ER-80212

LARGE STORAGE TANK MASS DETERMINATION STUDY

QUARTERLY REPORT

PHASE I

In Support of

Contract No. NAS8-11311

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Huntsville, Alabama

GIANNINI CONTROLS CORPORATION
1600 South Mountain Avenue
Control/Nucleonics Division
Duarte, California

9 April 1965

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WORK COMPLETED DURING THIS QUARTER

The analytical development of a radiation method has been completed. Various types of radiation; i.e., charged particles, neutrons and electro-magnetic radiation of various wavelengths were considered. Various geometrical arrangements were studied. The requirements for a workable system have been established and are documented herein.

WORK TO BE ACCOMPLISHED NEXT QUARTER

The design approach will be reviewed with MSFC contract supervision. Upon their approval detail design and fabrication of the prototype system will commence.

1.0 ANALYTICAL DEVELOPMENT

The work statement under Contract No. NAS8-11311 requires an analytical development of a radiation method of measuring the mass in large propellant containers. "Large" is defined only loosely as "greater than 5 x 50 feet."

In addition to the analytical development Contract NAS8-11311 requires that a workable prototype system be provided. By agreement with the contract supervisor, the required prototype is to be built for evaluation on the S-IVB LH_2 slosh tank at MSFC. The first requirement has been fulfilled and is documented herein.

A preliminary design for the prototype system has been completed and is also presented in this report. Upon approval of the preliminary design by NASA, detail design will be commenced. Approval of the detail design will be secured prior to fabrication.

1.1 Factors Constraining the System Design. The specific requirement is to measure mass using radiation. The interactions of radiation with matter depend upon mass, but also on radiation type, intensity, quantum energy, the geometrical relations between the source(s), detector(s) and mass being measured, the atomic constitution and density of the mass being measured.

In addition to the basic physical laws several practical constraints such as cost, ease of handling, health hazards, loss of sources in case of accident, size, weight, and hardware availability had to be considered. The following paragraphs treat each of these constraints in detail.

1.2 Selection of Type of Radiation

1.2.1 α and β Radiation. The large tank sizes involved and the requirement for direct mass measurement preclude the use of α or β radiation. Thus, only neutrons and electromagnetic radiation are to be considered.

1.2.2 Neutrons. Assume that the neutron source is located in the center of the fuel tank and that the personnel approach no closer than one foot outside the tank. The tank is assumed to be 1 [illegible] feet in diameter. If studies of this case indicate that an unacceptable health hazard exists for the personnel, then the use of neutrons may be neglected because any other source-detector configuration would result in an even greater radiation dose rate.

A typical source is a mixture of Am-241 and Be-9. The Am-241 has a 458 year half-life and decays by the emission of 5.5 Mev alpha particles which interact with the beryllium according to:

$$_4Be^9 + {}_2He^4 \longrightarrow {}_6C^{12} + {}_0n^1 + 5.71 \text{ Mev}$$

Not every alpha particle produces a neutron. In fact, for 5.5 Mev alphas, the neutron yield in the suggested source is about 100 neutrons per 10^6 alphas; i.e., an efficiency of 0.01%. The neutrons so produced will have a continuous energy distribution varying from thermal to approximately 11 Mev. Some 50% of the emitted neutrons will have energies in excess of 3 Mev, while approximately 85% of them will have energies greater than 1 Mev.

Consider the following table of allowed neutron dose rate based on 0.3 rem/40-hour week*.

Neutron Energy	Neutron Flux (n/cm^2/second)
.025 ev	2,000
10 ev	2,000
10 Kev	1,000
0.1 Mev	200
0.5 Mev	80
1 Mev	60
2 Mev	40
3-10 Mev	30

In view of the expected neutron energy spectrum and the above table, the radiation health hazard will be calculated by assuming that all of the neutrons have an energy of 2 Mev and that the allowable flux (for 2.5 mrem/hour) is 13 n/cm^2/second at one foot outside fuel tank walls. The radiation dose due to 60 Kev gamma rays from the Am-241 will be negligible if the tank walls are $\gtrsim$ 0.4 inch stainless steel. This will be assumed to be the case.

In the following calculations, the source strength will be selected so that the neutron dose rate at the point of nearest approach to the tank (10 feet from source) is never greater than 13 1-Mev neutrons/cm^2/second, or their equivalent. To calculate the required detector area, an average source-detector distance of 13 feet will be selected to take into account the probability that the detectors will have to be scattered over the entire tank surface in order to obtain the necessary accuracy under different

* Price, Horton, Spinney, Radiation Shielding, p. 10, (McMillan, New York, 1957)

operating conditions. To obtain the detector area, it is first necessary to calculate the counting rate required for the desired fuel accuracy of 0.25%.

It is required that the number of counts N during the response time T be such that the change in count rate due to a 0.25% change in the full tank fuel mass (M) will be as great as the standard deviation (σ) of the counting rate. For example, consider the case of an empty tank where there is a neutron flux ϕ at the position of the "average" detector. Assume a response time of T = 2.5 seconds. The total number of counts during one response period will then be $N_c = \phi \times A \times E \times T$ where A is the detector area and E is its neutron detection efficiency. Then it is required that $\Delta N_c = \sigma = \sqrt{N_c}$ where ΔN_c is the change in N_c resulting from an increase in fuel mass of .0025M.

For simplicity, assume that the decrease in counting rate is directly proportional to the increase in fuel mass, and furthermore that the addition of the last drop of fuel to fill the tank causes the counting rate to become zero. (This is an extremely optimistic assumption, but will serve for these simple calculations.) Then, when the tank is empty, the required value of N_c will be $N_c = \frac{\sqrt{N_c}}{.0025}$; i.e., $N_c = 1.6 \times 10^5$ counts/second. As the tank fills, the counting rate N_c will decline (and so will $\sigma = \sqrt{N_c}$), but $\Delta N_c / \Delta M$ will remain constant, so that the accuracy condition $\Delta N = \sigma$ will always be maintained or exceeded for quarter percent fuel changes.

In order to obtain $N_c = 1.6 \times 10^5$ counts/second at the average detector position when the tank is empty, while allowing a neutron flux of only 13/cm^2/second at 10 feet from the source, the product A x E will have to be $\frac{1.6 \times 10^5}{13} \times (\frac{10}{1})^2 = 2.1 \times 10^4$ cm^2 = 2.1 m^2. However, since the efficiency E is less than 10% for fast neutrons when using any detector of an acceptable size, the detector area required will be approximately 21 m^2. Obviously, such a system size is unacceptable. In fact, a detector area of 0.2 m^2 would seem to be the maximum compatible with obtaining a significant weight reduction over present systems.

In addition to the health hazard problem with neutrons, source costs would be quite high. Assume that a detection system which gives the desired accuracy within tolerable dose rate limits could be devised. Then, to obtain the required 13 $cm^{-2}sec^{-1}$ at 10 feet, the source strength must be:

$$I_o = 13 \times 4\pi \times (10 \times 30.5)^2$$

$$= 1.5 \times 10^7 \ \eta \ sec^{-1}$$

This in turn would require 1.5×10^{11} α particles per second. This corresponds to about 4 curies of Am-241. The cost of the Americium alone would be about $8,000.

1.2.3 Electromagnetic Radiation. The previous paragraphs lead to the conclusion that the desired system can best be synthesized using electromagnetic radiation. If this conclusion is accepted, the problem becomes one of selecting the proper wavelength or quantum energy. This problem is best approached analytically,

from a general consideration of the interactions of electromagnetic energy with matter.

Description of Uncollided Flux - As a beam of electromagnetic radiation traverses matter, a variety of interactions may occur. A detailed description of these interactions and their relative probabilities is given in Appendix 1. For the purpose at hand the nature of the processes are not of great concern, since the effects of the interaction on a radiation detector are all the same; i.e., interaction of the radiation beam with the matter between the source and detector is observed as removal of energy from the beam incident on the detector, regardless of the physical nature of the individual photon interactions.

The above remarks are illustrated by Figure 1. Individual photons may be either scattered from the beam or completely absorbed. In either case they do not reach the detector. The situation is somewhat complicated by the fact that a photon scattered from the beam may be scattered again back into the beam. Such a photon will have lost considerable energy as a result of the scattering, and consequently will produce a smaller pulse in the detector output than will a photon which has reached the detector with no collision of any type. Thus, multiply scattered photons may be rejected from the detector output by pulse height discrimination. The photons which traverse the entire path between source and detector without interaction are referred to as the uncollided flux.

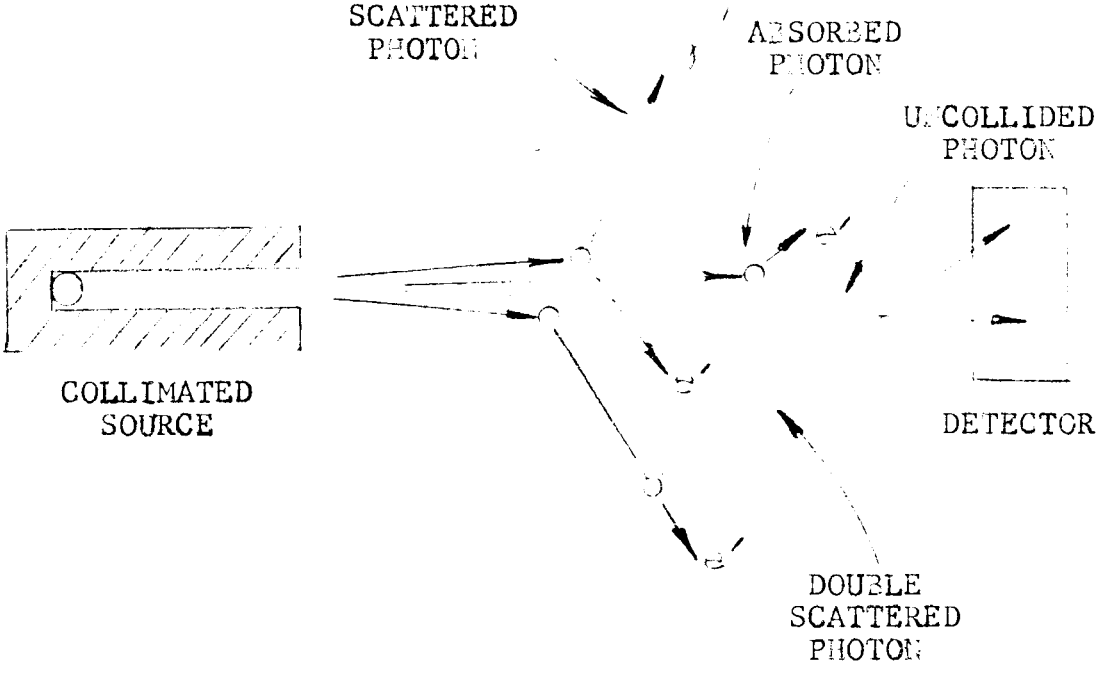
SCATTERED
PHOTON
ABSORBED
PHOTON
UNCOLLIDED
PHOTON
COLLIMATED
SOURCE
DETECTOR
DOUBLE
SCATTERED
PHOTON

FIGURE 1

Significance of Uncollided Flux - In the quantum energy range of interest in this discussion all interactions between photons and matter involve only the electrons of the matter. The interactions are all of a statistical nature, and it is convenient to describe the processes in terms of the probability that a photon will, in traversing a given amount of matter, undergo a given interaction. This probability can be expressed as a cross-section per electron. The cross-section has dimensions of cm^2 per electron. Let φ denote the number of photons per square centimeter per second in the radiation beam. φ is called the flux. Let the cross-section for scattering be denoted by σ_s. Then, if the flux φ traverses a region containing n_e electrons, then Δn, the expected number of scattering events per second is:

$$\Delta n = n_e \varphi \sigma_s \qquad (1)$$

Similar relation holds for absorption. The total cross-section for all events is the sum of the cross-sections for the individual events since the probabilities are independent. Letting $\sigma = \sigma_a + \sigma_s$, the number of photons in the beam at any point follows the law:

$$dn = -\sigma \varphi n_e \qquad (2)$$

Equation (2) leads to the familiar exponential law of absorption. In Figure 2, the relation between radiation absorption and mass is depicted. The source S emits I_o photons per second. If there is no matter between the source and detector the flux at the detector would be:

