# EVALUATION OF GAMMA DENSITOMETER PERFORMANCE

# EVALUATION OF THE PERFORMANCE OF THE GAMMA DENSITOMETERS OF ATOMIC ENERGY OF CANADA LIMITED

By

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# ABSTRACT

The Three Beam Gamma Densitometers developed by AECL-WNRE for measurement of void fraction in flowing steam/water mixtures were investigated to determine the major causes of drift and slow response to changes in void fraction. Available remedies were evaluated. The study indicated the following:

(1) Using the existing current mode system, considerable reductions in drift and response time may be possible through the following inexpensive modifications:

   (a) design changes in the photo multiplier tube high voltage circuit,

   (b) replacement of the detectors with Cadmium Telluride semi-conductor detectors,

   (c) replacement of the scintillation phosphor with one which exhibits no afterglow such as Bismuth Germanate or Cesium Fluoride,

   (d) matching voltages of photo multiplier tube outside wall and photocathode,

   (e) improved stabilization of high voltage and detector temperature.

(2) Drift would probably be reduced to less than 0.1%/hour if the existing current mode system were replaced with a simple integral counting mode system at an approximate cost of $5,200 per densitometer.

(3) Additions to the above counting mode system of a single channel analyser (S.C.A.) and an automatic gain control unit which uses a reference light would probably completely eliminate drift as well as substantially improve system response. This would require an additional $4,900 per densitometer.

It is recommended that these modifications be implemented in the same order as above, on a trial basis, as far as further expenditure is justified.

# ACKNOWLEDGEMENTS

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# 1. INTRODUCTION

In many experiments involving flowing vapour/liquid mixtures, the spatial distribution of the phases must be determined. The Three Beam Gamma Densitometers developed by WNRE for this purpose measure the intensity of gamma beams which have been attenuated by the mixture, using a scintillation detector system (Figure #1). Direct current output signals representing beam intensities are used in attenuation calculations to determine the quantities of interest.

Although most modern gamma beam intensity measurement systems use photon counting, current mode devices such as these have the following advantages:

(1) They are relatively inexpensive.

(2) Photo beam intensity may generally be increased beyond the point where the detector can distinguish individual photons. This can result in faster response to density changes and smaller statistical error.

However, they are generally more prone to drift. Some distinguishing features of AECL's units (Figure #1) are as follows:

(1) Maximum beam intensity is about three orders of magnitude greater than the maximum recommended intensity for NaI (Tl)* detector systems operating in the count mode.

(2) Only two of the ten available amplification stages (dynodes) of the photomultiplier tube are used.

(3) The voltage between the dynodes is about half of the usual value.

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* Tellurium activated sodium iodide crystal

