NDA 2131-34

MASTER

CONCEPTUAL DESIGN OF A VAPOR
VOLUME FRACTION INSTRUMENT

M. H. Kalos
S. A. Davis
P. S. Mittelman
P. Mastras

Project Engineer: J. H. Hutton

April 15, 1961

Work Performed under Contract AT(30-1)-2303(IX)
for the United States Atomic Energy Commission

NDA -

NUCLEAR DEVELOPMENT CORPORATION OF AMERICA

WHITE PLAINS, NEW YORK

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, express or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission to the extent that such employee or contractor prepares, handles or distributes, or provides access to, any information pursuant to his employment or contract with the Commission.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NDA 2131-34

CONCEPTUAL DESIGN OF A VAPOR
VOLUME FRACTION INSTRUMENT

M. H. Kalos
S. A. Davis
P. S. Mittelman
P. Mastras

Project Engineer: J. H. Hutton

April 15, 1961

Work Performed under Contract AT(30-1)-2303(IX)
for the United States Atomic Energy Commission

NUCLEAR DEVELOPMENT CORPORATION OF AMERICA
White Plains, New York

CONTENTS

1. INTRODUCTION AND SUMMARY	1
2. THEORY OF THE MEASUREMENT	3
2.1 Discussion of Counting Statistics	5
2.2 Measurement of Average Density	9
3. SYSTEM DESIGN	11
3.1 System Concept	11
3.2 System Operation	11
3.3 Mechanical Design	15
3.3.1 Source Assembly	15
3.3.2 Detector Assembly	15
3.3.3 Linear Traverse	20
3.3.4 Angular Position	20
3.3.5 Vertical Position – Support Assembly	21
3.3.6 Support Structure	21
3.3.7 Instrument and Power Leads	21
3.4 Instrumentation and Control	21
3.4.1 General Operation	29
3.4.2 Gamma Count Channel	29
3.4.3 Linear Position	29
3.4.4 Angular Position	30
3.4.5 Instrument Assembly and Location	30

FIGURES

1. Conceptual Design – Vapor Volume Fraction Meter – Isometric	13
2. Conceptual Design – Vapor Volume Fraction Meter Assembly (Sheet 1 of 2)	17
3. Conceptual Design – Vapor Volume Fraction Meter Assembly (Sheet 2 of 2)	19
4. Conceptual Design – Instrumentation and Control Block Diagram – Vapor Volume Fraction Meter (Sheet 1 of 3)	23
5. Conceptual Design – Instrumentation and Control Block Diagram – Vapor Volume Fraction Meter (Sheet 2 of 3)	25
6. Conceptual Design – Instrumentation and Control Block Diagram – Vapor Volume Fraction Meter (Sheet 3 of 3)	27

1. INTRODUCTION AND SUMMARY

Experiments presently being conducted at the Columbia University Heat Transfer Research Facility are aimed at providing information in the area of boiling burnout. A motor-generator unit supplies power to a loop in which the power reactor fuel element performance is simulated. Pressurized water enters a simulated fuel assembly where boiling occurs. Individual fuel elements are simulated by electrically heated tubes. It would be of considerable value to the analysis of the experiment, and to further the application of the data, to know the average coolant density as a function of coolant channel length. Even more valuable would be a knowledge of the local coolant density at all points in a cross section of the simulated fuel assembly.

Accordingly, a technique was sought which would provide both average and local coolant densities. Because (1) high pressures and temperatures are involved, (2) metallic tubes are extensively employed, and (3) internal probes might cause perturbations, it was decided that gamma radiation probing was the only feasible technique.

The problem was analyzed mathematically and a procedure was evolved from which either local densities or average densities could be determined from the results of a series of gamma ray transmission experiments.

A preliminary design of the equipment necessary to perform such experiments has been prepared. Based on this design, it appears that:

1. The determination of average densities can be accomplished in a matter of a few seconds to within an error of less than 1%.
2. A determination of a complete density map (with 5% error) across a plane of the assembly will require approximately one hour of experimental measurement. However, the local density at any given point can be determined in several minutes.

The results of the experimental observations will be analyzed on a digital computer. Test programs have verified the computational procedure.

It should be noted that the device discussed here may have additional applications since it can determine local density inside a closed surface regardless of the shape of the confining surface or the distribution of material inside that surface.

1

2

3

4

5

2. THEORY OF THE MEASUREMENT

The attenuation of γ rays provides a measure of the line integral of the macroscopic total cross section along the line from source to detector. If the attenuation were measured along all lines through a figure in a plane, then enough information is presumably known to determine the (unknown) total cross section at any point.

When the materials which make up any portion of the interior are known, then the macroscopic cross section, μ (cm^{-1}), may be related to the density, ρ (gm/cm^3), and the cross section for γ rays in that material, σ (cm^2/gm), by

$$\mu = \rho\sigma$$

so that when μ is known, ρ may be determined.