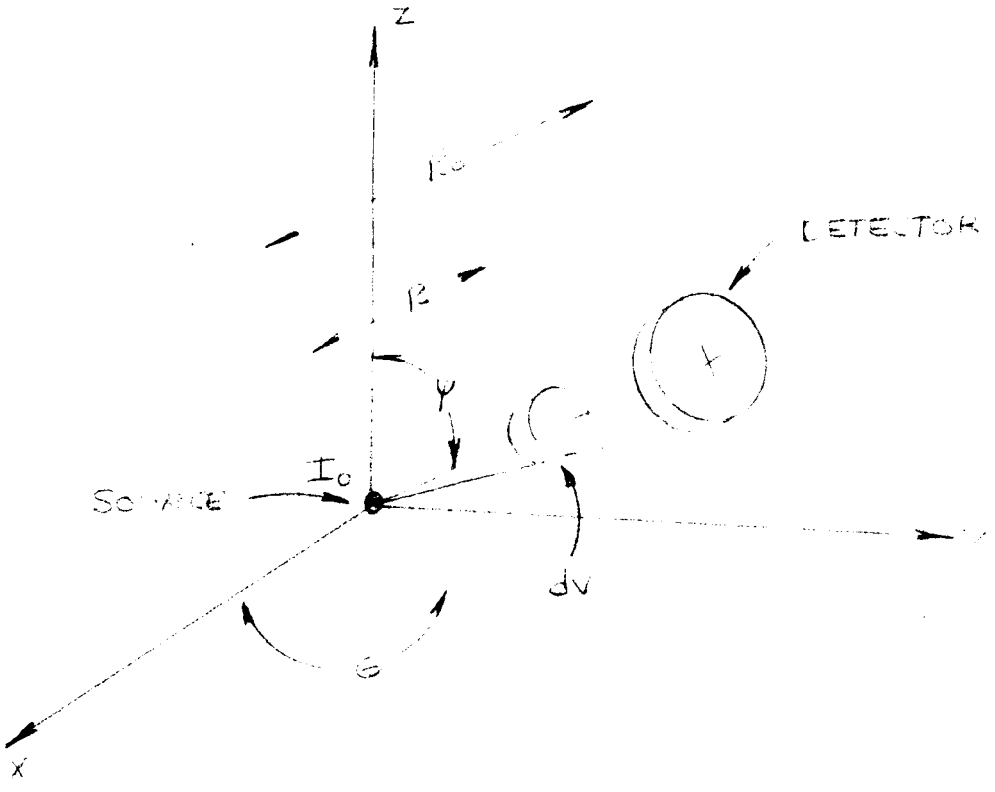

FIGURE 2

$$\varphi_o = \frac{I_o}{4\pi R_o^2} \tag{3}$$

The number of photons per second N_o reaching the detector is:

$$N_o = \frac{I_o A_D}{4\pi R_o^2}$$

If the space between the source and detector is filled with matter of atomic number Z, density ρ, and atomic weight A, then the number of electrons present in the small element of volume dv is:

$$n_e = \frac{NZ}{A} \rho \, dv \tag{4}$$

where N is Avogardro's number.

The variation of the number of photons per second from the beam by the matter in dv is given by:

$$dn = -\left(\sigma \frac{NZ}{A}\right) \rho \varphi \, dv \tag{5}$$

The quantity in parenthesis is of interest. The dimensions of σ are cm^2 $(electron)^{-1}$. Those of N, Z, and A are respectively atoms per mole, electrons per atom, and grams per mole. The quantity $\left(\sigma \frac{NZ}{A}\right)$ may then be replaced by μ and the dimensions of μ will be cm^2 per gram. If the cross-sectional area of this element of volume dv is dA, then dv = dAdR. Further $\varphi = \frac{n}{dA}$, where n is the number of photons per second entering dv. Using these facts and replacing $\sigma \frac{NZ}{A}$ by μ equation (5) becomes:

$$\frac{dn}{n} = -\mu \rho \, dR \tag{6}$$

Integration of equation (6) gives the exponential law:

$$n = n_o e^{-u \int_o^{R_o} \rho \, dR} \qquad (7)$$

Note that n_o is the number of photons which would reach the detector in unit time if the space between the source and detector is empty. Let f_o be the detector output frequency with no mass between the source and detector, and let f denote the number of uncollided photons per second counted by the detector. Then:

$$\frac{1}{\mu} \log \frac{f_o}{f} = \int_o^{R_o} \rho \, dR \qquad (8)$$

μ is a constant for a given material and radiation wavelength. Therefore, measurement of the indicated frequency ratio gives the mass per unit area along the path between the source and detector. In the remaining discussion, equation (8) forms the basis for finding an acceptable system configuration.

1.3 Geometrical Considerations. The requirement is to measure mass directly. Furthermore, it is very strongly desired that the methods developed be capable of extension to low gravity environments. Even in the gravity case, the liquid will be subject to density variation, sloshing and boiling. Therefore, the system operation must be made as independent as possible of the mass distribution within the tank. In this section, it is shown that this requirement can be met by using the uncollided flux in a rectangular coordinate system. While it is not specifically proved

that no other method is possible, the number of alternatives considered is sufficient to make one feel strongly that such is the case for tanks whose dimensions preclude the possibility of "linear" rather than exponential absorption.

1.3.1 Necessity of Using Uncollided Flux. The flux available for detection includes the uncollided flux and the scattered flux. The exponential law discussed in section 1.2 applies strictly to the uncollided flux. The attenuation given by equation (7) will always be larger than the observed attenuation if the multiply scattered flux is included in the detector count rate. Except under very special conditions*, admitting the scattered flux makes the system dependent on the mass distribution. This is illustrated in Figure 3. When only the uncollided flux is counted the attenuation is a measure of the mass per unit area along the straight path between the source and detector. In all cases of Figure 3 the fuel mass is the same. The amount of flux scattered out of the beam is the same in cases (a) and (b). The detector count rate will be appreciably higher in case (a), however, since the probability of the scattered flux being scattered again into the detector is higher.

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* For small tanks; i.e., those less than about 2 photon mean free paths (40 cm of water for Co-60) one can find a mixture of scattered and uncollided flux which shows a photon count attenuation that is approximately linear with absorber mass. If one then provides uniform gamma ray flux throughout the tank the mass of the tank contents is measured. The measurement is independent of position of the mass inside. This cannot be done in large tanks.

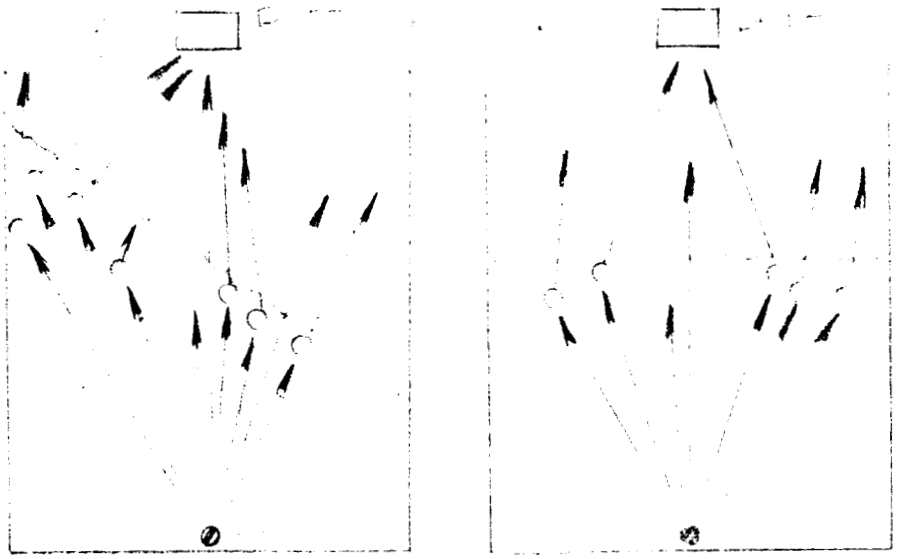
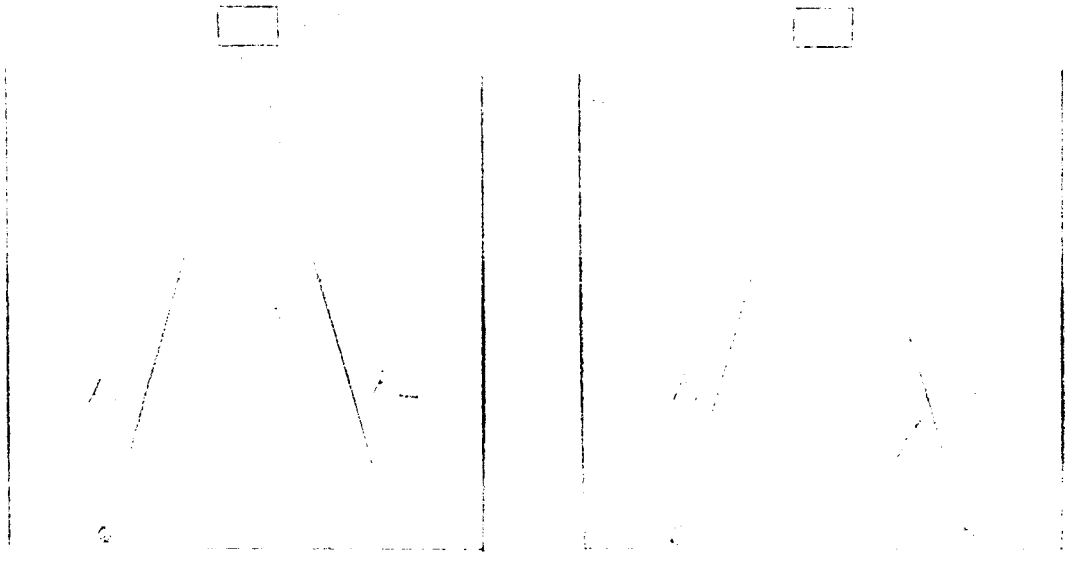


FIGURE 3

In the case of a gamma ray system a very large practical advantage is obtained by using the uncollided flux. First of all some of the uncollided photons which strike the detector will not be fully absorbed. They will scatter and hence leave only a portion of their energy. To be sure that only uncollided photons are counted one must look at only the full absorption peak. The maximum energy that a scattered Cs-137 photon can leave in the detector is about 460 Kev. A fully absorbed photon leaves 660 Kev. In other words one can set the pulse height discriminator so that only pulses representing energies between 560 Kev and 760 Kev are counted. Under these conditions a detector gain change of about ±5% can be tolerated without appreciable change in the counting of the full absorption peak. This removes the need for highly sophisticated gain controls on the detector. In addition, all noise pulses except those in the relatively narrow 200 Kev band are eliminated.

1.3.2 Necessity of Collimating The Source. It will be shown subsequently that to measure the mass in a large volume several sources must be used. In this section it is shown that if one detector can see more than one source, then the system becomes sensitive to fuel movements.