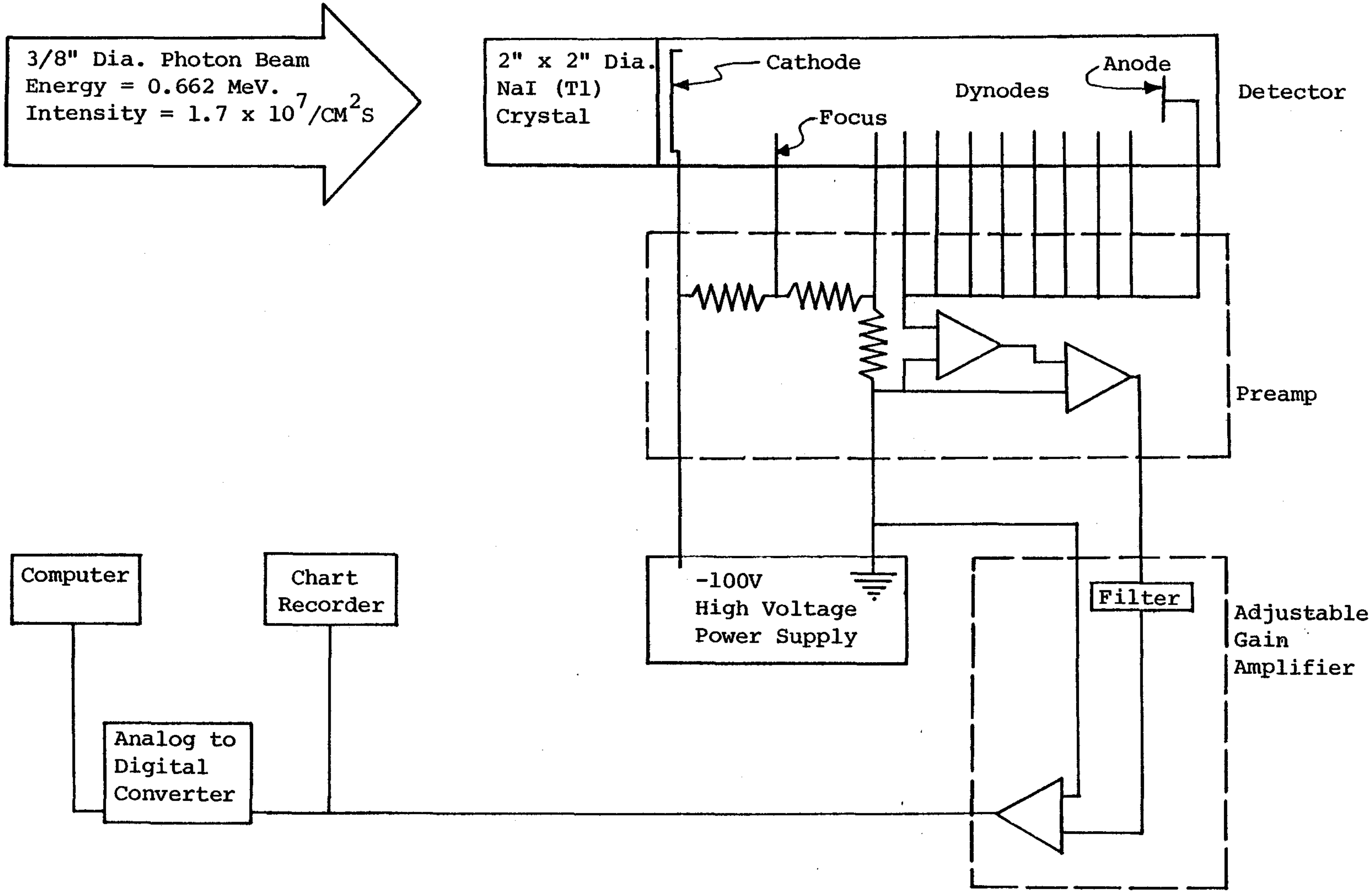

FIGURE 1: SIMPLIFIED SCHEMATIC OF EXISTING DETECTION SYSTEM

## 2. SCOPE OF THE INVESTIGATION

The investigation was concerned with the following densitometer problems:

(1) Drift in the empty pipe voltage measurement is typically one percent in four hours, but can be as much as four times this amount. It is a major source of error in experiments of long duration.

(2) The last ten percent of the response to a step change in beam intensity is exponential with a time constant of about five seconds. In transient two phase measurements this would introduce a significant error.

(3) Sensitivity of the densitometers to density changes, particularly at high void, is less than desired.

A considerable portion of the study consisted of an investigation of the origins of the drift and response problems within the detectors, and of remedies consisting of modifications of the detectors themselves. However, there is considerable potential for alleviation of these problems through changes in the method of processing the detector signal. Energy discrimination and automatic gain control in count mode systems were investigated.

With respect to problem (3) the idea of increasing sensitivity through a change in source photon energy was briefly examined.

## 3. DETECTOR DRIFT

Each of the existing detectors consists of a 2" x 2" diameter NaI (Tl) crystal attached to one of the following photomultiplier tubes:

(1) RCA 6342A in Harshaw 858 detectors,

(2) RCA 6342-V1 in Bicron 2M2 detectors,

(3) SRC L50B01 in Bicron 2M2 detectors.

### 3.1 Photomultiplier Tube Drift

Drift in these detectors is thought to be mostly attributable to the photomultiplier tube. This drift may be due to:

(1) poor focusing of electrons,

(2) fatigue of dynodes and photocathode,

(3) changes in temperature,

(4) changes in high voltage,

(5) deterioration of photocathode due to current leakage across the glass envelope.

The empty pipe voltage typically drifts at a rate of 0.25 to 1.0 percent per hour. In comparison, photomultiplier tube manufacturers claim that drift normally decreases to zero over extended periods (days), and that after a warmup period of forty minutes, net drift will generally be less than three percent.

### 3.1.1 Electron Focusing

The voltage between the cathode and dynode #1 is presently about 84V, whereas the recommended operating range is 100 to 400V dc. If this voltage is too low, electron focusing deteriorates and space charges build up within the tube. Representatives of R.C.A., Bicron and Harshaw all agreed that the voltage between the cathode and dynode #1 should be increased by at least a factor of two. Secondly, the voltage difference between the focus and dynode #1 should not be more than ten percent of the difference between the cathode and dynode #1. It is presently at the fifty percent level. Furthermore, the voltage between dynodes number one and two should be increased from 16V to 50V. Thus, the recommended voltages are as follows:

| | |
|---|---|
| Cathode | -250V |
| Focus | -70V |
| Dynode #1 | -50V |
| Dynodes #2-10 | 0V |

### 3.1.2 Fatigue

Although dynode fatigue is the most common source of photomultiplier tube drift, it is not expected to be a problem in this case (see Appendix B). However, the unusually high beam intensity may be causing the photocathode current to exceed the maximum recommended value of $10^{-9}$ A. This would cause fatigue of this element as well as nonlinearities due to saturation. This possibility should be checked by measuring the photomultiplier tube output current.