To measure the attenuation, a source of γ rays and a counter are needed. One or both of these must be collimated so that a narrow beam is used. The apparatus is aligned so that the attenuation is measured along a series of lines of known coordinates. As shown later, these lines may be arranged in several ways and the calculation of the density is straightforward. Thus, in principle, the measurement of the density on the interior of a configuration whose materials are known may be carried out. Whether the measurement is a practical possibility depends upon the configuration in question, the number of points at which the density is required, the accuracy required, and upon the time available for the experiment. The establishment of feasibility requires an investigation of the actual methods which might be used and their applicability to vapor volume.

Consider the configuration of materials shown in the illustration. Suppose that in each of the areas inside or between circles the materials present are known together with their relative proportions so that a microscopic cross section σ_i for the i^{th} region may be assigned. At any point the macroscopic cross section for γ ray attenuation is

$$\mu(\vec{r}) = \rho(\vec{r}) \sigma_i.$$

Suppose a source and a collimated detector are set up and aligned as shown. Suppose further that the source emits γ rays of one energy only and that the detector has pulse height discrimination which permits it to count only those γ 's which travel from source to detector uncollided. Then counting rate N is related to counting rate N_0 with vacuum between source and detector by the equation

$$\frac{N_0}{N} = \exp \left[\int_L ds \mu(\vec{r}) \right], \quad (1)$$

where the integral shown is the line integral along the line joining source and detector. The basic information required is the line integral determined as

$$\int_L ds \mu(\vec{r}) = \log \frac{N_0}{N}. \quad (2)$$

To determine the density at a point P in region i , the following procedure may be used. Draw a line of length t making an angle φ with (say) the x axis. Let $L(t, \varphi)$ be perpendicular to this line. Define

$$g(t, \varphi) = \frac{1}{\sigma_i} \int_{L(t, \varphi)} ds \mu(\vec{r}). \quad (3)$$

According to the previous discussion, this is a measurable quantity. Now assume that, for fixed t , g is determined at many angles φ , to permit the calculation of

$$G(t) = \frac{1}{2\pi} \int_0^{2\pi} g(t, \varphi) d\varphi. \quad (4)$$

Slater* has shown that the density $\rho(\vec{P})$ may be computed as

$$\rho(\vec{P}) = -\frac{1}{\pi} \int_0^T \frac{dG(t)}{t}, \quad (5)$$

*M. Slater, NDA Internal Memos, Physics-Math 1482, 1491.

where T is that value of t such that L no longer passes through the region; $G(t) = 0$ for $t \geq T$. If G is measured for $t = 0, t_1, t_2, \dots, t_K = T$, then the integral in Eq. 5 may be approximated as:

$$\rho(\bar{P}) = -\frac{1}{\pi} \sum_{k=1}^K \frac{G(t_k) - G(t_{k-1})}{\frac{1}{2}(t_k + t_{k-1})}. \quad (6)$$

This is not the only method whereby line integrals such as Eq. 2 may be reduced to give density. Consider dividing the configuration into many small areas over which the density is approximately constant. If as many independent line integrals are measured as there are areas, then a set of linear equations containing the unknown densities may be set up and solved. Since this would involve the inversion of very large order matrices of unknown conditioning and, moreover, which contain statistical errors and other inaccurate information, it is impossible to say now whether this method would work.

Another possibility lies in establishing a few parameter representations of the unknown density. The parameters could be fixed by adjusting computed line integrals to agree with the measurements. Since no suitable representation seems to be available, it is necessary to return to the method implied by Eqs. 4, 5, and 6.

To assess the difficulties in reconstructing the density from measurements of this kind, a code was written for the Datatron computer to simulate the measurements and their reconstruction. A cluster of seven solid rods each surrounded by a thin layer of another material was placed inside another thin layer of material (see figure above). The code computes $g(t, \varphi)$ for a number of φ for given t , then $G(t)$, and finally carries out the operations indicated by Eq. 6. It was used to determine the steps in t and φ required to reconstruct the density to some required accuracy.

Generally it was found that 200 equally spaced points for φ together with a mesh in t (which near $t = 0$ is about as fine as the structure being looked at) yielded a density within about 20% of the density of the thin layers. In one case it was necessary to use a spacing in t half the thickness of the thin layer. A brief look was made at the improvement which occurs when the heavier material was made into a vacuum. This simulates the effect of measuring $g(t, \varphi)$ with and without water. Assuming the rods remain unchanged, the difference gives a g for the extra material alone. Since the structural material that might remain unchanged is heavy, this is expected to improve the results. Indeed, in the most difficult case tried, where the original mesh in (t, φ) introduced an error of 67%, elimination of heavy material reduced the error to 7% with the same mesh.

Thus it may be surmised that taking differences will generally reduce the error.

2.1 DISCUSSION OF COUNTING STATISTICS

According to Eq. 2, $\log N_0/N$ must be measured.