In Figure 4, this effect is illustrated. In Figure 4(a), assuming that both sources are equidistant from the detector and of equal strength, the detector count rate in Figure 4(a) is:



(a)

$$f = f_o(e^{-\mu\rho R_1} + e^{-\mu\rho R_2}) \tag{9}$$

If R_1 and R_2 are changed:

$$\Delta f = -f_o\mu\rho(e^{-\mu\rho R_1}\,\Delta R_1 - e^{-\mu\rho R_2}\,\Delta R_2) \tag{10}$$

From the figure, if $R_1 \cong R_2 \cong R$. Also:

$$(\Delta R_2 - \Delta R_1) > 0 \tag{11}$$

Therefore:

$$\Delta f = \mu\rho f_o e^{-\mu\rho R}\ (\Delta R_2 - \Delta R_1) \tag{12}$$

Equation (12) shows that the detector output can change without a change in mass. This error can become quite large if large displacements of the fuel occur.

1.3.3 Necessity for Rectangular Array of Sources and Detectors. In section 1.2 it was shown that the mass per unit area along a known path (i.e., the path between a specific collimated source and detector) is measured by the uncollided flux along the path. It has also been shown that the knowledge of the path is lost unless the sources are collimated and the scattered flux is eliminated. The problem now arises of finding a geometry which converts mass per unit area to mass in a manner which does not depend on the spatial distribution of the mass.

Mathematically, the mass in a closed region is given by:

$$m = \iiint_V \rho dv \tag{13}$$

This integral may be set up in various ways depending upon the system of coordinates used. For example in polar coordinates:

$$m = \int_0^{2\pi} \int_0^{\pi} \int_0^{R(\varphi,\theta)} \rho R^2 \sin\theta \, d\theta \, d\varphi \, dR \tag{14}$$

In cylindrical coordinates:

$$m = \int_0^{2\pi} \int_0^{Rm} \int_0^{z(R,\theta)} \rho R \, d\theta \, dR \, dz \tag{15}$$

In rectangular coordinates:

$$m = \int_0^{Xo} \int_0^{Yo} \int_0^{Z(x,y)} \rho \, dz \, dy \, dx \tag{16}$$

Now recall the quantity which is measured by radiation absorption. Equation (8) is repeated here for convenience:

$$\frac{1}{\mu} \log \frac{f_o}{f} = \int_0^{R_o} \rho \, dR = \int_0^{Z} \rho \, dz \tag{8}$$

Note that equation (16) can be written:

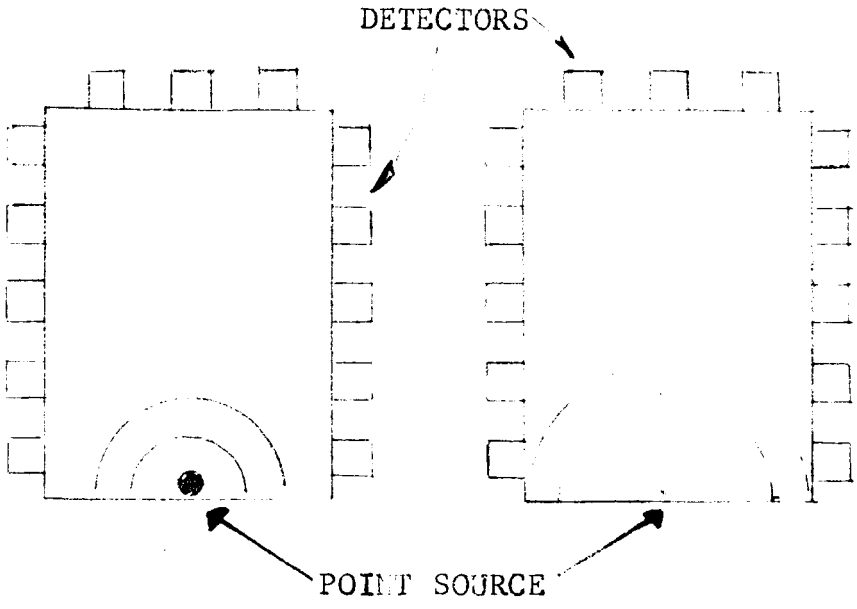
$$m = \int_0^{X_o} \int_0^{Y_o} \left[\int_0^{Z(x,y)} \rho dz \right] dy\, dx \qquad (17)$$

When this is evaluated over a region of area A:

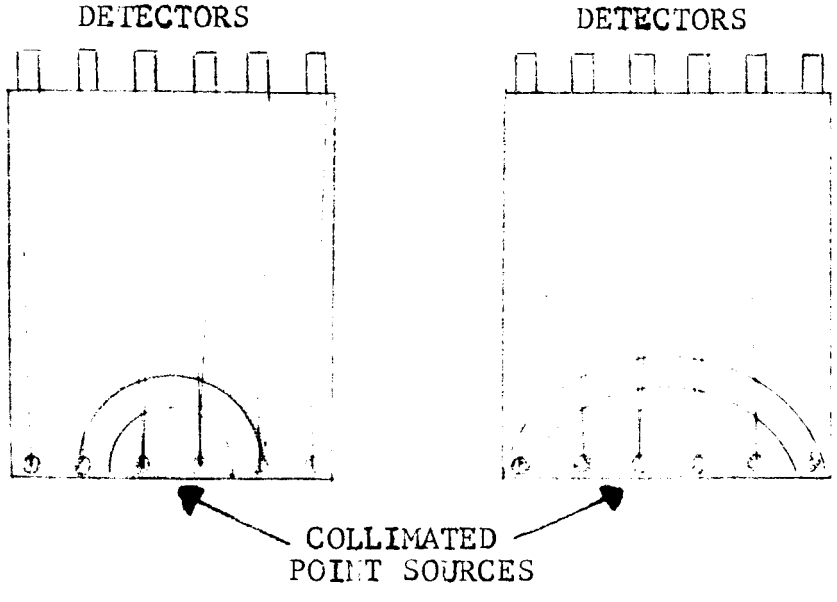
$$m = A \int_0^{Z(x,y)} \rho dz \qquad (18)$$

Equations (14) and (15) can be evaluated in terms of the measurement provided by equation (8) only if ρ and R can be determined separately. This cannot be done from a measurement of radiation attenuation alone. For example, a 10 foot column of density 1 would give the same answer as a one foot column of density 10. The possibility of evaluating the mass integral from the absorption measurement alone then can best be accomplished in rectangular coordinates.

The above considerations are entirely mathematical. Physically, the meaning of the remarks made can be seen from Figure 5. Polar coordinates correspond to a point such as shown in Figure 5(a). A rectangular system corresponds to the situation depicted in Figure 5(b). In Figure 5(a) two distributions are shown. Both distributions have the same mass, but different detector readings. In one case, the mass corresponding to a given mass per unit area is much greater than in the other.


DETECTORS
POINT SOURCE

(a)


DETECTORS
DETECTORS
COLLIMATED
POINT SOURCES

(b)

FIGURE 5

The same situation is depicted in Figure 5(b) for a rectangular system. In this case, the total detector output is not changed. It will be seen that for a given mass, the area covered by the mass is inversely proportional to the average distance traveled by photons going through the mass in the indicated direction. In other words, the mass per unit area is constant for a given mass regardless of how the mass is distributed. This point is made clearer by considering a constant density case. This then is just one average height for a given mass above the fixed area.

1.4 Summary of Geometry Problems. A line source corresponds to cylindrical coordinates, and also will not work. One may find various source arrangements corresponding to other mathematical coordinate systems. Only those corresponding to parallel transmission seem to provide the desired result. A large number of possibilities have been considered in this work, and only two others seem to warrant mention and then only to explain why they will not work.

One is the tracer technique. This is highly dependent on the mass distribution, and would probably have large uncertainties owing to the difficulty of getting uniform tracer diffusion.

The other is backscatter of radiation. This is also dependent on mass distribution, and for a given source strength will work to only about 1/4 of the depth of the transmission method.

1.5 Error Analysis. So far, it has been shown that a rectangular array of point sources and detectors will measure mass in terms of the uncollided flux along each source-detector path. This gives enough of a basis to perform a general error analysis. The information provided by the error analysis will supply a basis for determining the other requirements that the radiation source and detectors must meet. It should be noted that to this point everything said is true for any source wavelength detector, detector area, source strength, and other system parameters will have to utilize the results of the error analysis as well as cost, development time, safety and other comparisons.

1.5.1 Error Equation. The fundamental equation of the system is equation (8):

$$\frac{1}{\mu} \log \frac{f_{oi}}{\bar{f}_i} = \int_0^{h_i} \mu dz_i = \bar{\mu}_i h_i \qquad (19)$$

where h_i is the length of the particular path along which the measurement is made. Table I is a list of the symbols used in the error analysis. There are two sources of error. One is electronic, the other is statistical because of the random nature of photon emission and absorption. The electronic error will consist of a curve fit error and a counting error. Since the required count rates will be moderate, there will be little or no count loss error.

TABLE I

			Units
f_{oi}	=	frequency of i^{th} detector when no mass is between i^{th} source and detector.	sec^{-1}
f_i	=	observed output frequency of i^{th} detector	sec^{-1}
$\bar{f}_i$	=	average value of f_i	sec^{-1}
μ	=	mass absorption coefficient of fuel	$cm^2 gm^{-1}$
ρ	=	fuel density	$gm\ cm^{-3}$
$\bar{\rho}_i$	=	average density between i^{th} source & detector	$gm\ cm^{-3}$
h_i	=	fixed distance between i^{th} source & detector	cm
$(\epsilon_c)_i$	=	relative curve fit error of i^{th} detector	
ϵ_{f_i}	=	relative standard deviation of f_i	
$(\epsilon_s)_i$	=	statistical error of i^{th} detector	
ϵ_i	=	$(\epsilon_c)_i + (\epsilon_s)_i$	
ϵ_s	=	total statistical error $= \sqrt{\sum_{i=1}^{n} (\epsilon_s)_i^2}$	

The major electronic error then is in the curve fit. Suppose that $g(\frac{f_o}{f_{io}})$ is the operation actually performed by the electronics. Then the relative curve fit error is:

$$(\epsilon_c)_i = \frac{\log \frac{f_{oi}}{f_i} - g\left(\frac{f_{oi}}{f_i}\right)}{\log \frac{f_{oi}}{f_i}} \tag{20}$$

f_{oi} may be considered constant, since even though it is a random frequency, it can be determined to any accuracy desired during calibration. Let $\bar{f}_i$ denote the average value of f_i. Then the relative standard deviation of f_i is:

$$\sigma_{f_i} = \frac{1}{\sqrt{\bar{f}_i \Delta t}} \tag{21}$$

where Δt is the time interval over which f_i is measured. Equation (21) is obtained from the fact that f_i follows a Poisson distribution. The "true" mass per unit area along the path z_i is given by:

$$\frac{1}{\mu} \log \frac{f_{oi}}{\bar{f}_i} = \bar{\rho}_i h_i \tag{22}$$

The system indication is given by:

$$\frac{1}{\mu} g\left(\frac{f_{oi}}{f_i}\right) = \left(\bar{\rho}_i h_i\right)' \tag{23}$$

The system error is the difference between equations (22) and (23):

$$\bar{\rho}_i h_i - (\bar{\rho}_i h_i) = \frac{1}{\mu}\left[\log \frac{f_{oi}}{\bar{f}_i} - g\left(\frac{f_{oi}}{f_i}\right)\right] \tag{24}$$

Solving equation (20) for $g\left(\frac{f_o}{f_i}\right)$ and substituting this in equation (24) gives:

$$\bar{\rho}_i h_i - (\bar{\rho}_i h_i) = \frac{1}{\mu}\left[\log \frac{f_{oi}}{\bar{f}_i} - \left[1 - (\epsilon_c)_i\right] \log \frac{f_{oi}}{f_i}\right] \tag{25}$$

The relative error is:

$$\epsilon_i = 1 - \frac{\left[1 - (\epsilon_c)_i\right] \log \frac{f_{oi}}{f_i}}{\log \frac{f_{oi}}{\bar{f}_i}} \tag{26}$$

It is convenient to express equation (26) in terms of the system sampling time Δt and the tank empty detector frequency f_{oi}, for from these parameters, the necessary source strength detector area, and optimum source quantum energy can be found. It should be noticed that the maximum error occurs when the tank is full. At half-full the statistical error is about 1/5 of that at full tank. At tank full:

$$\bar{f}_i = \frac{1}{k} f_{oi}$$

where $k = e^{\mu \bar{\rho}_i h_i}$. In addition let $f_{oi}\,\Delta t = a$. Then for a one sigma deviation of f_i, the maximum error would be:

$$\epsilon_i = (\epsilon_c)_i + \frac{\left[1 - (\epsilon_c)_i\right] \log\left(1 + \sqrt{\frac{k}{a}}\right)}{\log k} \tag{27}$$

Since $(\epsilon_c)_i$ must be small compared to 1 if high accuracy is to be had we may use the simpler expression:

$$\epsilon_i = (\epsilon_c)_i + \frac{\log\left(1 + \sqrt{\frac{k}{a}}\right)}{\log k} \qquad (28)$$

without serious error.