### 3.1.3 Temperature Variations

Temperature increases are most often associated with increases in dark current and decreases in spectral response. Since the response due to the incident photon beam is high compared to the dark current, only the latter effect is of interest. Although the temperature effect is expected to be negligible in the existing system, this should be verified by controlled variation of cooling water exit temperature.

### 3.1.4 High Voltage Variations

The photomultiplier tube output current is extremely sensitive to high voltage variations. Literature [10] on the RCA tubes indicates that at the present voltage between the dynodes the variation in output current will be about 23 percent per percent change in voltage across the tube. Since the existing high voltage supply variation is less than 0.001%*, this is not expected to be a significant source of error.

However, if voltage divider current does not exceed the photomultiplier tube current by at least a factor of ten (fifty is standard), nonlinearities will occur with changing intensity which will decrease the sensitivity of the densitometers at high void fractions. Since intensity is unusually high and voltage divider resistances are standard, it is quite probable that the problem exists in the case of the densitometers. This could easily be determined by measuring the dynode voltages and currents.

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* Based on specifications of regulated power supply and measured input voltage variations.

### 3.1.5 Current Leakage

Generally, for negative H.V. systems such as this, specially coated photomultiplier tubes are used in order to prevent damage to the photocathode due to current leakage across the glass envelope. It is not known whether the practice is required at supply voltage levels less than 250V, but this could easily be determined by testing with one of the special tubes.

## 3.2 Scintillation Phosphor Drift

Although NaI (Tl) crystals surpass all other types in terms of scintillation conversion efficiently, they are generally not recommended for use in current mode systems where high intensity beams vary with time. This is because they exhibit long term light decay following intense excitation, which is usually referred to as afterglow (see Appendix A). For constant beam intensity, afterglow will gradually build up to a certain constant intensity. As incident beam intensity changes with void fraction, the rise and fall of the intensity of the long term components of afterglow will manifest itself as a drift in the output voltage readings. Because of afterglow, neither Bicron nor Harshaw recommend the use of NaI (Tl) detectors when photon incidence rate exceeds 5 x $10^5$ per second. Table 1 shows the relevant properties of the alternative detectors considered.

On the basis of afterglow, any one of the other detector types would be more suitable than NaI (Tl) for use in a current mode system.

## 3.2 Scintillation Phosphor Drift (continued)

In a counting mode system in which afterglow effects may be screened (as described in Section 5.1), detectors with short decay times and large pulse height are preferred (Plastic, NaI (Tl)). For counting mode systems with stabilization (Section 5.2), good energy resolution (small percentage figure in Table 1) is also desirable (NaI (Tl), Cd Te). Although Cd Te could only be used in a current mode system, it has the potential of substantially reduced drift. This modification would require extensive testing since fabrication of the devices to avoid the characteristic problem of polarization still seems to be an art.

## TABLE 1

## PROPERTIES OF ALTERNATIVE DETECTOR TYPES

| Detector | Afterflow | Primary Decay Constant (μs) | Resolution at $Cs^{137}$ Photopeak | Pulse Height at $Cs^{137}$ Photopeak in Relative Units | Reference |
|---|---|---|---|---|---|
| NaI (Tl) | Up to 25% | 0.25 | 6.4% | 100 | 11 |
| $Bi_4$ $Ge_3$ $O_{12}$ | Negligible | 0.30 | 15% | 8 | 4 |
| Cs F | Negligible | 0.006 | 43% | 2.5 | 8 |
| Plastic | Negligible | 0.002 | No Photopeak | 5 | |
| Cd Te (Semi-conductor) | N/A | 6.0 | 6% | N/A | 5,6 |

## 4. DETECTOR RESPONSE

Although the theoretical intensity and effective time constant of the crystal afterglow is not known for this case, the form of the observed response to step changes in beam intensity is identical to the expected response of a detector in which afterglow is significant. This is true of the response to both increases and decreases in beam intensity. Although it is possible that the incomplete response phenomenon could result from effects in the amplifiers, the form of the response would be different, and checks on the theoretical time constants indicate that this is not the case.

According to a Bicron representative the slow response may also be a result of a hysteresis effect in the photomultiplier tube. If this is the case, an increase in high voltage as described in Section 3.1.1 should reduce this effect.