It may be assumed that N_0 is measurable with much greater precision than N by counting for a comparatively long time. The error in $\log N$ is approximated from

$$\text{Var} (\log N) \approx \left(\frac{\sigma N}{N} \right)^2, \quad (7)$$

where σN is the standard deviation or error in N . Since

$$\sigma N = \sqrt{N}, \quad (8)$$

$$\text{Var} \log N \approx \frac{1}{N},$$

$$\text{Var} g(t, \varphi) = \frac{1}{\sigma^2} \frac{1}{N},$$

$$G(t) = \frac{1}{n} \sum_{i=1}^n g(t, \varphi_i) \quad (9)$$

and

$$\text{Var} G = \frac{1}{n^2} \frac{1}{\sigma^2} \sum_{i=1}^n \frac{1}{N_i}.$$

where N_i is the number of counts used in obtaining $g(t, \varphi_i)$. Assuming all N_i are about the same and that $n\bar{N}$ equals N , the following holds true:

$$\sum_{i=1}^n \frac{1}{N_i} \approx \frac{n}{\bar{N}}$$

so that

$$\text{Var} G = \frac{1}{\sigma^2} \frac{1}{N}, \quad (10)$$

where N is now the total number of counts found in the counting to obtain G . Thus, as far as statistics are concerned, subdividing the angular range finer does not change the precision.

N refers to the total counts detected in determining G . The counting time depends upon the required N , the source strength, the fraction of the source which reaches the counter, and upon the counting efficiency.

The width of the beam at the detector is determined by the requirement on the size of the region, the density of which is being measured. This is taken to be a millimeter in the vapor volume experiment. The height of the beam may be larger; it is assumed to be 2.5 cm. For a source-detector separation of 1 ft, the geometrical efficiency is about 2×10^{-5} . With an assumed counter efficiency of 50%, about 10^{-5} of the γ 's from the source would be counted in the absence of attenuation.

The γ attenuation depends, of course, upon the γ -ray energy. This should be chosen, as far

as the availability of radioactive sources permit, so as to make the measurement of g as efficient as possible. For example, in a single medium

$$\frac{N}{N_0} = \exp (-\sigma \int \rho ds) \quad (11)$$

and

$$\text{Var } G = \frac{1}{N_0} \frac{1}{\sigma^2} \exp (+\sigma \int \rho ds) \quad (12)$$

The minimum in $\text{Var } G$ with respect to σ occurs when

$$\sigma \int \rho ds = 2, \quad (13)$$

that is, when the medium is exactly two mean free paths thick to the source γ rays.

When the medium contains several materials, for example, as iron and water in the proposed experiment, then $\text{Var } G$ may be minimized numerically with respect to the source energy. The result is not far from the condition expressed by Eq. 13 – two mean free paths for the entire path. This follows because in the important energy range near 1 Mev water and iron are not substantially different in their γ attenuation properties. The optimum source energy for a possible experimental arrangement with a 2 in. tube and a 5 in. jacket is about 850 kev. Cs^{135} and Co^{60} sources are about equally good from this point of view.

In terms of the γ 's emitted by the source, N_0 , (and including now the counting efficiency),

$$\text{Var } G = \frac{10^5}{N_0} \frac{1}{\sigma_0^2} \exp (\int \sigma \rho ds) \quad (14)$$

With $\sigma_0 = 0.064 \text{ cm}^2/\text{gm}$ for Co^{60} γ 's in H_2O ,

$$\text{Var } G \approx \frac{10^8}{N_0} \equiv \frac{V}{N_0} \frac{\text{gm}^2}{\text{cm}^4}$$

Using Eq. 6, which relates the density to the measured G 's, it is possible to find the variance in ρ which results from those in the G 's, as follows:

$$\rho = + \frac{1}{\pi} \left[\frac{G(0)}{\bar{t}_1} + \sum_{k=1}^{K-1} \left(\frac{1}{\bar{t}_{k-1}} - \frac{1}{\bar{t}_k} \right) G(t_k) - \frac{G(t_K)}{\bar{t}_{K-1}} \right],$$

where

$$\bar{t}_k = \frac{1}{2} (t_k + t_{k+1}). \quad (15)$$

From this

$$\text{Var } \rho = \frac{1}{\pi^2} \left\{ \frac{1}{\left(\frac{1}{2} t_1 \right)^2} \text{Var } G(0) + \sum_{k=1}^{K-1} \left(\frac{1}{\bar{t}_{k-1}} - \frac{1}{\bar{t}_k} \right)^2 \text{Var } G(t_k) + \text{Var } G(t_K) \left(\frac{1}{\bar{t}_{K-1}} \right)^2 \right\} \quad (16)$$