Equation (28) shows the following important facts.

(1) The curve fit error and statistical error are independent and additive.

(2) The maximum statistical error depends on the maximum attenuation, the tank empty frequency, and the sampling time.

The statistical error given by the second term of equation (28) is controlled by the following factors:

(1) Number of detectors

(2) Source strength

(3) Detector area

(4) Detector efficiency

(5) Source quantum energy

(6) System time response

(7) Fuel density and atomic number

(8) Tank dimensions

The ranges over which these parameters can be suitably adjusted will be shown in the next section.

The curve fit error can be reduced to any required value depending upon how sophisticated the computer is made.

It can be anticipated that a computer consistent with the 0.25% accuracy which has been assumed as a design goal would cost in the neighborhood of $25,000 per unit after development costs. This is entirely too expensive for the prototype hardware to be delivered under the present contract. Therefore, in the prototype system it is recommended that the sensor outputs be tape recorded and the curve fitting accomplished on a ground station computer. Thus, the prototype system costs are greatly reduced.

2.0 SYSTEM DESIGN CONSIDERATIONS

Up to this point it has been shown that:

(1) Total radiation attenuation is a measure of mass per unit area.

(2) Mass per unit area is a true measure of mass in a rectangular array.

(3) The accuracy attainable with a radiation system can be analytically predicted.

The remarks up to this point have been general and apply to any radiation wavelength, tank size or propellant. In this section the constraints imposed by these and other practical considerations are discussed.

2.1 Use of Equation (28). If the statistical error is denoted by ϵ_σ, equation (28) can be put in the form:

$$\frac{k}{a} = (k^{\epsilon_\sigma} - 1)^2 \qquad (29)$$

Equation (29) is plotted in Figure 6. For each curve ϵ_σ is constant and k/a and k are the abscissas and ordinates respectively. Thus, if a given error ϵ_σ is specified one first determines the value of k from the relation:

$$k = e^{\mu \rho_i (h_i)_{max}} \qquad (30)$$

μ is a constant which depends on the source wavelength and atomic number. Values of μ for x and gamma rays of various wavelengths are given for several materials in Figure 7. Assuming that the

maximum value of ρ is known for the propellant of interest, $(h_i)_{max}$ is determined by the tank depth.

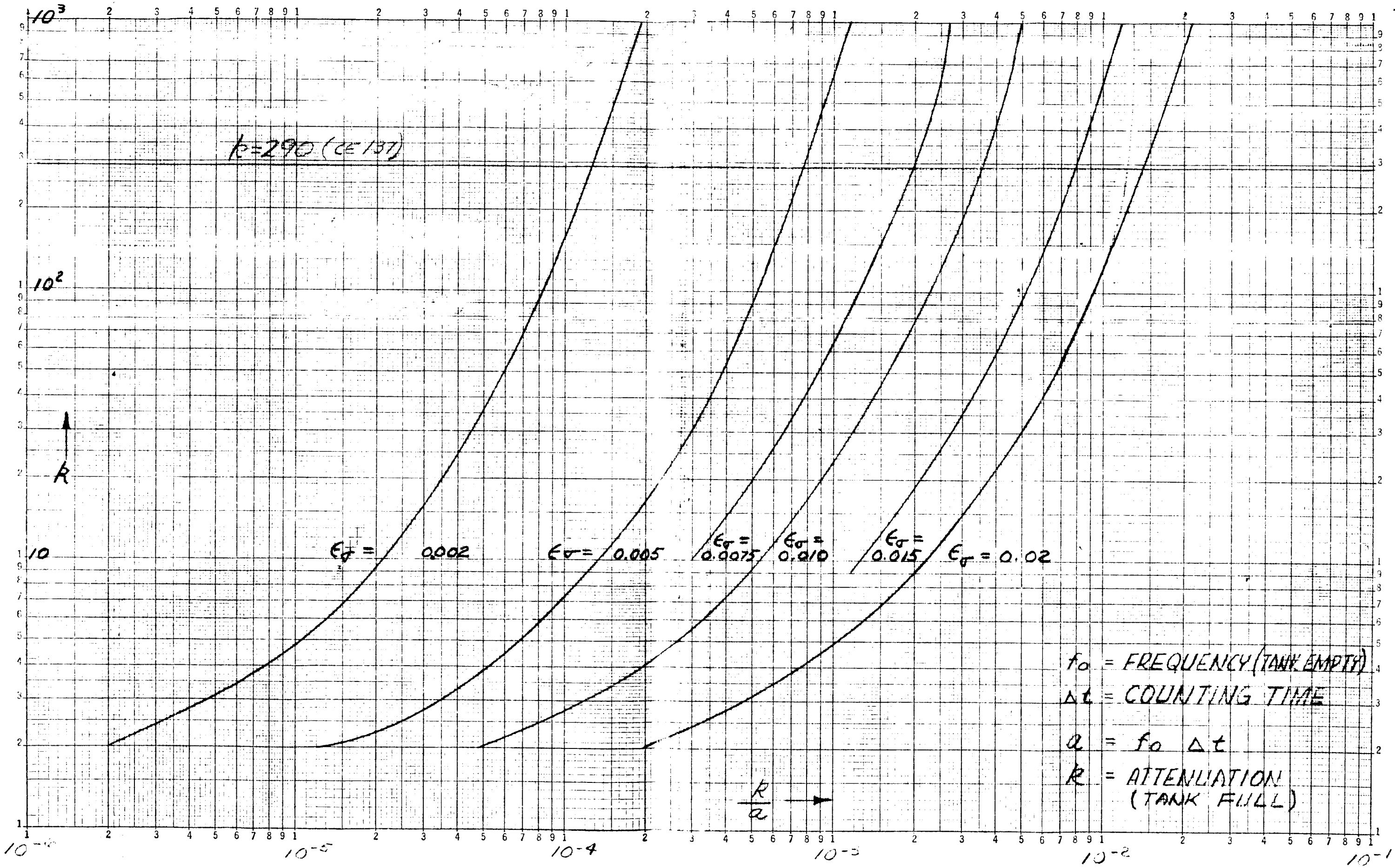
Having found k, one may find from Figure 6 the value of $\frac{k}{a}$ required to give the desired statistical accuracy. Since now k and $\frac{k}{a}$ are known, a is known. If one then specifies the permissible sampling time, the tank empty frequency f_o is determined. From f_o, the required source strength and effective detector area can be found. In addition, if n detectors are to be used, the overall statistical error will be $\frac{1}{\sqrt{n}}$ times the statistical error of one detector. Thus, if the overall statistical error (tank full) is to be 0.25% and 16 detectors are to be used, then it is permissible to use the value $\epsilon_1 = 0.01$ in finding f_o from Figure 6.

2.2 Selection of Source Wavelength

2.2.1 Comparison of Optical and Gamma Ray Spectra. A considerable amount of attention was given to selection of the appropriate wavelength. Visible, x-ray, and gamma ray wavelengths are considered. The problem of utilizing the visible spectrum was studied by Dr. N. L. Moise of The California Institute of Technology. His report is given in Appendix 2. To briefly summarize the results, it was concluded that:

(1) On purely physical grounds the use of optical frequencies is feasible.

(2) A complete investigation of the application of optical methods was not possible within the budgetary limits of the present contract since a great deal of hardware development would be required. For example, all sources and detectors would have to



CURVES OF CONSTANT STATISTICAL ERROR

FIGURE 6

be inside the tank and would have to operate from room temperature (for calibration) to liquid hydrogen temperature. This alone seemed a formidable enough problem. In addition the scattering of light is through the classical scattering mechanism discussed in Appendix 1. This scattering occurs without loss of photon energy. It would therefore be necessary to use polarization effects to separate the scattered light from the direct transmission. Finally, all the known absorption bands are too strong, so that one would have to produce a very narrow spectrum on the tail of an absorption band to obtain suitable values of k.

All these problems will require a considerable experimental development program. On the other hand it is distinctly possible that one may be able to measure mass at much greater depths with optical frequencies, than with gamma rays. Thus, further study of optical methods may be warranted.

The tremendous advantage of the gamma ray wavelength is that the tank wall can be penetrated permitting the detectors to be installed outside. In addition, gamma ray sources are virtually fool proof and simple reliable detectors are available. The disadvantage of gamma methods is the limitation of depth (which is severe with any system) and this can be removed if the equipment is put inside the tank.

In summary, it appears that for a given tank size, the gamma ray method compares favorably with most other techniques, and is definitely superior for the range of tank sizes to be established in a subsequent section.

2.2.2 Source Quantum Energy. Examination of equation (28), Figure 6 and Figure 7 reveals the following:

(1) The minimum value of $\frac{k}{a}$ occurs for a k value of about 7. Thus, for a given accuracy this value of k will require the lowest source strength.

(2) $\frac{k}{a}$ rises slowly with k above this value. $\frac{k}{a}$ remains within reasonable bounds until k is about 10^3 and the allowable ϵ_σ is less than 0.01.

(3) The value of μ (and hence k for a given situation) decreases rapidly with increasing photon energy up to about 10 Mev.

In finding the optimum source, the following factors must also be considered.

(1) Detector efficiency decreases with increasing photon energy. This offsets the advantages of reduced k.

(2) Weight required for collimating increases with photon energy.

