The other beam is transmitted through the electrically heated test section. A D.C. signal voltage from each of two scintillation detectors, located behind each test section, is fed into a differential amplifier which subtracts the reference signal from the void fraction signal. The purpose of the reference signal is to minimize the effects of fluctuating high voltage to the detectors and fluctuations in x-ray tube output. The D.C. output signal from the differential amplifier drives one axis of an X-Y recorder, and a high speed recording oscillograph, which are calibrated to read void fraction directly. Void fraction calibrations are made by placing materials of various density, corresponding to known void fractions in Santowax-R, in the path of the void fraction x-ray signal.

Photon Source

Analysis of the radiation attenuation characteristics of the test section indicated that dynamic void fraction measurement could best be accomplished using low energy gamma or x-rays. In establishing the source requirements, the following criteria were used:

- a) Source energy and intensity must be high enough to penetrate the test section with an intensity of 10^8 to 10^9 photons/sec at the detector.
- b) Source energy must be low enough to permit measurement of void fractions as low as 0.03 to 0.01.

It was determined that the source energy should be within the range, 30 to 150 kev, and that the intensity should be no less than 100 R/hr. In the energy range of interest, 30-150 kev, there is only one isotope available which can be obtained with a high specific activity and a half-life which is long enough to permit its use. This isotope is Thulium-170 (half-life = 129 days) which can presently be obtained with specific activities of about 100 curies/gm. The Tm^{170} spectrum consists of a continuous background of bremsstrahlung due to the slowing down and stopping of electrons emitted by Tm^{170} . Superimposed on the background are two peaks due to decay of the ytterbium-170 (Yb^{170}) daughter of

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Tm^{170} . These peaks result from decay gamma-ray (84 kev, 3% yield) and K x-ray (53 kev, 5% yield) transitions in the Yb^{170} .

Although it is possible to obtain Tm^{170} sources of sufficient intensity to adequately perform the desired measurements, the cost of a one-year supply of sources is greater than the cost of an x-ray machine of comparable or greater output.

Measurement of rapid changes in void fraction dictated that the x-ray machine output should be constant, i.e., rectified and filtered power supply. An investigation of constant potential x-ray machines disclosed that there were two almost identical devices, (Siefert and Muller) which had sufficient output and adjustability of photon energy. The Muller x-ray machine, with a maximum output of 3.8×10^7 R/hr, was chosen as the void fraction detector photon source.

This device is the MG-150 industrial unit which is continuously adjustable in the ranges from 25 to 75 and from 50 to 150 KV-D.C. Continuous rated output of the apparatus is 3 Kw. An automatic line voltage connection unit maintains the incoming line voltage constant to within $\pm 1.5\%$ for voltage fluctuations up to ± 40 volts. The x-ray tube is a Norelco MG-150/1 double focus, beryllium window, 150 KV-D.C. tube. At a target to specimen distance of 3 inches, the dose rate output is 6.9×10^6 R/hr, when operated at 100 KV and 18 ma. Focal spot sizes are 0.7 and 2.5 mm.

Elevator Assembly

The elevator table consists of two plates separated from each other by ball-bearings and tracks. Rigidly attached to the bottom plate is a horizontal drive motor, reduction gears, left and right limit switches, and horizontal position transducers. The x-ray tube, collimators, dummy test section, and shielding are mounted on the top plate. The horizontal drive motor is a bi-directional, capacitance motor, which is actuated by a remote (left-off-right) switch located on the elevator control panel. A screw and nut drive device couples the motor and reduction gears to the top plate, transforming rotational to rectilinear motion. The top plate has a total horizontal movement of 1 inch but can be adjusted to about 2 inches for larger or rectangular test sections. Initially the elevator table is manually adjusted so that the narrow x-ray beam will pass through the center of the test section. The test section can then be remotely scanned horizontally ± 0.5 inches either side of the center line. Left and right limit switches stop the drive motor when the top plate reaches ± 0.5 inch. A synchro-position transmitter sends an electrical signal to a remote synchro-receiver unit located on the elevator control panel. Horizontal position is indicated in thousandths of an inch. A ten-turn heli-pot, mechanically coupled to the gear train, provides an electrical position signal for input to the X-Y recorder whenever plots of void fraction vs. position are required. A complete horizontal scan of the test section takes approximately 15 seconds.

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The elevator vertical drive mechanism is essentially identical to the horizontal drive with the exception of a more powerful motor. A sprocket wheel and chain raises and lowers the elevator table. Counter weights were used to reduce drive power to that required to overcome friction only. The elevator can be stopped at any elevation simply by cutting off power to the drive motor. Vertical position transducers, which are identical to the horizontal transducers, are used to indicate vertical position to within 0.1 inch. A 12-foot vertical scan takes approximately 30 seconds.