Each $\text{Var } G(t_k)$ is equal to $V/N_0(t_k)$, and it is reasonable to ask whether the total counts

$$\sum_{k=0}^K N_0(t_k)$$

may be minimized subject to the constraint that $\text{Var } \rho$ be no greater than some fixed value, say, σ^2 . Slater has shown that this minimum is attained when the $N_0(t_k)$ for $k = 0, 1, \dots, K$ are proportional to $1/\bar{t}_0, 1/\bar{t}_0 - 1/\bar{t}_1, \dots, 1/\bar{t}_{K-2} - 1/\bar{t}_{K-1}, 1/\bar{t}_{K-1}$, respectively, and that the total counts are

$$N_T = \sum N_0(t_k) = \frac{V}{\pi^2 \sigma^2} \left(\frac{2}{\bar{t}_0} - \frac{1}{\bar{t}_K} \right)^2 \approx \frac{V}{\pi^2 \sigma^2} \frac{4}{\bar{t}_0^2} = \frac{16V}{\pi^2 \sigma^2 \bar{t}_0^2} \quad (17)$$

Note also that half of the total counts are used in determining $G(0)$. Using

$$V = 10^8 \text{ gm}^2/\text{cm}^4$$

$$t_1 = 0.1 \text{ cm}$$

$$\sigma = 0.05 \text{ gm/cm}^3$$

$$N_T = 6 \times 10^{12}$$

This is the total number of γ 's that the source must emit for the density to be measured at one point. With a source of 1 curie ($3.7 \times 10^{10}/\text{sec}$), the time required is about 160 sec or about 2.7 min.

It has been suggested that the sequence of measurements implied by this analysis presents an inconvenient instrumental arrangement. Specifically, the objection is to the necessity of rotating source and detector about the point at which the density is measured as a center. Mechanically, a more satisfactory arrangement is to fix φ (say) and move source and detector so as to sweep the experimental test section. Whether the motion is continuous or intermittent depends upon the exigencies of mechanical design. In any case, if the sweep in t covers every millimeter with a millimeter beam width, and if enough angles φ are used, the $g(t, \varphi)$ may be extracted. The difficulty may be understood from the sketch. Lines separated by constant Δt are drawn for $\varphi = 0$ and $\varphi = \varphi_1$, (referring to the origin). While one line with $\varphi = 0$ passes through a selected point, P, neither of the lines with φ does so. Presumably, interpolation of some sort may be used to find the integral along the line through P.

It seems that, in this arrangement, it is inconvenient to count for a longer time at any one point. On the other hand, if every point is covered, it should be possible to reconstruct the density everywhere. The total counts at each point to permit this to be done with the assumptions mentioned above are obtained as follows. Each point must have the statistical accuracy required to give $G(0)$. If n angles are used, then each line integral requires $1/n$ of the counts required to obtain $G(0)$. The latter is $\frac{1}{2} N_T$, so taking $n = 100$, 3×10^{10} emitted photons are obtained for each point. For a curie source this requires about 1 sec.

To cover a device 5 in. wide, 100 strips, each 1 millimeter wide, are required; with 100 angular steps, 10^4 points are required.* With a curie source, about 3 hr would be required just for counting, which is likely to be too long. A 3-curie source brings the counting time down to 1 hr. If the movement of the source and detector and the read-out time do not introduce additional delay, this might be acceptable.

2.2 MEASUREMENT OF AVERAGE DENSITY

Suppose the line integral of Eq. 2 is measured along a series of parallel lines which cover the apparatus and spaced Δt apart. Let

$$q(t_i) = \int_{L(t_i)} \mu(\vec{r}) ds \quad (18)$$

then

$$\Delta t \Sigma q(t_i) \approx \int \mu(\vec{r}) dA \quad (19)$$

where the integral on the right is a surface integral, which is rewritten as

$$\int \rho(\vec{r}) \sigma(\vec{r}) dA.$$

Now suppose that this experiment is performed twice, with and without vapor. Then, assuming that the contribution to $\int \rho \sigma dA$ from structural material remains the same or its change from one experiment to the other is computable, it is possible to take the difference as the integral over the vapor alone. For this integral σ is a constant so $\int \rho_V(\vec{r}) dA$ may be deduced. The average vapor density may be obtained from

$$\overline{\rho_V} = \frac{\int \rho_V(\vec{r}) dA}{\int dA}.$$

If the difference can be taken, and if the experiment without vapor is assumed to introduce no statistical error, then

$$\text{Var } \overline{\rho_V} = \frac{(\Delta t)^2}{A^2} \frac{1}{\sigma_0^2} \sum_i \frac{1}{N_i} \quad (20)$$

where N_i are the total counts in the detector. As before,

$$N_i = 10^{-5} N_{0i} \exp(-\int \sigma \rho ds),$$

*The total time of counting is not substantially changed if the number of angular points is changed.