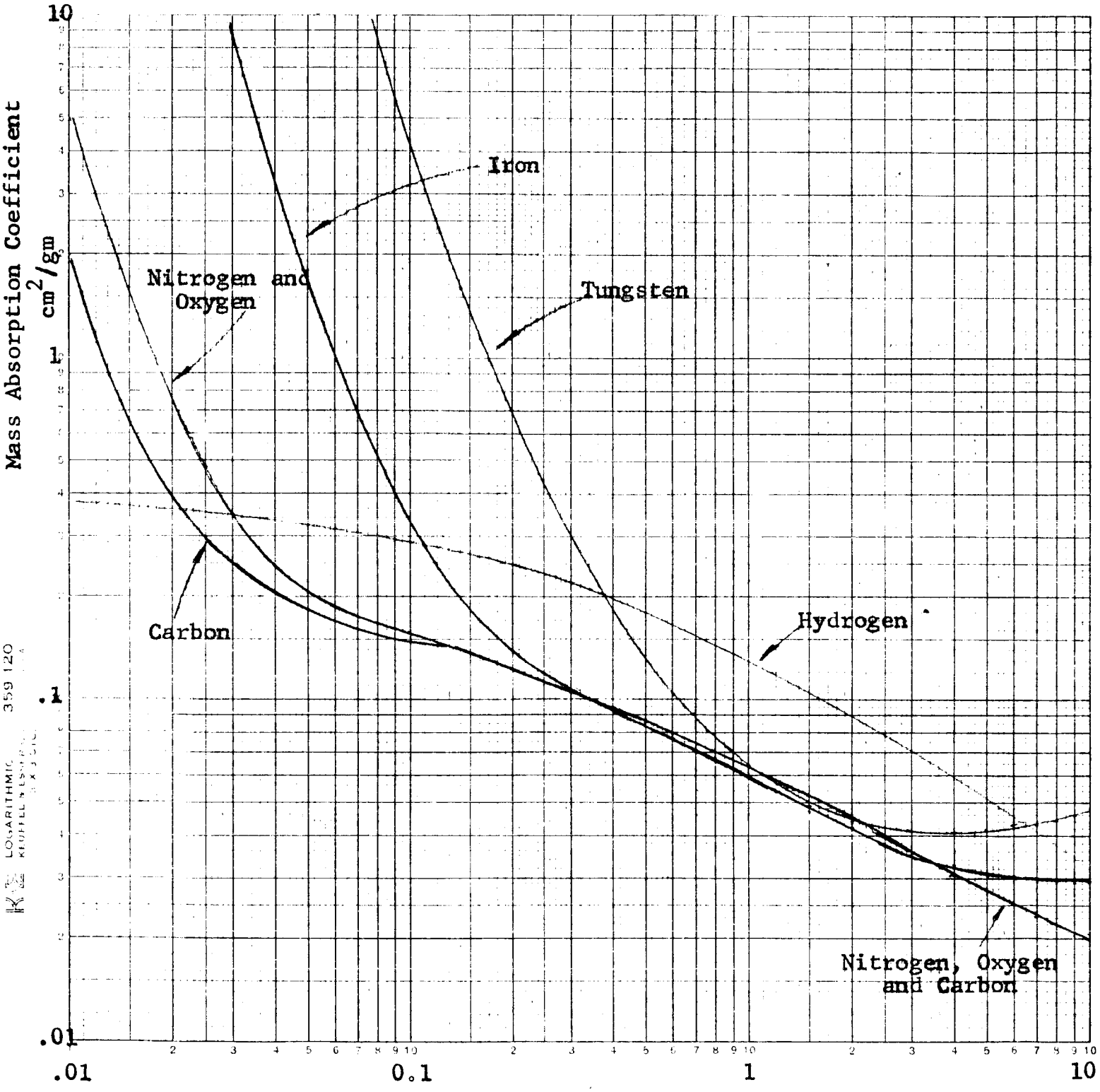
(3) The dose rate per photon increases with photon energy.

(4) The source should be monochromatic to retain the simple logarithmic curve fit.

(5) The source should be cheap.

(6) The source must have a reasonably long half-life.

A consideration of all these factors has led to the conclusion that Cs-137 is the best available isotope source. Its use in the prototype system is recommended. Cs-137 emits a



Mass Gamma Ray Total Absorption Coefficients

FIGURE 7

single gamma ray line at 662 Kev, is readily available at a cost of only about $2 per curie.

2.2.3 Detector Selection. As shown, only the fully absorbed uncollided photons are to be counted. By far the greatest number of fully absorbed particles are those which are photo-electrically absorbed. At the Cs-137 gamma line the available scintillation detectors having good photo-electric cross-sections at this energy are sodium iodide, cesium iodide and calcium tungstimate. Sodium iodide, and cesium iodide which are roughly comparable on a cost versus efficiency basis, and sodium iodide is somewhat faster and has better light output. Calcium tungstimate is available only in small crystals. Germanium solid-state detectors are fair, but at the present time are more expensive and must be cooled. In all cases, the detector prices rise sharply as the size is increased beyond certain limits. At the present time, a 2 inch diameter by 2 inch long sodium iodide detector seems to be the best choice. This detector has about 17% photo-electric efficiency at the Cs-137 gamma line.

2.2.4 Effect of Tank Size and Propellant. The mass absorption coefficient, μ, for hydrogen at the Cs-137 gamma line is 0.165 $cm^2 gm^{-1}$ (see Figure 7). For nitrogen and oxygen, μ is about 0.072 $cm^2 gm^{-1}$. The density of liquid hydrogen is about 0.07 gm cm^{-3}, liquid oxygen is about 1.140 gm cm^{-3}, and liquid nitrogen is about 0.81 gm cm^{-3}. Assume that the maximum external gamma dose rate shall not exceed 10 mr/hr. It is also assumed that a 15-second

counting period is tolerable (this is equivalent to a 7.5 second system R-C time constant as shown in Appendix B). The requirement for an external dose rate at the tank surface of 10 mr/hr implies that the maximum flux at the tank wall does not exceed 7200 photons $cm^{-2}sec^{-1}$ when the tank is empty. This will correspond to an f_o of 24.5 KC with the detector described in the previous section. This is equivalent to an a of 3.68×10^5. The maximum practical value of k is limited by background noise consideration. In the Cs-137 window the background count for the 2 x 2 detector will be about 2 or 3 sec^{-1}. The standard deviation of this background rate is 5 or 6 counts in the 15-second sample. The tank full standard deviation should exceed this by at least a factor of 5, thus the tank full count rate must not be less than about 60 sec^{-1}. Thus, k should not exceed about 400. For this value of k, $\frac{\sigma}{I}$ is 1.10×10^{-3}. Referring to Figure 6 this corresponds to an accuracy (per detector) of about 0.6%. If 25 detectors are used this would give a statistical accuracy of 0.12% tank full. The statistical error would become negligible as the tank empties.

The limitation of 400 times on k is somewhat arbitrary but shows that for liquid hydrogen with μ = 0.155 and σ = 0.07, the maximum depth is around 550 cm or 18 feet. For liquid oxygen the maximum depth would be about 84 cm (2.7 feet) and for nitrogen about 105 cm (3.4 feet). Tanks of these sizes and smaller can be handled with one set of sources and detectors. For larger tanks, the problem can still be solved but one must divide the tank into sections and use additional detectors.

Each application would have to be considered separately, since obviously many possible arrangements exist. For example, if the sources and detectors are arranged as in Figure 8(a), a liquid hydrogen tank 36' long would fall within the limits established above. The number of detectors is doubled, and in many configurations some of the detectors would have to be inside. Under zero gravity conditions, it is immaterial whether the measurement is made along the tank axis or across. Hence, the arrangement of Figure 8(b) could be used. This allows external location of all detectors and will work on liquid hydrogen tanks up to 36 foot diameter of any length. The number of detectors required is quite large, but this will not be too serious a limitation with solid-state detectors. Figure 8(c) depicts a third possible arrangement which might be used with very dense propellants in large containers. As many iterations as required can be used.

2.3 Radiation Safety Considerations. For the larger tank sizes which may come under consideration, the total source strength required becomes rather large. This is of no consequence under normal conditions since:

(1) The system has been designed with external dose rate as the limiting factor.

(2) The sources can be removed and installed by remote control if the total activity is high enough to warrant this.

(3) The source material is cheap.

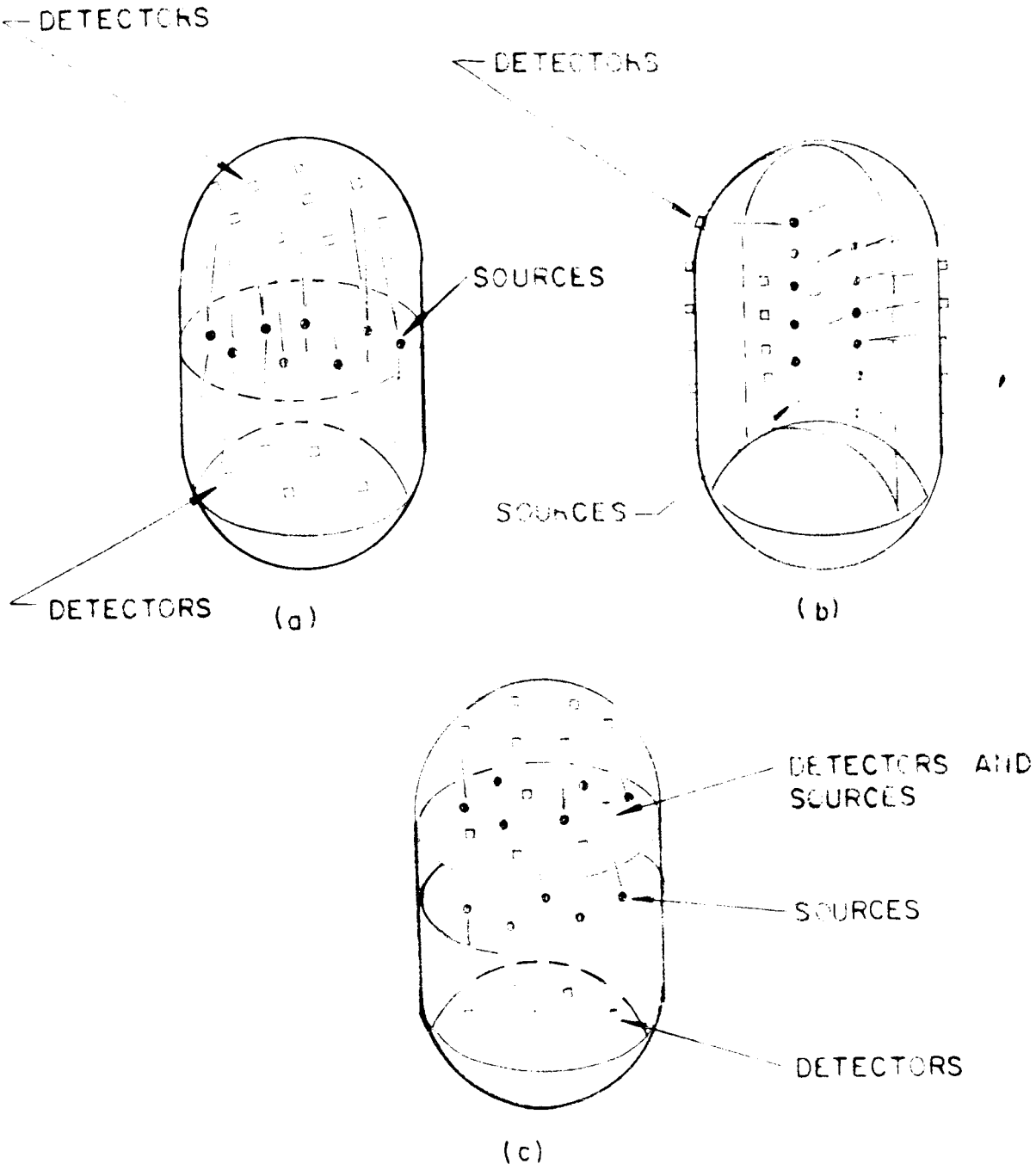

DETECTORS
DETECTORS
SOURCES
SOURCES
DETECTORS
(a)
(b)
DETECTORS AND SOURCES
SOURCES
DETECTORS
(c)

FIGURE 8

The only radiation hazard involved is in accidental loss of the sources. Again, the consequences of loss are not severe unless the radioactive material is scattered in a way which makes recovery difficult or impossible.

The sources will be Cs-137 pellets. The Cs-137 is bound in ceramic material (3M Corporation micro spheres) which will remain intact under severe mechanical shock, acid or water attack, and temperature up to about 1600°K. Since the temperature in a hydrogen fire may reach as much as 6700°R, (3823°K) additional temperature protection is required. This will be provided by the tungsten collimating shield completely enclosed in 1" of graphite. The combined oxidation and sublimation of graphite in air at 4000°K is less than 3 inches per hour. It is tentatively assumed that this is sufficient protection. If not, more can be provided. The sources then, will remain intact in the event of an accidental fire or explosion, and can be recovered. The Cs-137 source strength per source required for 0.5% accuracy with various depths of hydrogen, oxygen and nitrogen are shown in Figure 9. A 2" x 2" sodium iodide detector and 7.5 second sampling time are assumed. It should be noted that different curves result if different source energy detectors or sampling times are used. For the very small hydrogen depths a softer source than Cs-137 would be preferable.