The elevator table is guided by four vertical steel rods of 1" diameter. The steel rods are maintained rigid by means of struts which connect to the main test loop support structure and to the building beams. The elevator table rides the steel guide rods on partial ball bushings which clear the guide rod support struts.

Because of the location of the x-ray tube at the edge of the elevator table, the center of gravity is displaced from the center of the table, resulting in an undesirable moment which would cause the elevator to bind. The C.G. is moved back to the geometrical center of the table by means of lead counter-weights.

The entire weight of the elevator table and counter-weights is supported from above by means of steel reinforced pillow blocks which are fastened to an overhead building beam. The total weight of the elevator assembly is approximately 300 pounds.

Collimators and Shielding

A 0.25" thick lead mask with two 0.5" by 0.1" slits, spaced 10 degrees each side of beam center, covers the x-ray tube window. Before and after passing through the reference and heated test sections the split beams are collimated by 0.5" by 0.1" lead collimators. The collimator slit position can be manually adjusted for system alignment purposes. After passing through the test section and collimators, the x-ray beam intensity at the detectors is normally about 10 R/hr, but can be adjusted between 0 and 100 R/hr.

A 1/4" lead shadow shield is placed behind the detectors to minimize the radiation escaping the test section enclosure. The maximum measured dose rate at the surface of the test loop enclosure is approximately 3 mr/hr. At any of the operating positions or locations where personnel normally work, the radiation is not detectable.

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CROSS-SECTION OF TEST SECTION
AND SUPPORT STRUCTURE

TEST SECTION — SEAMLESS NICKEL TUBING, 0.479 INCH I D
WITH 0.042 INCH WALL THICKNESS

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Transients Instrumentation

Test Section Installation

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Instrumentation Line Voltage Regulator

A Sorensen model 2501, 2500 VA, rack mounted regulator unit supplies regulated power to the detector high voltage power supply, the differential amplifier, and the X-Y recorder. Regulation accuracy is $\pm 0.01\%$ for input voltage variation of $\pm 10\%$. The time constant for 63% recovery from maximum input voltage variation is 0.2 seconds. Output voltage is adjustable from 110 to 120 VAC.

Detector Power Supply

The detector high voltage power supply is a John Fluke model 412 A. Output polarity can be either positive or negative and is adjustable from 500 to 2010 volts at a maximum current of 15 milliamperes. The power supply is normally operated at -1200 VDC at an output current of 5 milliamps. Output voltage stability is 0.005% per hour and 0.05% per day.

Differential Amplifier

The differential amplifier is a wide band, chopper stabilized, 12 transistor unit. Upon entering the amplifier the reference detector signal is subtracted from the test section detector signal. As shown in the "Void Fraction Detector" Block Diagram, d-c and very low frequency signals are impressed across resistors in the input circuit and are converted to a 390 cycle square wave by a chopper and transformer T2. This signal is amplified 21,000 times by a 4 stage direct coupled A-C amplifier and is then demodulated to d-c. After filtering, the d-c signal is added to high frequency signals which are passed directly through transformer T1. The composite signal is then amplified by a six stage direct coupled amplifier. Zero stabilization is achieved by the chopper amplifier during alternative half cycles to temperature compensate the input transistor of the wide band d-c amplifier. Negative feedback, enclosing the entire amplifier from the output to the input bridge network, flattens the response and stabilizes gain.

Amplifier gain is continuously adjustable from 30 to 1000. Frequency response is flat from 0 to 20 Kc. When the amplifier is properly balanced and zeroed at a gain setting of 250, the output voltage is 0 volts for a void fraction of 0%. At 100% void the amplifier output is +10 volts. Maximum output current is 25 ma. at 10 volts. The amplifier response time is 25 micro-seconds for a void fraction change of 80%, and 90 micro-seconds for a 100% change. Total measurement error due to amplifier gain instability and temperature caused drift is $\pm 0.013\%$.

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X-Y Recorder

The X-Y recorder is a Moseley model 3S "Autograf" two axis graphic recorder which will accept DC signal information from related sources and automatically produce representative cartesian coordinate curves on standard $8\frac{1}{2}$ " x 11" graph paper. Normally the Y axis is used to record void fraction signals from the differential amplifier and the X axis is connected to either the horizontal or vertical position transducer. The device may also be used as a direct writing, low frequency oscillograph by utilizing its built in time base or sweep circuit as an independent function for the X axis.