$$\frac{1}{\sigma_0^2 N_i} = \frac{10^8}{N_{0i}} \equiv \frac{V}{N_{0i}} \quad (21)$$

$$\text{Var } \overline{\rho_V} = \left(\frac{\Delta t}{A} \right)^2 V \sum_{i=1}^n \frac{1}{N_{0i}} \quad (22)$$

Let

D = diameter of the test cylinder,

then

$$\Delta t = D/n,$$

and

$$D/A = \frac{4}{\pi D} \quad .$$

Then

$$\text{Var } \overline{\rho_V} \approx \left(\frac{4}{\pi D} \right)^2 \frac{V}{n^2} \frac{n}{N_{0i}} = \left(\frac{4}{\pi D} \right)^2 \frac{V}{N_T} \quad . \quad (23)$$

If

$$\text{Var } \overline{\rho_V} = \sigma^2,$$

$$N_T = \left(\frac{4}{\pi D} \right)^2 \frac{V}{\sigma^2} \quad .$$

With

$$\sigma = 0.05$$

$$V = 10^8$$

$$D = 12.5 \text{ cm}$$

$$N_T = 4 \times 10^8 \text{ counts.}$$

A Co^{60} source of about 10 millicuries will carry out the experiment in about 1 sec.

3. SYSTEM DESIGN

3.1 SYSTEM CONCEPT

The design presented is an attempt to obtain the best combination of theoretical requirements and mechanical considerations. An isometric of the mechanical concept is shown in Fig. 1.

The device consists of a free standing all aluminum structure, approximately 3 ft wide, 3 ft deep, and 6 ft high, supporting three distinct but interrelated subassemblies, namely:

1. A carriage assembly, upon which the source and detector are mounted, to permit an automatic continuous linear traverse of the test section.
2. A rotating frame assembly to permit automatic programmed step-wise angular orientation of the carriage assembly about the fixed center of the test section.
3. A vertical support assembly to permit manual vertical positioning of the carriage assembly over the test section length of interest.

The test section is enclosed by and centered within the structure with a 3 curie source and detector, mounted on either side of the carriage assembly. The carriage assembly is perpendicular to the transverse axis of the test section and the collimating apertures of the instruments are directly opposed. Movement of the source and detector is continuous as controlled by a single electric drive mechanism for a traverse of 127 mm, capable of scanning the entire test section diameter at a rate of 3.3 mm/sec.

Angular rotation of the carriage assembly is accomplished by the rotating frame assembly to which it is connected. A spur gear mounted with centerlines coincident with that of the test section is driven by a pinion which in turn is driven by an electric motor through a servo clutch. Although angular positioning is accomplished in a step-wise fashion, 2° per increment after each complete linear traverse, the motor is designed for continuous operation with motion controlled through the clutch. By eliminating the inherent time lag due to the relatively large inertial forces of the motor, it is estimated that accurate angular repositioning can be obtained within 4 sec. An electric brake eliminates coasting after the correct angular position has been achieved.

Vertical positioning of the above two assemblies is obtained by a mechanical jack installed on the vertical support assembly. At the conclusion of each scan through a preselected plane, the entire assembly may be either raised or lowered to a new position by manual operation of the jack. If the time factor for this operation proves to be of importance, the entire operation may be automated by a relatively simple modification of the design.

3.2 SYSTEM OPERATION

Since the time of measurement is an extremely important factor in determining the feasibility of the device, a continuous linear traverse for each angular step is used. In this manner

Fig. 1 — Conceptual Design — Vapor Volume Fraction Meter — Isometric

a total scan at each plane for an unsymmetrical test section can be performed in 7578 sec (about 2 hr), and for a symmetrical test section in 3789 sec (about 1 hr) as tabulated below:

Operation	Unsymmetrical Sections	Symmetrical Section
Time per linear traverse (127 mm), sec	38.1	38.1
Time per angular step (2°), sec	4	4
No. of angular steps	180	90
Total traverse time, sec	6858	3429
Total angular rotation time, sec	<u>720</u>	<u>360</u>
Total Time per Scan at One Plane, sec	7578	3789

At the reference angular start position, the linear traverse is started. The integrated pulse count for each $\frac{1}{8}$ mm of travel is stored in the memory circuit of a 400 channel analyzer, used as a scaler. At the end of one complete traverse, 127 mm in 38.1 sec, the drive is automatically stopped by a limit sensor, and the angular programming system is actuated. In 4 sec the counter and detector are automatically rotated 2° about the center of the test section and the analyzer has discharged its stored information to a magnetic tape; ready for a new traverse. Information with respect to the position of the source vs time during a traverse, as well as angular position at which each traverse is made, is also recorded.

After a scan has been finished, complete traverse at all required angles, the stored data is coded and programmed in proper units on magnetic tape. Analysis utilizing a digital computer, such as the Datatron at NDA, is then made to determine the local coolant density.

3.3 MECHANICAL DESIGN

The assembly of the vapor volume fraction meter is shown in Figs. 2 and 3 and is depicted isometrically in Fig. 1.