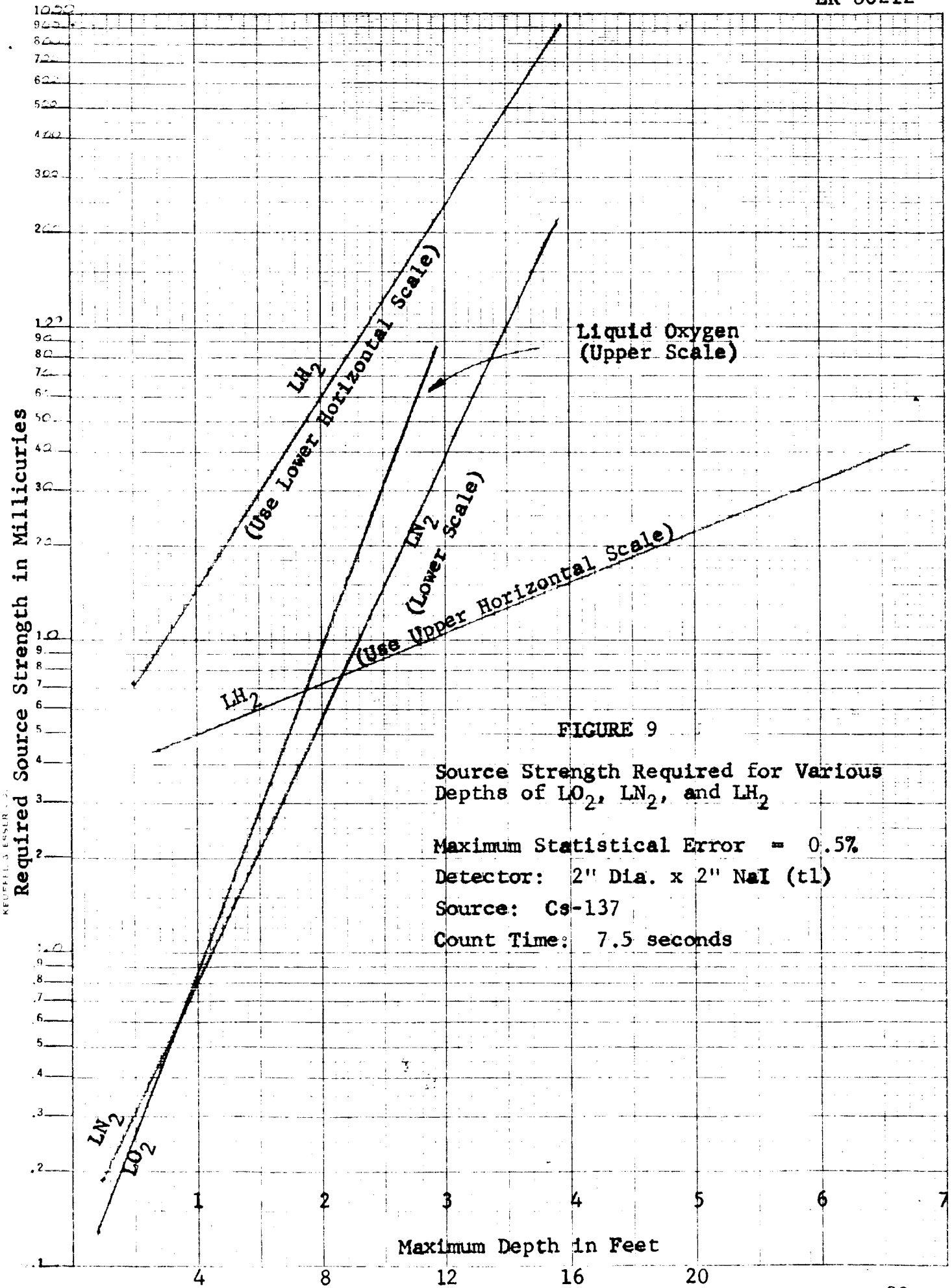


FIGURE 9

Source Strength Required for Various Depths of LO_2, LN_2, and LH_2

Maximum Statistical Error = 0.5%

Detector: 2" Dia. x 2" NaI (tl)

Source: Cs-137

Count Time: 7.5 seconds

3.0 DESCRIPTION OF RECOMMENDED PROTOTYPE SYSTEM DESIGN

Figure 10 is a functional diagram of the prototype system. There will be several identical channels measuring the mass in various sections of the tank. The separate channels will be averaged to obtain the total mass.

Each channel comprises a source, detector, collimating shield, differential pulse height discriminator, integral pulse height discriminator, integrator, power supply, pulse shaper, and one magnetic tape into a computer where appropriate curve fitting and averaging will be accomplished. The detector data may be analyzed in a number of ways to provide a better system evaluation. For example, fast averaging can be used to monitor transients, and slow averaging to record steady-state conditions to high accuracy.

The differential pulse height analyzer separates the counts under the Cs-137 full absorption peak from the remainder of the spectrum. These pulses are suitably shaped and recorded.

The integral pulse height discriminator is used to maintain constant detector gain. The gain control function is accomplished in the following way.

An alpha particle emitting source is painted on the detector. A suitable source is Am-241 which emits a 60 kev gamma and 3 lines between 5.3 and 5.5 mev. The 60 kev gamma is far below the Cs-137 full absorption peak and hence contributes nothing to the signal.

The light output efficiency of the detector for α particles is about 40% of that for gamma photons. Hence, a 5 mev α particle

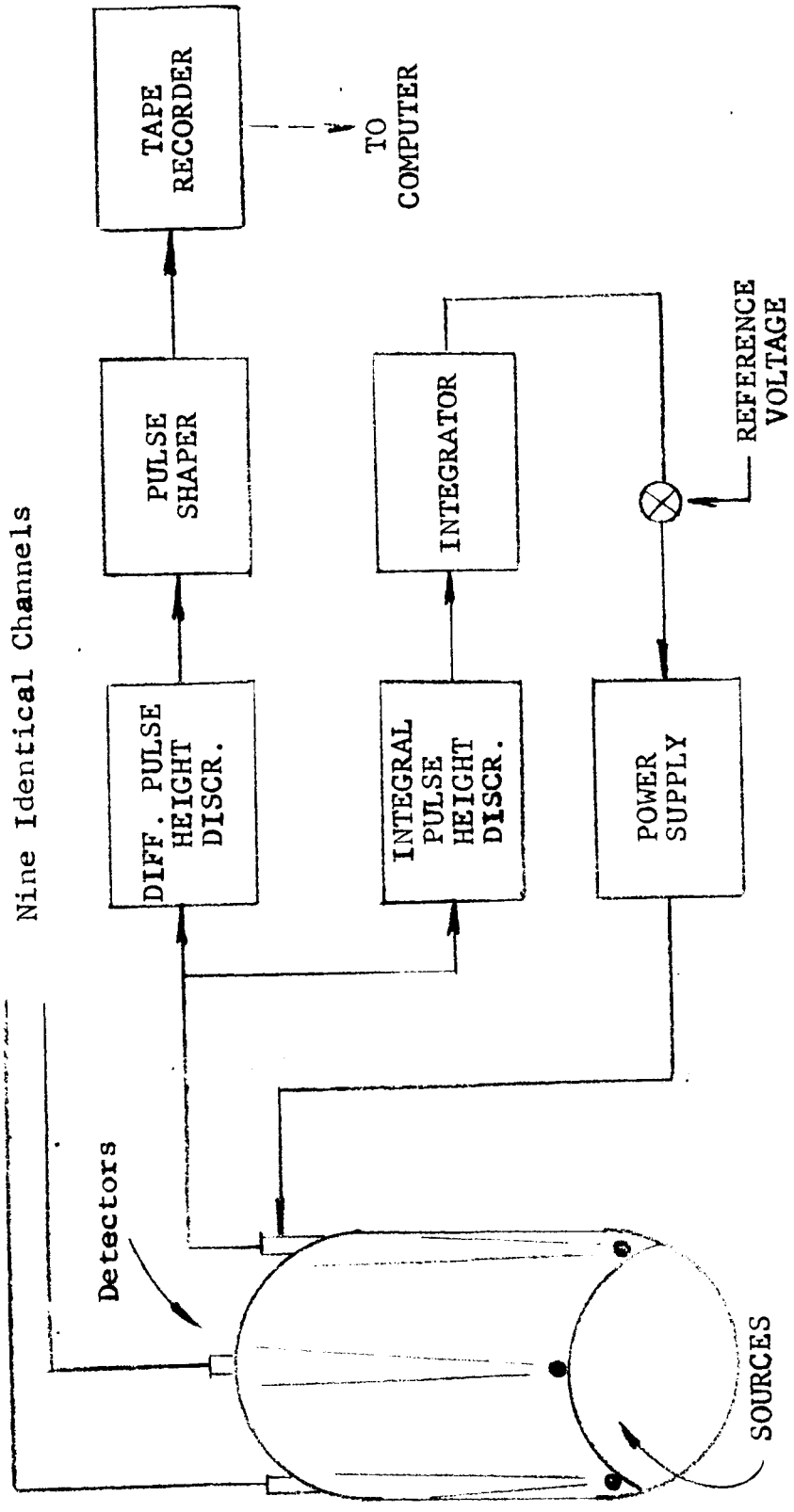


FIGURE 11

PROTOTYPE SYSTEM DESIGN

will produce a pulse height equivalent to the full absorption of a 2 mev gamma particle. This is well above the Cs-137 peak. The half-life of Am-241 is about 450 years, so that the particle frequency may be assumed to be constant over the period of interest. The pulse height spectrum of the detector is shown in Figure 11. If the detector gain is low, the count rate above the discriminator threshold will be too low. The count rate above this threshold is integrated to obtain a control voltage for the power supply. In the case of low gain, the low output from the integrator commands an increase in supply voltage. As the supply voltage increases the detector gain and hence the count rate above the integral discriminator threshold increases. The increase will continue until the integrator output reaches the reference voltage. Further increase of gain will cause the integrator voltage to exceed the reference and thus give rise to a decrease gain command. In this way, the detector gain is automatically maintained at the calibration value. Note that the gain control loop includes both the scintillator and photomultiplier tube so that stable gain is assured over a wide range of ambient conditions.