## 5. COUNT MODE SIGNAL PROCESSING

Drift and response problems may be substantially reduced through detector modifications suggested previously, but most modern systems can circumvent the problems to a large degree through standard count mode signal processing techniques.

### 5.1 Energy Discrimination

Whereas in the current mode a change in gain manifests itself directly as a change in output, in an integral count mode it changes the size of each pulse, but not the count rate. Thus, integral count mode systems should theoretically be free of drift which results from photomultiplier tube gain shifts. However, other sources of drift, non-linearity and slow response would still be present in the integral counting mode, namely:

(1) afterglow of the scintillation crystal,

(2) photomultiplier tube dark current,

(3) photomultiplier tube hysteresis,

(4) buildup of scattered photons.

These could all be substantially reduced by using a single channel analyser to pass only the pulses in the photopeak. This would make the densitometer much more sensitive to void fraction since the peak to total count ratio for the existing system is only about 0.25. For this application NaI (Tl) is the best choice of scintillation phosphor since it has relatively good energy resolution and a fast scintillation response (afterglow is screened).

## 5.1 Energy Discrimination (continued)

A standard integral count mode system (Figure #2) was tested on the constant intensity beam of a two inch densitometer. This system had a maximum drift rate of 0.13% per hour as compared to 0.25 - 1.0% per hour for the existing equipment. Unfortunately no drift measurement was done when the S.C.A. was engaged, passing only pulses within the photopeak energy window.

## 5.2 Automatic Gain Control

One of the major effects of detector drift in an energy discriminating count mode system is a change in pulse height or apparent energy of the incident photons. As the photopeak energy shifts with respect to the energy window of the S.C.A., the count rate downstream of the S.C.A. will change, resulting in a drift. Automatic gain control (A.G.C.) circuits adjust pulse amplification through feedback, to negate the apparent shifts in energy of a photopeak which result from detector drift. The major types of A.G.C. circuits and their associated errors are listed in Appendix C.

A standard stabilizer unit was inserted into the count mode system of Figure #2 and tested. The stabilizer was set to the .662 MeV photopeak and the D.V.M. measured a signal representing the total integral count rate. There was no drift in this signal (to the three significant figures of the D.V.M. reading) over twenty-one hours.