3.3.1 Source Assembly

The gamma emitter is a 3-curie Co^{60} source encased in a lead cylindrical enclosure with a collimated aperture in one face. Source strength provides a sufficiently high count rate for statistical accuracy in a time interval conforming to the requirements of the experiment, namely, 1.11×10^{11} emitted photons/sec for a count of 10^6 per sec. This permits complete experimental measurement in approximately 1 hr. The emitted beam is collimated to $\frac{1}{8}$ mm wide by 2.5 cm high to permit count resolution in conformance with the $\frac{1}{8}$ mm line spacing upon which the traverse scan is based.

The lead enclosure is approximately 1 ft in diameter by 1 ft in length and is designed to provide laboratory radiation tolerance levels of 2.5 mr/hr at the surface. A shutter in the front face is also provided for closing the aperture when the source is not in use, thereby preserving shield integrity.

3.3.2 Detector Assembly

The detector is of the scintillation type consisting of a NaI crystal, focusing collimator and a standard probe. Supplementary shielding will be provided as required to minimize effects of background radiation. A separate preamplifier and linear amplifier increase the magnitude of

Legend:

- 1 Base assembly
- 2 Vertical support assembly
- 3 Rotating frame assembly
- 4 Carriage assembly
- 5 Spur gear
- 6 Ball bearing spline shaft
- 7 Potentiometer
- 8 Worm gear
- 9 Shaft
- 10 Bearing
- 11 Worm gear
- 12 Ball screw
- 13 Ball nut
- 14 Pinion
- 15 Spur gear
- 16 Bodine motor
- 17 Coupling
- 18 Roller bearing
- 19 Track
- 20 Ball nut
- 21 Ball screw
- 22 Thrust bearing
- 23 Leveling screw
- 24 Ball bearing spline nut
- 25 Guide strip
- 26 Source assembly
- 27 Detector assembly
- 28 Electric brake
- 29 Limit switch
- 30 Servo clutch
- 31 Electro brake

NOTES:

1. FOR PLAN VIEW SEE DWG 12516

Fig. 2 — Conceptual Design — Vapor Volume Fraction Meter Assembly (Sheet 1 of 2)

NOTES

1. FOR DESCRIPTION OF ITEMS SEE DWG NO 11971

Fig. 3 — Conceptual Design — Vapor Volume Fraction Meter Assembly —
(Sheet 2 of 2)

the detector output pulses. The preamplifier is mounted on the assembly closely coupled to the detector. Flexible leads transmit the preamplifier output to the linear amplifier, mounted in a relay panel independent of the meter mechanical structure.

3.3.3 Linear Traverse

Carriage Assembly

The source and detector assemblies are mounted on a movable carriage, capable of traversing 127 mm. They are fixed to the carriage on opposite sides of the test section, approximately 12 in. apart, with the collimating apertures directly opposed and parallel to the test section transverse axis. Relative positioning of the source and detector with respect to each other as well as to the test section remains fixed throughout the test measurement.

The carriage rests on and is guided by two 36-in. long ball spline shafts chosen for their low coefficient of sliding friction. It is driven along the shafts by a 14.5-in. long ball screw, attached to a worm gear. This gear in turn meshes with another worm gear attached to a shaft driven by the position drive motor assembly. The shaft is contained by two single row solid-race type radial ball bearings.

The entire assembly including the drive is supported on and within an aluminum channel box structure positioned with respect to the test section at the exact center and capable of rotating through 360°.

Position Drive Motor Assembly

A reversible constant speed $\frac{1}{15}$ HP electric motor is coupled through a gear reduction unit to the drive shaft. Operation of the traverse mechanism is automatic. It receives a command signal from the meter control system to start and then stops at the end of the complete traverse on a signal from a position sensor. A complete traverse of 127 mm is required in 38.1 sec at a constant rate of speed requiring a gear reduction of 1725 to 1 between the motor and shaft. An electric brake is provided to eliminate coasting at the end of each complete traverse.

In addition to the controls described, a continuous record of position with respect to time, throughout each complete traverse, is provided by means of a multiturn potentiometer geared to the drive shaft. The analog signal is converted to a digital signal by means of an encoder and stored on a magnetic tape.

During the development stage, if it is revealed that step-wise scanning is preferable to a continuous traverse, the required modifications may be made rather easily. The position sensing system can be used to feed a servo clutch coupling the shaft after the gear reduction unit, thereby permitting continuous operation of the motor and gear reduction unit. This system would minimize the relatively large inertial and frictional forces of these units. However, a system of this type must inherently increase the total measurement time due to the repositioning sequence required between each point.

3.3.4 Angular Position

Rotating Frame Assembly

The aluminum channel box structure supporting the carriage assembly is designated as the rotating frame. It is fixed to a large spur gear, 18-in. pitch diameter, which in turn meshes with a pinion gear driven by the angular drive motor assembly. The spur gear is retained in a fixed position relative to the test section and is supported and guided by a series of 16 ball bearing rollers. The entire assembly is carried by the aluminum vertical support assembly.