5.1 Number and Placement of Sources and Detectors. It is easy to see that if the number of detectors used is large, then large sampling errors are extremely unlikely under anticipated operating conditions. For example, suppose 100 detectors are used. Then even with the tank half full lying on its side under one g conditions, with the fuel static, the maximum sampling error would not exceed 5%. It should be noted that this imaginary

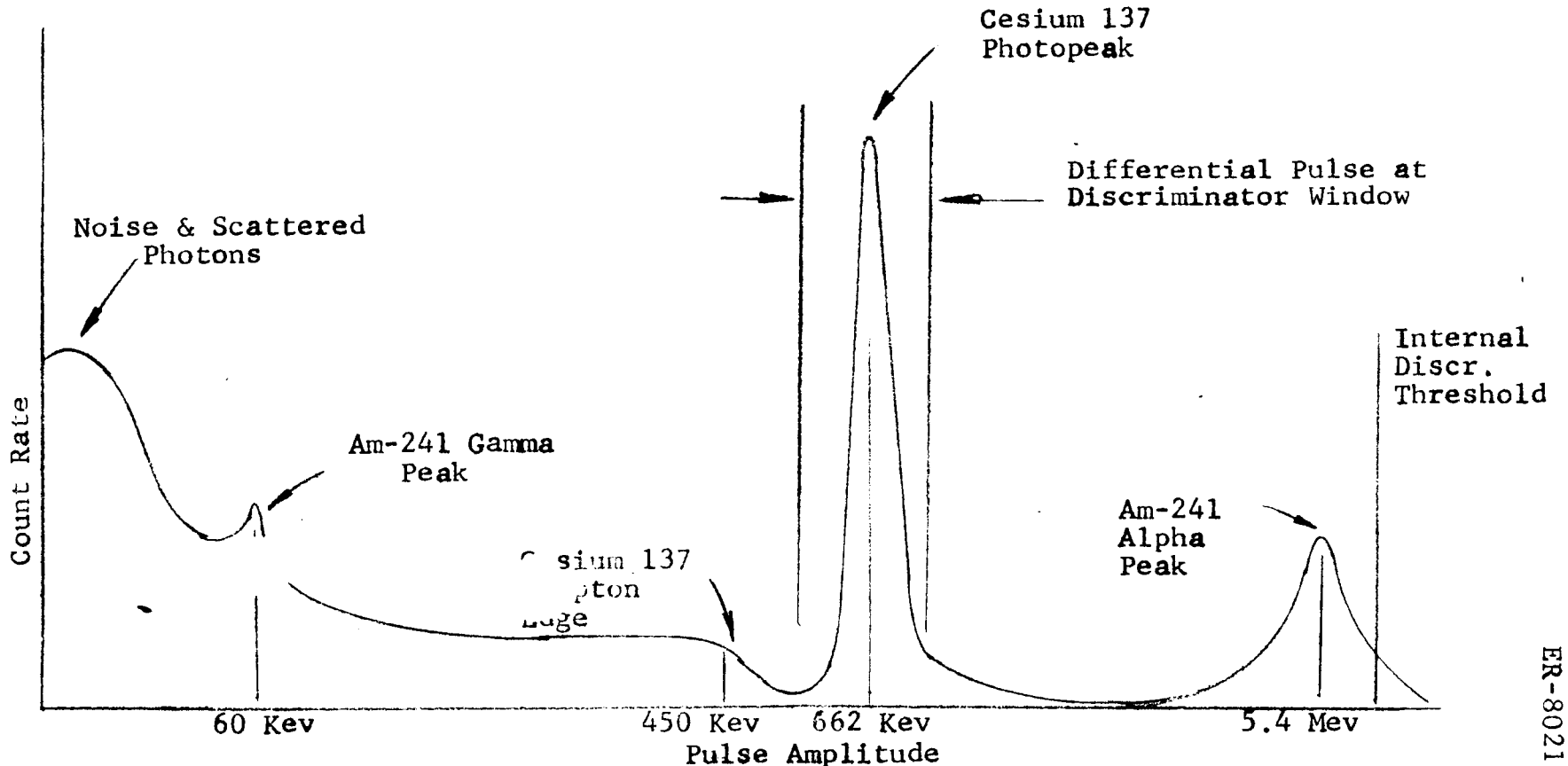

Cesium 137
Photopeak
Differential Pulse at
Discriminator Window
Noise & Scattered
Photons
Internal
Discr.
Threshold
Am-241 Gamma
Peak
Am-241
Alpha
Peak
Count Rate
60 Kev
450 Kev
662 Kev
5.4 Mev
Pulse Amplitude

FIGURE 11

situation is far worse than would be encountered in practice, even at low g.

On the other hand, it is possible that one might find an optimum location for a single detector such that satisfactory results would be obtained for at least some range of conditions.

It seems that at the present time the best course of action is to determine experimentally for the slosh tank, the minimum number of detectors required. The number to be used in initial experiments should be determined in cooperation with the user, since the trade-off is purely an economic one, involving the user's facilities. For example, the necessary information can be obtained with a single detector. The mass distribution within the tank can be found by locating this detector at various points and repeating runs under similar conditions. The same information can be obtained with a larger number of detectors with a proportionate decrease in test stand time required. It is estimated that the cost to deliver one detector and source unit will be about $18,300. Each additional detector channel will increase the cost about $1,620. The reduction in test stand time will be proportional to the number of detectors.

3.2 System Parameter Calculations. The detector area has been selected as 20 cm^2, since the detector price rises sharply above this size. Cs-137 was selected as the source because it is cheap, of long half-life, relatively easy to shield, and has a suitable absorption coefficient. The detector will be NaI(tl) since a high photo-electric cross-section is needed.

The detector efficiency is about 17%. The source strength per source will be 750 millicuries if 5 sources are used. The total source strength would be essentially constant regardless of the number of sources. Hence, in the following we assume one detector and 3.75 curies. The curve fit error will be assumed zero, since a sufficiently large computer will be used. Since the computer permits variable averaging time, it is desirable to express the accuracy as a function of the averaging time used. Full tank is the most severe condition. The tank full count rate is given by:

$$f = \frac{I_o A_D \eta}{4 R_o^2} e^{-\mu \rho R_o} \qquad (1)$$

where I_o is the source strength in photons sec^{-1}, A_D the detector area, η the detector efficiency, ρ the fuel mass density, μ the fuel mass absorption coefficient, and R_o the source-detector separation. For the values mentioned above:

$$f = \frac{(3.75 \times 3.17 \times 10^{10}) \times 20 \times 0.17}{12.56 \times (520)^2} \times \frac{1}{300} \qquad (2)$$

$$= 465 \text{ sec}^{-1}$$

In addition, the graphite shield and tank wall introduce a factor of 7.7 reduction. Hence, the detector frequency, tank full will be about 61 sec^{-1}. The relative standard deviation of the count rate is:

$$\sigma_f = \frac{1}{\bar{f} \Delta t} \qquad (3)$$

At full tank, the percent of full scale mass error (per detector) is:

$$\frac{dm}{m_o} = \frac{f}{h_o} = \frac{\quad}{h_o \sqrt{f\Delta t}} \qquad (4)$$

Or, solving for Δt:

$$\Delta t = \frac{1}{(\quad h_o)^2 \, f\left(\frac{dm}{m_o}\right)^2} \qquad (5)$$

Thus, at tank full, an accuracy of 0.25% requires Δt = 81 seconds. 0.5% can be obtained in 20 seconds. These correspond to system time constants of 40 and 10 seconds, respectively. These times are halved when about 11% of the fuel has been used. One may use equation (4) to determine the time required for a given accuracy at any level.

It should be noted that the large tank wall attenuations could be avoided if the tank were designed to accommodate the system. If the tank wall and heat shield losses are only a factor of 2, then the response times mentioned above are improved by a factor of 4.

3.3 Estimated Size and Weight of Prototype System.

3.3.1 Shields. An estimate of the shielding required to reduce the external dose rates to allowable values indicates that the inboard sources will weigh about 4.8 pounds. The outboard sources will weigh about 6.7 pounds. These estimates are made for a 5-source array.

In the event that a single source is used, the outboard shields will still be sufficient for installing and removing the

source. Additional shielding can be installed externally when the source is located near the tank wall. If the number of sources used is greater than 5, then each source is weaker and the individual shield weights are reduced.

The outboard sources can be approached to within 2 feet on one side. The dose rate at 2 feet for 750 millicuries of unshielded Cs-137 is about 600 mr/hr. The tank wall and graphite heat protector together will reduce this by a factor of 2.3. Assume the allowable dose rate is 5 mr/hr. Then an additional factor of 54 is needed. The dose build-up factor in 4.7 mean free paths of tungsten is about 2. Therefore, if a tungsten shield of 4.7 mean free paths is added, an attenuation of a little more than 55 is obtained. The tungsten thickness required is 2.6 cm. Practically no shielding is required except on the side near the wall, since only on this side can the source be approached. It is estimated that a spherical shield of about 4 cm diameter with the source located off center enough to give the required 2.6 cm on the tank wall side will suffice. The weight of tungsten will be about 1.4 pounds. This only takes care of shielding. An additional 1.4 pounds is needed for collimation. The graphite heat shield will weigh about 3.9 pounds. The total comes to 6.7 pounds. Similar estimation shows the inboard shields will weigh about 4.8 pounds. The total shield weight will then be about 50.8 pounds.

3.3.2 Detectors. Each detector including its power supply and associated electronic circuits will weigh about 1.7 pounds.

The total detector weight is then 15.3 pounds.

3.3.3 Total System. The weight of the major components is 66.1 pounds. Making allowance for miscellaneous mounting and wiring, it is expected that the total system weight will be around 80 pounds.

3.3.4 Power Consumption. The detector power consumption is estimated as follows:

Maximum signal frequency = 3.1 kc

Peak current per pulse = 0.1 ma

Pulse width = 250 ns

Average current (max. signal) = 0.08 ma

Dynode Bleeder Current = 5.0 a

Anode volts = 2000

Total power per detector = 100 mw

Total for nine detectors = 0.9 watt

The electronic circuits will require about 3 watts per channel or 27 watts total. The system total is then about 28 watts.

4.0 RADIATION SAFETY

The system design is based on limiting the external dose rates. Hence, under normal conditions there is no radiation problem. The problem arises in the case of a catastrophic accident. The source design is such as to minimize the risk in this eventuality.

Since temperatures as high as 6700°R may be reached in a hydrogen fire, there is no known material that is completely immune to the environment.

Graphite will survive for a considerable time, however. The combined loss of material due to oxidation and sublimation from the carbon in an arc at 4000°C (6800°R) is about 3 inches per hour. There are coatings such as the 3M Corporation silicized silicon carbide which will reduce this rate considerably.

Based on present knowledge of the problem, the source design is as shown in Figure 12. The Cs-137 is alloyed with a ceramic material (3M Corporation microspheres) which prevents leakage of the Cs-137 up to about 1100°C. This greatly reduces the usual sealing problems encountered with Cs-137. The microspheres are bonded in the tungsten shield and the entire assembly is enclosed in a one-inch shell of silicon carbide coated graphite. This assembly should remain intact and be easily recovered in the event of a disastrous failure of the test stand.

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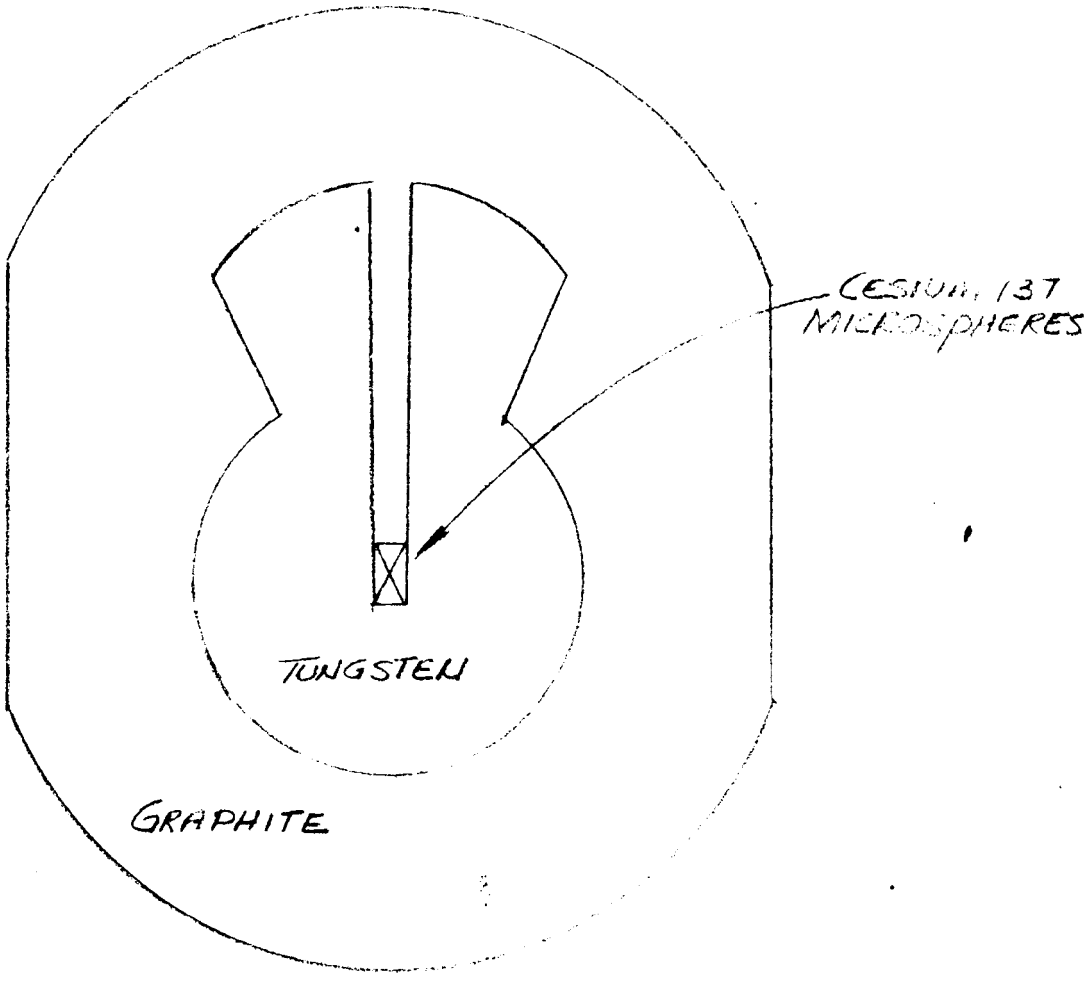

FIGURE 12

APPENDIX I
INTERACTIONS OF ELECTROMAGNETIC RADIATION WITH MATTER

As electromagnetic radiation passes through matter the result may be to impart motion to the particles of the matter. The way in which this particle motion is produced depends on the energy of the radiation.