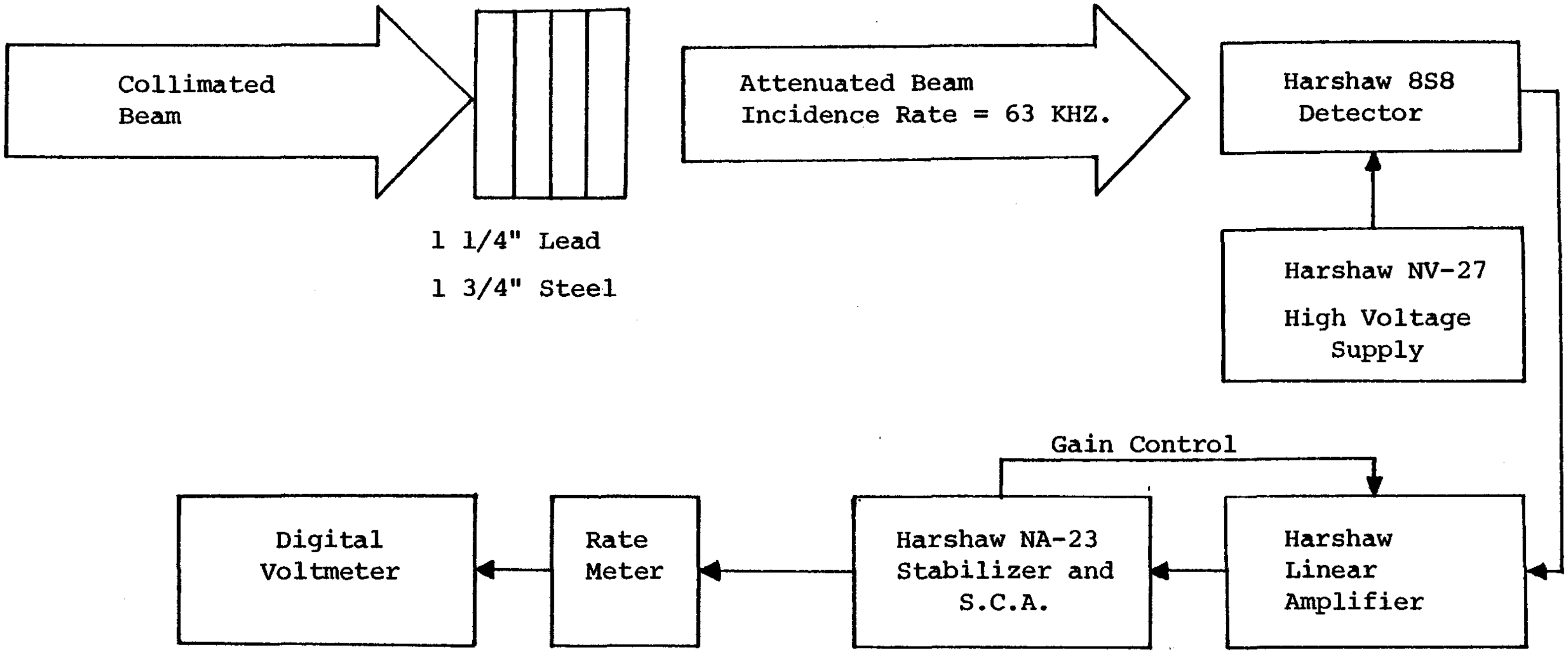

FIGURE #2: TESTED AUTOMATIC GAIN CONTROL SYSTEM

## 5.2 Automatic Gain Control (continued)

However, the system was unable to adjust to even small changes in beam intensity. The reason for this is probably base line shift in the amplifier, since at this high count rate pulse pile-up is about 38%. Since high count rates are required for low statistical error, and fast variations in light intensity are present, an additional reference signal of constant intensity would be required in this case. An alpha emitter doped crystal (Appendix C) should be chosen on the basis of superior stability. Harshaw makes standard NaI (Tl) detectors with part of the crystal doped with $Am^{241}$ which produces a reference pulse with an equivalent energy of about 3 MeV.

A combination of amplifier, S.C.A. and stabilizer by Canberra (models 2010, 2031 and 1720) when used with the above detector would give good response and accuracy in a nominal 5 MHz system. At three percent maximum pulse pile-up (complete void, 150 KHz) and sampling rate of 10 Hz, the maximum standard statistical error (at zero void) would be ±1.0%. This would require a reduction in beam intensity by a factor of 82. The preamps would have to be replaced with faster ones with pulse clipping (ex. Harshaw NB-15X).

## 5.3 Time Averaging and Data Collection

The pulses in a count mode system must be time averaged and this count rate must be recorded using the existing computer as well as displayed. A system in which the count rate signal remains in a digital form would be free of the drift associated with the existing data collection system. However, since this drift is thought to be negligible, the question of how to process the output of the S.C.A. becomes one of cost and convenience. The following three methods were considered:

## 5.3 Time Averaging and Data Collection (continued)

(1) Averaging, amplification and data collection using existing amplifiers (probably modified) and existing A.D.C.'s and computer.

(2) A standard ratemeter could perform the averaging of the S.C.A. current giving a D.C. millivolt signal as well as a meter count rate readout. The signal would go directly to existing data collection system amplifiers.

(3) The count of a simple decimal counter downstream of the S.C.A. could be transferred at regular intervals through an interface to the computer. The interface would make use of the existing real time clock of the computer and would ideally have multiplexer capability of at least nine channels.

Approximate costs of this count mode equipment are as follows:

| Item | Cost $ |
|---|---|
| 2" x 2" NaI (Tl) detector | 300 |
| Americium reference light | 230 |
| Preamp (Harshaw NB-15X) | 250 |
| Amplifier (Canberra 2010) | 800 |
| Stabilizer (Canberra 1720) | 1,090 |
| S.C.A. (Canberra 2031) | 300 |
| Ratemeter (Canberra 1481) | 370 |
| Counter (Ortec 770-01) | 1,130 |
| Register Interface | 450 |
| I.O. Extender for HP2100A Computer | 5,570 |

## 5.3 Time Averaging and Data Collection (continued)

The costs of systems (1), (2) and (3) per densitometer are $8,870, $9,980 and $10,880 respectively. This assumes:

(a) negligible modification of amplifiers in system (1),

(b) stabilization on reference peak for all systems,

(c) cost of computer interface in system (3) is split between three densitometers,

(d) differential counting of .662 MeV peak in all systems.

Since systems (1) and (2) are more convenient for calibration and cost less, the digital system (3) should not be considered further. The S.C.A. represents a small investment compared to its potential benefits. Testing of the faster stabilization system would be required before its worth can be evaluated in light of its substantial cost.

The components of the system shown in Figure #3 should be borrowed, assembled and tested for drift and response under rapidly varying beam intensities with count rates as high as 150 KHz.