Angular Drive Motor Assembly

The drive system utilizes a continuously running constant speed motor and gear reduction unit transmitting the required torque to the drive pinion through a clutch and brake assembly. The angular rotation is made in steps, namely 2° increments, requiring accurate position control. Therefore, the clutch is of the servo type with rate damping control, receiving its position error signal from a servo amplifier. At the end of each traverse the programmed control signal initiating a step change in angular increment, received from the servo amplifier, engages the clutch for maximum velocity of angular movement. As the required position is reached, the error signal decreases and is accompanied by a proportional decrease in velocity of the rotating frame assembly. When the new programmed angular position is reached, the brake is actuated. Proper setting of the servo system rate response in conjunction with brake actuation should enable fast repositioning with a minimum of cycling. The angular position is measured by a multiturn potentiometer also geared to the drive shaft. In addition a second unit is also provided for continuous record of angular position. The analog signal is converted to a digital signal by means of an encoder and stored on a magnetic tape.

It has been estimated that approximately a $\frac{1}{15}$ HP motor will be adequate for repositioning through 2° in from 1 to 4 sec. The concept of a continuously running motor and gear reduction unit minimizes the inertial and frictional forces of these units allowing for this type response.

The time estimate is within the 4 sec minimum time requirement necessitated at the end of each linear traverse by the meter instrumentation as discussed in Section 3.4.

The system is designed for a complete revolution through 360° to permit scanning of an unsymmetrical section, but it may be used for any total angular movement required. At the completion of the measurement, the system may be manually reset to the start position.

3.3.5 Vertical Position – Support Assembly

The rotating frame assembly, described in the preceding paragraphs, rests on a vertical support assembly fabricated as an aluminum weldment of plates and channels. A manually operated ballscrew permits positioning in a vertical direction through a travel of 10.5 in. Upon selection of a plane for measurement, as determined by visual and manual inspection, the screw is locked in place. The frame is supported against lateral thrusts by six roller bearings which ride in two 1 in. by 1 in. by 24-in. long channels attached to the main support structure.

3.3.6 Support Structure

The support structure is fabricated of two vertical 6 in. channels welded to an H-shaped steel channel base. Four leveling screws with tightening nuts have been provided at the corners of the base plate channels to permit compensating adjustment for floor conditions.

3.3.7 Instrument and Power Leads

All electrical connections to the meter are made through continuous flexible leads adequate to permit full movement of the various subassemblies. The wires are retained in position by curtain rod type traverse mechanisms.

3.4 INSTRUMENTATION AND CONTROL

A conceptual design of the instrumentation and control system is shown on the instrument and control block diagrams, Figs. 4, 5, and 6. The design is based on presently available instrumentations. If more advanced instrumentation, i.e., solid state scalars, are available at the time a vapor volume fraction meter is to be fabricated, the appropriate instrument substitutions and system revisions should be made.

GAMMA COUNT CHANNEL

SEE SHEETS 2 & 3
FOR CONTROL

DETECTOR LINEAR POSITION DRIVE

DETECTOR ANGULAR POSITION

Fig. 4 — Conceptual Design — Instrumentation and Control Block Diagram — Vapor Volume Fraction Meter (Sheet 1 of 3)

Fig. 5 — Conceptual Design — Instrumentation and Control Block Diagram — Vapor Volume Fraction Meter (Sheet 2 of 3)

Fig. 6 — Conceptual Design — Instrumentation and Control Block Diagram — Vapor Volume Fraction Meter (Sheet 3 of 3)

Only that instrumentation needed for control of the meter and for recording the required data is considered as part of the system. The computer required for analysis of the recorded data as well as associated data encoders and tape transports are considered to be part of the facility equipment.

3.4.1 General Operation

With the traverse mechanism at the starting point position and the rotating frame assembly at its home position, the scan sequence is started by actuating a start button. Through a system of relay interlocks, the holding brake is released and the linear drive motor is actuated in the forward direction initiating the first linear traverse. Simultaneously a start count signal is sent to the multichannel analyzer and the electronic timer. The total pulse count at each $\frac{1}{3}$ mm of traverse is stored in a separate channel of the analyzer, switched automatically at preset times by the timer. Coincident with the pulse count, linear position is also being continuously recorded.

At the end of the traverse, a limit position sensor signals the linear drive mechanism to stop and the brake is engaged. Through the same interlock circuitry the angular stepping switch is advanced one position which in turn actuates the rotation of the assembly through 2° by means of the angular position servo system. After the assembly is in its new angular position, as indicated by a zero servo amplifier error signal, the linear traverse mechanism is actuated in the reverse direction. In this manner the test section is continually scanned in forward and reverse directions through the preset number of angular positions. Upon completion of the measurement, the scanning system is automatically stopped and the traverse mechanism and rotating frame assembly are returned to their respective starting points.