Low energy photons can interact only with free or loosely bound electrons. As the energy increases interaction with tightly bound electrons occurs. At even high energies nuclear interactions occur.

The processes which may occur and their relative magnitudes depend on the atomic number, atomic weight, and density of the matter and the radiation energy. The probability of each process may be expressed as a cross-section can be obtained by adding the individual cross-sections. This total cross-section gives the probability of some type of interaction and is the one of interest to the mass gaging problem. Examples of the total cross-sections or absorption coefficients for photons from 10 Kev to 10 Mev are given in Figure 7 for several materials of low, medium, and high atomic numbers. In this appendix, a qualitative description of the various processes included in Figure 7 is given.

SCATTERING

There are a number of ways in which photons may be scattered by matter. Among these are Rayleigh scattering, Mie scattering,

electric field or Delbruck scattering, nuclear Thomson scattering, nuclear resonance scattering, and Compton scattering.

Nuclear resonance scattering is the nuclear analog of ordinary fluorescence and has a very small cross-section. In fact the cross-sections for all the scattering processes except Compton scattering are negligible for the photon energy ranges from .2 to 1.0 Mev, which is the range of interest in the gamma ray system. In the optical region Rayleigh scattering will predominate.

Nuclear Thomson scattering is essentially the same as Rayleigh scattering except the nucleus is involved rather than the electrons. This type of scattering is just barely detectable.

While the several types of scattering which are observable are of considerable theoretical interest only Rayleigh scattering and Compton scattering are of practical importance in the gaging system.

The essential characteristic of Rayleigh scattering is that no energy is converted from the electromagnetic form. A photon interacts with a bound electron without ejecting the electron. The electron is caused to vibrate and as a result re-radiates the energy it received. Thus, a portion of the energy is propagated in a new direction. The scattered radiation has the same wavelength as the incident radiation. The total Rayleigh cross-section is very small compared with the Compton cross-section in the Cs-137 mass gaging system. The ratio of the total Rayleigh cross-section to the Compton cross-section is about 2×10^{-5} at 662 Kev. In an optical system Rayleigh scattering is a major process.

Compton scattering is an interaction between a photon and a free electron. The electron receives kinetic energy as a result and hence the photon energy is degraded. A Compton collision can occur between a photon of high energy and a loosely bound electron and the electron is ejected. In this case the photon energy is degraded by the sum of the electronic kinetic energy and binding energy. A single Compton event can be visualized as an elastic collision between a photon and an electron. Energy and momentum are conserved. Compton scattering is the dominant process in the Cs-137 system.

ABSORPTION

In addition to the scattering processes in which photon energy may or may not be absorbed, there are a number of purely absorptive processes which occur. In the photon energy range of interest only the photo-electric effect is of importance.

Photo-electric absorption occurs when a photon ejects a bound electron. The photon energy is completely spent in ejecting the electron and reining its kinetic energy. The photo-electric cross-section becomes high for low energy photons and high Z materials. The photo-electric process is an important factor in the energy range of interest, but has a lower cross-section than does Compton scattering in the Cs-137 range.

Nuclear reactions occur at photon energies above about 15 Mev. Nuclear disintegration, photo neutron production, meson production all occur but are of no concern in the energy range of interest.

Pair production may occur at energies above 1.02 Mev, but is of no practical concern in the gaging system. In pair production a photon is converted into a positive-negative electron pair. The kinetic energy of the pair is equal to the original photon energy minus the energy equivalent to the rest mass of the pair. The process occurs in reverse also; i.e., a positron electron pair may annihilate with production of a photon. The processes of pair production, annihilation and Bremsstrahlung together make it possible for a single high energy particle (either a photon or charged particle) to "create" many lower energy particles. Photons are produced by charged particles through the Bremmstrahlung process, or charged particles are produced by pair production. Then photons are produced by annihilation and so on. The interaction of a single very high energy particle with matter then can result in production of an extremely large number of particles of all kinds.

In summary, the various processes are listed together with the approximate photon energy ranges where their effects are considerable.

1. Rayleigh (Classical) Scattering - (below 100 Kev)
2. Compton Scattering - (0.1 to 10.0 Mev)
3. Photo-Electric Absorption - (Low Z up to 100 Kev / High Z up to 1.0 Mev)
4. Pair Production - (Threshold 1.02 Mev / Cross-section increases up to very high maximum above 100 Mev)
5. Photo Nuclear Reactions - (Threshold about 7.0 Mev for very high Z, 10 to 15 Mev for low Z)

APPENDIX II

PRELIMINARY STUDY OF OPTICAL TECHNIQUES FOR FUEL TANK MEASUREMENT. LO_2, LH_2

STATEMENT OF PROBLEM FROM OPTICAL STANDPOINT

The main problem stems from the tank size involved. The approximate dimensions of a typical subject will be 30 feet x 20 feet feet. It is the fact which makes [illegible]-radiation detection difficult. The second important difficulty from the optical standpoint is that the tanks used to hold the LO_2 or LH_2 are opague to optical radiation. From X-ray wave lengths deep into the infrared region, metals have very strong opacity so that the sources or detectors used must be inside the tank. Therefore, both sources and detectors must operate at LH_2 temperatures.

The problem then is to choose a source and detector system which operates at LH_2 temperatures and which interact linearly with the atoms or molecules of the fuel so that the detection of mass will be independent of geometry.

FEASIBILITY OF INFRARED SYSTEM

One possible range of wavelengths studied was from 9000 Å to 11,000 Å. This is a particularly good region since there are known characteristic absorption bands in this region - Liquid Oxygen has a band from 10,700 Å to 11,100 Å. This is a combination liquid level interaction with rotational energies. One might expect that the interaction would be linear if the path half-length is long. Two problems arise. The first is that the strength of the band is too high. The characteristic half-

length is of the order of 10 centimeters. Thus at the great lengths involved here, the non-linearities would be large. However, the bands are very broad and if a sharp line source would be available near the tail of the absorption band, the problems would be diminished. Therefore, a source is needed which operates between the narrow limits of 10,950 Å at liquid oxygen temperatures. There are excellent detectors in this region.

The questions are then:

(1) To obtain a line source.

(2) To measure the amount of non-linearities in LO_2.

The problems involve engineering problems as well as certain basic physics problems. The transition involved is a magnetic dipole electronic-rotational one. As such, second order induction effects are of some importance. However, these effects are primarily density dependent and would differentiate between liquid and gaseous states, rather than geometric factors. The feasibility of this technique requires experimental verification.

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FEASIBILITY OF MICROWAVE TECHNIQUES

Considerable study of the literature indicates that not enough experimentation has been done on the absorption of microwave frequencies by liquids. The main work has to do with the

changes in the index of refraction at microwave frequencies. The apparatus required for measurements of this kind is large and difficult and the use of a missileborne system does not appear to offer a practical solution without a long term research project. In view of other possibilities with visible and infrared techniques, the entire microwave bands were dropped from consideration.

FEASIBILITY OF OPTICAL TECHNIQUES

There are two well known absorption bands in LO_2 at 4835-4900 Å and 4200-4230 Å. The latter of these is weaker and has a more linear characteristic. The lower wavelength transition is electric dipole and should be basically linear if a narrow band source can be found. Apparently, there are scintillation Yt sources available. However, the most likely approach would be to use a combination of the two bands and to experimentally determine the best mixture of the data to enhance the linearity.

The scintillator sources have the advantage that they can be placed in the tank. These optical frequencies can be detected with semi-conductors which are available or with a light collection system and photo tube measurement similar to the one used with the scintillation system now employed. Some experimental work is required to furnish complete information. A combination of two bands is required to remove the exponential part of the mass dependence.

Not much literature is available on LH_2. However, it is known that at least four bands are in the visible spectrum and it would be relatively simple to isolate them for the purpose of

this subject.

The difficulties are primarily engineering ones. That is, the actual sources, detectors, and filters need to be studied further. The problems are then:

1. To find adequately strong sources, preferably for both regions.
2. To develop a detection and mixing scheme for the two bands.
3. To find which bands to use in the LH_2 tanks.

These problems are surmountable in a reasonable time with limited funds, and represent a definite advantage over the infrared region because of the temperature problems.

SUGGESTED EXPERIMENTAL PROGRAM

It is suggested that a single approach be made to examine both the visible and infrared techniques. A cylindrical tank, approximately 2 feet in diameter by 6 feet long, with ports for four sources at one end and four detectors at the other, will be required. The sources and detectors should be evenly dispersed on the planar ends of the tank. Simple linearity tests can then be made to study the zero gravitational geometry problem.

For the visible region, the tests would be done in three phases. Phase I would consist of using a mercury vapor ultraviolet source with quartz windows. The spectrum would be analyzed witha prism spectrograph (Hilger Quartz Type). On a photographic plate the spectrum should be photographed at every tenth fractional

fluid level and with as low an input intensity as practical. An ultraviolet 1/64 Corning filter would be sufficient to block unwanted visible spectra from the experiment. For the first run a simple two lense system should be used for a focused beam, while on the second run an unfocused system should be used. With all detectors operating, the source should be moved from one position to another and the results analyzed in terms of geometrical dependence. This must be done to analyze the scattering problem. When the source and detector are aligned, only the absorption is involved and the scattered light should be very low. In an actual tank scattering must be accounted for. Phase III should consist of selection and trial of line sources and detectors and the trial thereof. The problems of weak sources must be handled since all available solid sources are very weak. However, the basic linearity should be studied before the expense of source detector determination is made. It will probably turn out that two kinds of sources are required for the two bands, but only one detector will be required. The mixing of the two bands can be done by filtering techniques over the individual sources.

The same tank will be usable for the infrared exploration. However, the sources must be used sooner. These should be induced emission sources or junctions which are now available. Similar devices may be used as detectors. For infrared techniques, Phases I and II should be combined. If the wavelengths can be produced as indicated in paragraph "Feasibility of Infrared System", then the geometry problem may be studied directly. Different source-

detector pairs will be required for LH_2, but it is more practical to study one type of level measurement at a time.

The size tank described here should be sufficient to determine which of the two techniques is more suitable to large volume.