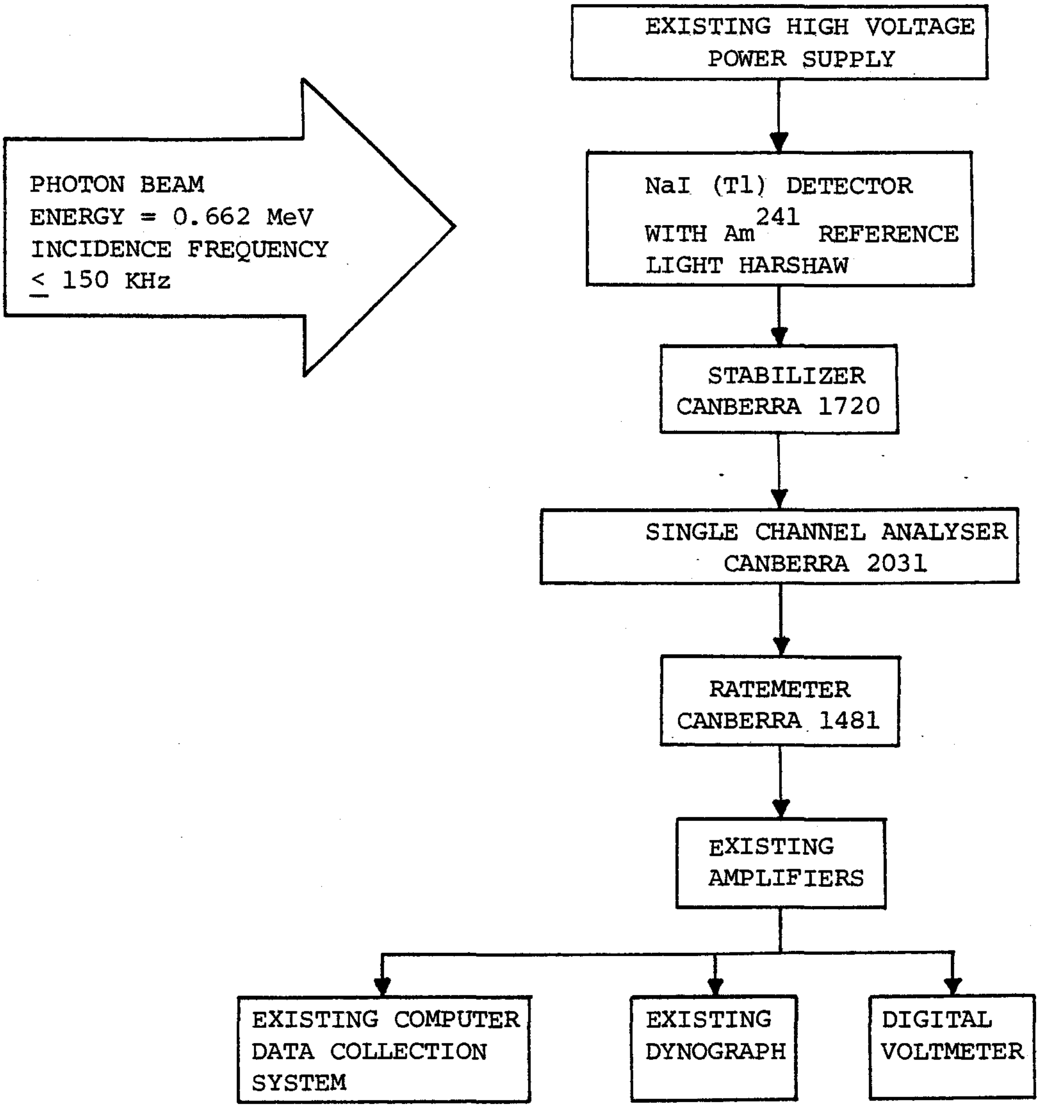

FIGURE 3: RECOMMENDED COUNT MODE SYSTEM

## 6. SENSITIVITY

Maximum sensitivity of the densitometer to fluid density will be attained when beam intensity and fluid attenuation are maximized (see Appendix D). Since the photon attenuation coefficient of water increases with decreasing photon energy, a decrease in photon energy would result in an increase in sensitivity. In an optimum system the attenuation by the fluid would be maximized to the point where the intensity for the zero void situation was at the lower limit of the detection system's capability as determined by background noise or statistical error considerations.

### 6.1 Current Mode System

The maximum intensity limit of the detector is probably being exceeded in the present system due to afterglow. Since the maximum signal to noise ratio is about $10^4$, this could be relaxed by two orders of magnitude in order to increase sensitivity by this factor through a reduction in photon energy.

### 6.2 Count Mode System

As mentioned in Section 5.2 the maximum standard statistical error due to the randomness of the source decay rate and the dynode electron emission for the stabilized system of Figure #3 is ±1%. Since this is on the verge of being unacceptable, a lower energy source for this system should not be considered. The source strength required for this system is only 0.29 Curies as compared to the present 23. Reduced source strength is preferred to attenuation because of better energy resolution. Future densitometer units using the count mode could benefit from a potential reduction in weight by a factor of about seventy if the source strength was reduced and the unit redesigned.