The recording mechanism employs a "drafting machine" type linkage, cable driven by independent servo motors which effectively convey Y-motion without cross coupling to X. Electrically isolated high gain amplifiers control the servo motors. Input ranges are in eleven calibrated steps from 5 millivolts to 500 volts on each axis. By means of a transfer switch each input range may be expanded and made continuously variable to permit the fitting of arbitrary voltages to any desired scale. The recorder also contains full range zero set and one full scale length of zero suppression on each axis. These features permit full scale recording resolution of any portion of the void fraction spectrum.

Recording accuracy is better than $\pm 0.25\%$ of full scale and resetability is $\pm 0.1\%$ of full scale. The maximum recording speed is 0.5 second for full scale travel on each axis.

Scintillation Detectors

The scintillation detectors consist of an NaI (Tl) crystal which is optically coupled through a polished lucite light pipe to a 6362 multiplier phototube. The crystal, light pipe, and phototube are encased by a water-cooled, light tight, magnetic shield.

The DuMont type 6362 is a 10 stage multiplier phototube with a flat end window type photo-cathode having an S-11 response. The tube diameter is $\frac{3}{4}$ inch and its length is $4\frac{7}{8}$ inches. The dynode string was designed for 1200 volt operation at a current of 2 ma. Supply voltage between the photo-cathode and 1st dynode is 200 volts. Dynode voltage is 100 volts/stage. The current amplification is approximately 150,000. Anode current during void fraction measurement is approximately $190\mu\text{A}$ with a maximum inherent noise level of $0.05\mu\text{A}$.

A sodium iodide (thallium activated) crystal of $\frac{3}{4}$ inch diameter and $\frac{3}{4}$ inch length is used for conversion of x-ray photons to light photons. The crystal which is designed for low energy gamma detection is backed with a 0.001" thick aluminum foil window.

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An optically polished lucite light pipe of $3/4$ " diameter by $3-1/8$ inches in length couples the NaI (Tl) crystal to the phototube. Under ideal conditions it would be best to couple the crystal directly to the phototube; however, the magnetic field generated by the test section heating current is so strong that the phototube had to be located some distance from the crystal. Magnetic field intensity at the crystal was calculated to be 96 gauss for a test section heating current of 2400 amps. At the photo-cathode the magnetic intensity would be a maximum of 24 gauss if shielding were not used. For good optical coupling, Dow Corning DC-200 silicone oil is used to connect the crystal to the light pipe and the light pipe to the phototube.

The phototube is surrounded by a thin mu-metal magnetic shield which effectively eliminates electron beam defocusing in magnetic fields of 0.3 to 0.8 gauss. The detector case, which serves as a high intensity magnetic shield, consists of three concentric tubes of $1/8$ " thick soft iron which are electrically insulated from each other by polystyrene rings. The detector case attenuates magnetic fields by a factor of 1000 and enables the detector to be used in magnetic fields as high as 100 to 200 gauss.

Cooling water is circulated through a coil of $1/4$ " diameter copper tubing which is brazed to the detector case. Serial cooling of the detectors substantially reduces temperature induced sources of measurement error.

During void fraction measurement, at zero void conditions, both the reference and test section detectors deliver a DC output signal of 190 millivolts to the input of the differential amplifier. The detectors are differentially connected to the amplifier so that the resultant input signal is zero volts. Since detector characteristics change somewhat with age, the detector output signals are periodically ballanced by means of adjustable 2000 ohm potentiometers which are connected in parallel with the anode load resistor. At 100% void the reference detector output remains at 190 millivolts and the test section detector output increases to 230 millivolts. The resultant differential signal at the amplifier input is 40 millivolts. Differential connection of the two detectors, with almost identical output characteristics, greatly reduced measurement errors caused by variation of detector high voltage and x-ray tube output. During calibration of the void fraction detector, an attempt to measure void fraction with just one detector could not be accomplished because of excessive fluctuation of detector output. Dynamic void fraction measurements using the differential detector circuit were found to correlate very well with void fraction data calculated on a 7090 computer. A discussion of void fraction measurement accuracy and errors will be the basis of a future report.