3.4.2 Gamma Count Channel

It is the function of the gamma count channel to count the gamma radiation pulses from a calibrated Co^{60} source, where the counting rate is modified by the interposing liquid-vapor mixture in the test section.

The scintillation detector consists of a standard probe of the type used in medical studies, which contains a photomultiplier, NaI crystal, and a focusing collimator. It may be necessary to design and fabricate a special collimator if a standard unit does not have sufficiently good resolution.

A conventional proportional preamplifier and linear amplifier of the nonoverloading type are used to amplify the detector output pulses to a level suitable for the multichannel analyzer input. Pulse height discrimination is included.

The multichannel analyzer is of the conventional type consisting of 400 channels with preset time and automatic readout provisions. In this application the unit is used as a scaler with a preset time mode set to advance channels every 0.1 sec. Each channel is capable of storing 10^6 counts/sec on a ferrite core.

Provision is made to store counts received during switching operations between channels. The stored information is then contained in the advanced channel. At the end of the scan on a preset signal, all 400 channels discharge their information as the total count per channel with proper channel identification to a magnetic tape storage unit. The total elapsed time for this readout is 4 sec.

3.4.3 Linear Position

Linear position is continuously measured by means of a multiturn potentiometer geared to the drive mechanism. The analog output is converted to digital information by means of an encoder and stored on magnetic tape, thereby providing a continuous record of linear position with

respect to time. End point positions both at start and finish of traverses is determined by means of microswitches interlocked to the relay circuitry for control of the scan sequencing operation.

3.4.4 Angular Position

The carriage assembly upon which the source and detector are mounted is positioned at each of the discrete angular points in the scanning sequence by means of a servo system.

An angular position reference signal for the servo is obtained by means of a stepping switch, actuated by microswitches indicating completion of a linear traverse. The stepping switch selects a voltage from a voltage divider, consisting of 180 precision resistors. Connections from the resistors to the switch are made through a program patch cord panel. This enables the scanning sequence to be programmed for any number of angular increments of any preselected size.

The reference signal is compared with a voltage fed back from a multiturn potentiometer, geared to the drive mechanism, to form a servo error signal. The servo amplifier output actuates a servo clutch to permit a shaft speed proportional to the error signal within the range of the amplifier. For error signals above the proportional range, the shaft operates at a constant maximum speed. The reference signal voltage divider and feedback potentiometer are supplied with the same regulated voltage to minimize errors due to voltage variation.

The servo system contains provision for adjustable gain and error rate damping. It may be necessary to use some sort of signal limiter to prevent damage to the servo amplifier if the error signal voltages during reset of the assembly become excessive.

Since the stepping switch is limited to a maximum of 50 points, a switch having four bank levels with 45 points each is used. When the switch reaches the 46th point in the scan sequence, a transfer relay switches to the next bank on the switch. At the end of the fourth bank, transfer is made back to the first bank, and a signal is sent out to advance the linear stepping switch one position.

At the completion of a bank, on operation of the reset button, the switch is returned to the home position by a self-stepping operation. This is accomplished by interrupter contacts on the stepping switch.

In addition to the control signal, a second multiturn potentiometer is used to provide a continuous record of angular position. Similar to the linear position unit, the analog signal is converted to a digital output and stored on the same magnetic tape unit.

3.4.5 Instrument Assembly and Location

With the exception of the detector, preamplifier, and multiturn potentiometers, for position information, all instrumentation and control circuitry will be installed in a remote control room. The equipment will be assembled in several housings containing the multichannel analyzer, the tape storage units, and a console for all operational controls. In addition provision can be made for remote viewing by closed circuit television.

DISTRIBUTION

	No. of Copies
United States Atomic Energy Commission	
Savannah River Operations Office	
N. Stetson	4
New York Operations Office	
J. Wise	2
H. S. Potter	1
Water Reactors Branch, Washington, D. C.	
A. Giambusso	2
Hanford Operations Office	
Paul G. Holsted	1
L. H. McEwen	3
Technical Information Service Extension	3
E. I. du Pont de Nemours and Co.	
Wilmington, Delaware	
D. Babcock	3
Savannah River Plant	
M. W. Wahl	2
Sargent and Lundy, Engineers	
F. W. McCloska	2
Massachusetts Institute of Technology	
T. J. Thompson	1
I. Kaplan	1
Atomic Energy of Canada, Ltd.	
H. G. Hembree, USAEC Scientific Representative	7
Julius H. Rubin, USAEC Liaison Representative	1
Carolinas-Virginia Nuclear Power Associates, Inc.	
E. C. Fiss	1
General Nuclear Engineering Corporation	
H. V. Lichtenberger	1
Columbia University	
J. E. Casterline	1
Westinghouse Electric Corporation	
P. G. De Huff	1