## 7. OTHER QUESTIONS

(1) Should buildup due to multiple Compton scattering be taken into account in attenuation calculations?

(2) What is the best choice of source for maximum sensitivity to fluid density in the current mode system?

(3) The present average lifetime of 400 working hours for the detectors is far below average according to the manufacturers. They say the usual reasons for detector failure in order of decreasing frequency are:

(a) mechanical shock of crystal,

(b) thermal shock of crystal,

(c) crystal hydration,

(d) photomultiplier tube fatigue.

Although no one seems to know the usual reason for failure of AECL's detectors, this information would be valuable from the point of view of reduction of drift as well as detector replacement frequency.

(4) Photomultiplier tube gain is known to be very sensitive to magnetic and electrical fields. Should the detectors be covered with mu-metal shields in some experiments?

## 8. CONCLUSIONS

Two significant problems connected with the use of AECL's densitometers are drift and slowness of response to beam intensity variations. The smallest drift rate that one must expect from an unstabilized scintillation detector is about 0.05% per hour, whereas the existing densitometers typically exhibit four to twenty times this amount. A great deal of potential exists for drift reduction and decrease in response time through relatively inexpensive modifications such as the following:

(1) adjustments in the photomultiplier tube high voltage circuit,

(2) reduction of beam intensity,

(3) change in scintillation phosphor,

(4) matching of photomultiplier tube outside wall and photocathode voltages.

The effectiveness of these modifications must be evaluated through "before and after" tests of drift, response, linearity and sensitivity.

Beyond these small modifications it has been shown that further drift reductions to less than 0.1% per hour are possible through the use of a simple integral counting mode system at a cost of $5,200 per densitometer.

## 8. CONCLUSIONS (continued)

Additions to the counting system of a single channel analyser and an automatic gain control unit using a reference light have the potential of completely eliminating drift as well as substantially improving system response. Since even the best of these A.G.C. devices may be unstable when subject to widely varying beam intensities, testing of the equipment is required before the additional expenditure of $4,900 per densitometer is considered further.

In the current mode system an increase in sensitivity of the densitometer to fluid density by two orders of magnitude without serious reduction in signal to noise ratio may be possible, by replacing the source with one of lower photon energy. The energy of the existing $CS^{137}$ source is perfect for the count mode system recommended. However, the intensity of the existing sources is too great for this system by about two orders of magnitude.

## 9. RECOMMENDATIONS

The following recommendations are listed in order of decreasing probability of improvement per unit cost. They should be implemented on a trial basis until there is an indication that additional expenditure will not be justified by the potential for further improvement.

(1) Determine the effect on drift and response of changing the photomultiplier tube high voltage distribution to that outlined in Section 3.1.1.

(2) Check for inadequate voltage divider current and photocathode saturation by measuring dynode and voltage divider currents.

(3) Measure the performance of a Cd Te (Bicron) semiconductor detector with respect to drift, response, linearity and sensitivity.

(4) Analyze existing test data to obtain information on the performance of the existing detectors as a function of beam intensity. Measure drift and response using scintillation detectors which are known to exhibit negligible afterglow, such as Bismuth Germanate and Cesium Fluoride.

(5) Check the effect on drift of matching photocathode and photomultiplier tube wall voltages using the specially coated tubes.

(6) Measure the variations in cooling water temperature and high voltage and the effects of these variations on amplifier output.

## 9. RECOMMENDATIONS (continued)

(7) Borrow the equipment required for the count mode system of Figure #3.

   (a) Test the system with the stabilizer fixed on the Cesium source photopeak and its output fed directly to the ratemeter.

   (b) If the above system is unstable as a result of rapid variations in beam intensity, test the system with the stabilizer fixed on the $Am^{241}$ reference peak.

   (c) Insert the S.C.A. and test with its window on the Cesium peak. Maximum total count rate should be limited to 150 KHz for the above tests.

(8) If performance in one of the configurations of recommendation #7 is adequate, investigate the possibility of modifying the existing amplifiers for use instead of the ratemeter.

(9) If drift and response problems in the current mode system can be sufficiently reduced through recommendations 1 to 6, investigate the possibility of replacing the source with one of lower photon energy.