VOID FRACTION DETECTOR BLOCK DIAGRAM

PART NO.	NAME	MATERIAL
2	Detector Housing	Steel
3	Detector Housing	Steel
4	End Cap	Steel
5	End Cap	Steel
6	Detector Housing	Steel
7	Magnetic Shield	Soft Iron
8	Magnetic Shield	Soft Iron
9	Light Seal	Aluminum
10	Insulating Ring	Polystyrene
11	Insulating Ring	Polystyrene
12	Insulating Ring	Polystyrene
13	Insulating Ring	Polystyrene
14	Receptable Support	Aluminum
16	Light Pipe	Lucite
17	Insulating Collar	Polystyrene

DETECTOR ASSEMBLY

7549-72009

SCINTILLATION DETECTOR SCHEMATIC

DUMONT-6362 MULTIPLIER PHOTOTUBE

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HIGH VOLTAGE
-1200 V.D.C.
B+ GROUND

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Dynamic Void Fraction Detector

Transient response of the detection system:

Although the void fraction detector transient response was calculated for an 84 kev (Tm^{170}) source, the results are valid for any energy from 50 to 150 kev.

This analysis determines the minimum void fraction change that can be measured in a given time interval (dt), for a given source intensity and beam geometry.

Solution of problem:

Starting with the attenuation equation,

$$I = I_0 e^{-\sum \mu_i x_i} \quad (1)$$

Where: I is the intensity of the photon beam impinging on the detector.

I_0 is the source intensity at the surface of the test section.

$e^{-\sum \mu_i x_i}$ is the attenuation of all the photon absorbers normal to the photon beam.

$$\sum \mu_i x_i = (A + B + C + \mu x (1 - \alpha)) \quad (2)$$

Where: $A + B + C$ are the relaxation lengths of the air, nickel pipe, and insulating material between the source and detector.
(all constants)

$\mu x (1 - \alpha)$ is the relaxation length of the coolant for any void fraction (α).

(The relaxation length of the vapor in bubbles is so small that it can be neglected)

$$\therefore I = I_0 e^{-[A + B + C + \mu x (1 - \alpha)]} \quad (3)$$

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When $\alpha = 1$, the test section is empty.

$$I_{\text{Empty}} = I_0 e^{-[A + B + C]} \quad (4)$$

When $\alpha = 0$, the test section is full of fluid (no boiling).

$$I_{\text{Full}} = I_0 e^{-[A + B + C + \mu x]} \quad (5)$$

Solving for I in terms of α :

$$\frac{I_{\text{Full}}}{I_{\text{Empty}}} = \frac{I_0 e^{-[A + B + C + \mu x]}}{I_0 e^{-[A + B + C]}} = \frac{e^{-[A + B + C]} e^{-\mu x}}{e^{-[A + B + C]}} = e^{-\mu x}$$

$$\frac{I}{I_{\text{Empty}}} = \frac{I_0 e^{-[A + B + C + \mu x (1 - \alpha)]}}{I_0 e^{-[A + B + C]}} = e^{-\mu x (1 - \alpha)}$$

$$\frac{I}{I_{\text{Empty}}} \times \frac{I_{\text{Empty}}}{I_{\text{Full}}} = \frac{I}{I_{\text{Full}}} = \frac{e^{-\mu x (1 - \alpha)}}{e^{-\mu x}}$$

$$I = \frac{I_{\text{Full}} e^{-\mu x (1 - \alpha)}}{e^{-\mu x}} = I_{\text{Full}} e^{\mu x \alpha} \quad (6)$$

Writing the differential equation for (6);

$$dI = \mu x I_{\text{Full}} e^{\mu x \alpha} d\alpha \quad (7)$$

$$\text{since } I = I_{\text{Full}} e^{\mu x \alpha},$$

$$dI = \mu x I d\alpha \quad (8)$$

Solving for $d\alpha$ in terms of dI

$$d\alpha = \frac{1}{\mu x} \frac{dI}{I} \quad (9)$$

Taking into account the effect of the statistical nature of photon release, whether from a radioactive source or an x-ray generator,

$$\frac{\Delta I}{I} = \frac{\Delta N}{N} = \frac{1}{(N)^{1/2}}$$

$$\text{Since } \frac{dI}{I} = \frac{\Delta I}{I} = \frac{1}{\sqrt{N}},$$

$$d\alpha = \frac{1}{\mu x \sqrt{N}} \quad (10)$$

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where (N) is the number of pulses produced in the detector for (N') photons arriving at the detector in any interval of time.

Assuming 10% detector efficiency;

$$N = .1N'$$

If I is expressed as a flux; ie, photons/cm²-sec,

$$N' = I At$$

$$\text{and } N = I At \times 10^{-1}$$

where A is the cross sectional area of the photon beam normal to the beam and t is the time interval over which the count is taken.

Therefore:

$$N = I_0 e^{-\sum (\mu_i x_i)} A t \times 10^{-1}$$

For a well collimated, parallel beam of 84 kev photons, impinging on the test section with an intensity of 100 R/hr,

$$I_0 = 100 \text{ R/hr} = 7.8 \times 10^8 \text{ photons/cm}^2\text{-sec.}$$

$$e^{-\sum (\mu_i x_i)} \approx 10^{-1}$$

$$\text{and } N = 7.8 \times 10^6 A t \text{ (photons)}$$

$$\mu x = .135$$

$$\therefore d\alpha = \frac{1}{.135 \sqrt{7.8 \times 10^6 A t}}$$

$$d\alpha = \frac{2.66 \times 10^{-3}}{\sqrt{A t}} \quad \text{Void detector transient equation} \quad (11)$$

For collimators 0.5" by 0.1",

$$A = .322 \text{ cm}^2$$

From equation 11,

For a change in void fraction of $d\alpha = 1.00 = 100\%$

$$t = 22 \times 10^{-6} \text{ seconds}$$

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For $d\alpha = 0.10 = 10\%$

$$t = 22 \times 10^{-4} \text{ seconds}$$

For $d\alpha = 0.01 = 1\%$

$$t = 22 \times 10^{-2} \text{ seconds}$$

The above analysis is concerned only with the effects of statistical photon emission on transient measurement. Instrumentation time delays and x-ray machine ripple will limit transient measurement time to about 10^{-3} seconds for $d\alpha$'s of 10 to 100%. (Transients of 10^{-3} seconds can be adequately handled by a recording galvo or scope. X-Y recorder will record transients of about 0.5 seconds or longer and will be used for average void fraction measurements.)

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Determination of Detector Output

1. One roentgen corresponds to the absorption of 84 ergs/gm in air-equivalent material. At a dose rate of 1 R/hr the absorbed energy is therefore $84/(3600 \times 1.6 \times 10^{-9})$ kev/gm-sec.
2. The number of photoelectrons, P , which are produced at the cathode of the photomultiplier tube, due to complete absorption of a charged particle of energy E_p in the scintillator, is given by the equation:

$$P = E_p \eta g / h\nu = E_p / f$$

where $f = h\nu / \eta g$

η - is the intrinsic efficiency of the scintillator, which is defined as the ratio of the light energy emitted to the kinetic energy of the absorbed particle.

$h\nu$ - is the energy of the luminescent quantum, energy per photon.

g - is the light efficiency of the optical system and photocathode, and is given as photoelectrons per fluorescent photon.

(f) is defined as the figure of merit of the scintillation detector and is the average energy which the ionizing particle loses in the scintillator for each photoelectron ejected from the cathode of the photomultiplier.

3. One electron per second corresponds to 1.6×10^{-19} amperes.

From the above statements the output current, I_o , of the photomultiplier is derived as follows:

$$I_o = 2.33 \times 10^{-12} \text{ AMR}/f \text{ amperes}$$

where A = amplification factor of the photomultiplier.

M = mass of the scintillator in grams.

R = dose rate in roentgens per hour.

This equation is good for air-equivalent scintillators at all energies and for other scintillators at energies where the absorption is almost completely determined by the Compton effect, i.e., 1 to 2 Mev. For a NaI(Tl) crystal and x-ray photon energy of 100 kev, the equation must be multiplied by the relative response I/D of the scintillator. I/D is the ratio of the scintillator response to the response of an air ionization chamber at a given energy.

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For a scintillation detector with good optical and geometrical light utilization, the figure of merit, f , is approximately $2/\eta^*$, where η^* is the light yield with reference to anthracene. For NaI(Tl), η^* is 2. Therefore for this case the figure of merit, f , is equal to 1.

For a $3/4"$ D x $3/4"$ thick NaI(Tl) crystal and an x-ray energy of approximately 100 kev, the relative response of the scintillator is $I/D = 10$. The detector output equation now becomes;

$$I_o = 2.33 \times 10^{-11} \text{ AMR}$$

A 6362 photomultiplier tube is used, and the x-ray beam impinges on the scintillation crystal with an intensity of 10 R/hr.

$$M = 5.43 \text{ grams}$$

$$A = 1.5 \times 10^5 \text{ for the 6362 tube.}$$

$$R = 10 \text{ R/hr}$$

$$I_o = 190 \times 10^{-6} \text{ amps}$$

Locating the operating point (190×10^{-6} amps) on the anode characteristics curve of the type 6362 photomultiplier indicates that the tube is not overloaded and that the void fraction signal will be almost 4 decades above the dark current noise. Therefore, both the X-ray generator and the photomultipliers can be operated at well below their maximum rated levels.

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