# APPENDIX A

## Afterglow

Although the main luminescent component of NaI (Tl) crystals has a time constant of 0.25 μs, there are other persistent components due to low energy capture levels (traps) with various associated time constants. Koicki et al.[1] showed that for a $Cs^{137}$ source, every fast pulse is followed by about 220 subsequent pulses with a characteristic time constant of 0.15 second. This component alone accounts for nine percent of the total photoelectron yield (or photomultiplier tube current). Others[2,3] have observed other components with decay times of 1.4 min. and 34 min., but the intensity of these components is unknown. Generally this increases with beam intensity, photon energy, irradiation time and temperature. Afterglow is thought to be responsible for up to twenty-five percent of the scintillation light.[11] The portion of this which is long term is sufficient to allow the possibility of the development of a dose meter using a NaI (Tl) crystal.

Although the most noticeable effect of afterglow is an increase in detector response time, it would also give rise to drift. This drift would be a function of the temperature and flux history of the crystal.[3]

# APPENDIX B

## Dynode Fatigue

Dynode fatigue typically occurs at the last dynodes where the electron current is the greatest. Although beam intensity in this case is greater than recommended by about three orders of magnitude, low dynode voltages used result in an amplification reduction by about the same factor. Since only two (and not ten) dynodes are being used, this results in a reduction in tube current by about five orders of magnitude. Thus, the maximum expected photomultiplier tube current is about five orders of magnitude less than maximum values in most applications.

Although reduction of the number of dynodes used to this extent was unheard of by the detector company representatives, this method of reducing photomultiplier tube drift due to fatigue has been verified in the literature[13] since the original paper by Youngbluth[12] which apparently inspired its implementation[14].

# APPENDIX C

## Standard Automatic Gain Control Circuits

Drift in photomultiplier tube amplification results in changes in pulse height or apparent energy of the photons. Most A.G.C. systems use two S.C.A.'s to measure count rate within equal width energy windows on either side of a photopeak. As the detector amplification drifts, a difference in these count rates results in a feedback signal to the high voltage supply or the amplifier, resulting in a gain adjustment in the direction which reduces the count rate difference (effectively brings the photopeak back to its original apparent energy).

Automatic gain control devices can be divided into two main groups according to the reference signal.

(a) A.G.C. with additional reference signal

   (1) Additional monoenergetic alpha emitter with its radiation energy out of the range of the measured spectrum. This method is subject to an error resulting from the difference in thermal coefficients of the scintillation phosphor for reference alpha particles and for detected gamma radiation.

   (2) Additional pulsed light source (L.E.D.) as a reference signal. This method is subject to error caused by the thermal coefficient of the light source used as a reference signal.

   (3) Additional gamma or beta reference source with periodically changing radiation intensity by means of a rotating shutter. This method introduces no errors but suffers from poor reliability since it requires rotating shutters.

Standard Automatic Gain Control Circuits (continued)

(b) A.G.C. systems using the same signal for stabilization and measurement by:

(1) Control of photopeak position in differential spectrum of detected radiation. This may exhibit errors for quickly varying, high intensity beams.

(2) Control of pulse amplitude of the highest pulses of the detected radiation spectrum.

A system with an additional reference signal would be required for the densitometers to avoid the instabilities of type B systems in the face of quickly changing beam intensity. Method A (1) is the most reliable and stable.

## APPENDIX D

### Sensitivity to Void Fraction

Assuming negligible buildup, an expression for the detector photon incidence rate N is as follows:

$$N = N_o A_p \exp\left[\frac{-\rho}{\rho_f} \mu_f D\right]$$

where $N_o$ = unattenuated incidence rate for collimated beam of monoenergetic photons.

$A_p$ = fraction transmitted through pipe walls.

$\rho$ = average fluid density.

$\rho_f$ = density of liquid phase.

$\mu_f$ = mass attenuation coefficient of the liquid phase.

D = internal diameter of pipe.

Maximum sensitivity of the densitometer to fluid density will be attained when the product $N_o A_p$ is maximized and when the variation in the fluid attenuation factor

$$(\exp\left[\frac{-\rho}{\rho_f} \mu_f D\right])$$

is maximized. In a photon counting system the upper limit on $N_o A_p$ is the maximum counting rate of the detection system. In the present current mode system the limit seems to be determined by detector afterglow. Note that although the pipe transmission factor $A_p$ decreases rapidly with decreasing photon energy, it plays only a minor part in the selection of optimum source photon energy (Section 4) since $N_o$ can generally be increased by increasing source strength in order to counteract this effect.

Sensitivity to Void Fraction (continued)

Provided the pipe is stationary relative to the densitometer, and thermal expansion effects are minimal, the only design consideration relevant to the decrease in pipe wall attenuation factor with decreasing photon energy is the increase in cost due to the increased source strength required. Source shielding required remains roughly constant as photon energy is decreased while source strength is increased to keep $N_o A_p$ constant.

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