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# LOFT ADVANCED DENSITOMETER FOR NUCLEAR LOSS-OF-COOLANT EXPERIMENTS

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## ABSTRACT

This report discusses a "nuclear hardened" gamma densitometer — a device which uses radiation attenuation to measure fluid density in the presence of a background radiation field. Data from the nuclear hardened gamma densitometer are acquired by time sampling the coolant fluid piping and fluid attenuated source energy spectrum. The data are used to calculate transient coolant fluid cross sectional average density to analyze transient mass flow and other thermal-hydraulic characteristics during the Loss-of-Fluid Test (LOFT) loss-of-coolant experiments.

The nuclear hardened gamma densitometer uses a pulse height analysis or energy discrimination, pulse counting technique which makes separation of the gamma radiation source signal from the reactor generated gamma radiation background noise signal possible by processing discrete pulses which retain their pulse amplitude information. Testing to verify the concepts of this pulse height analysis technique has been conducted at LOFT located at the Idaho National Engineering Laboratory. Results have shown that reactor primary coolant fluid chordal average density can be calculated from gamma radiation source signal data.

## INTRODUCTION

The LOFT facility includes a 55-MW nuclear reactor used for reactor safety experiments. One of the many measurements needed in these experiments is the measurement of the density of an inhomogeneous steam-water mixture flowing through the 14-in. primary coolant piping. This measurement is accomplished by a gamma densitometer, which is "nuclear hardened", or designed to operate in the presence of background radiation (beam)[1].

Gamma densitometers operate on the principle that a greater density of fluid in a radiation beam will attenuate the beam intensity. A beam intensity measurement gives a quantitative indication of fluid density. The theory is discussed in the "Physical Principles" section.

Three sets of tests have been completed for this LOFT densitometer system:

- Laboratory tests with the densitometer mounted on LOFT-size pipe.
- In-place testing on the LOFT system during a nonnuclear experiment, in which there was no real nuclear fuel in the reactor and no background radiation.
- An actual application of the densitometer during a normal LOFT experiment (with the nuclear core and the radiation background), in which four of these densitometers were used in different locations in the LOFT system.

These three sets of tests all indicated that the densitometer works well. The following sections of this report describe various aspects of the densitometer system.

## SYSTEM OVERVIEW

The design of the LOFT densitometer system is indicated schematically in Figure 1. There is an 11-Curie Cobalt-60 gamma radiation source outside the primary coolant pipe. Three gamma radiation detectors are arranged to detect radiation which passes unscattered from the source, through the pipe, and into the detectors. These three direct paths are designated as beams A, B, and C. A fourth detector (referred to as beam D) is arranged so that it cannot receive radiation directly from the cobalt source. All four detectors receive scattered cobalt radiation and various types of reactor background radiation.

The radiation detector emits a pulse for each gamma photon that interacts with the detector[2]. (Sometimes several pulses may be overlapping or coincident, so that they appear as one single pulse.) The amplifier performs three distinct functions:

- Amplify and shape the pulses and send them to the energy (pulse height) analyzer

- Count the pulses

- Generate an amplifier live time indication, or a measurement of the time during which the amplifier was capable of counting incoming pulses. (*Live time will be discussed later.*)

The energy analyzer measures the height of each pulse and generates a spectrum, or a record of the number of pulses in each of several pulse height intervals. The analyzer also generates a live time indication which is combined with the amplifier live time to form a system live time indication.

For each preset time interval and for each beam, the data recording system records the spectrum, the system live time, the amplifier live time, and the total counts. The electronic system is the same for all four beams, with two exceptions.

- The D-beam spectrum comprises 512 channels, including zero energy, while the other spectra comprise only 64 channels each and do not include zero energy.

- The data acquisition time interval is 50 ms for the D beam, but only 12.5 ms for the other three beams.

The data acquisition time intervals are synchronized so that each 50-ms interval begins at the same time as a 12.5-ms interval and exactly coincides with four contiguous 12.5-ms intervals. Data acquisition is continuous in the sense that there are no gaps between the data acquisition intervals.

The recorded data are computer processed to separate the cobalt spectra from the background radiation and to correct for dead time and coincidence effects. The result of this processing is an indication of the cobalt spectrum magnitude for each time interval for each of beams A, B, and C. These cobalt spectrum magnitudes can be used to determine the chordal average densities, or the fluid densities averaged along the beam paths, for beams A, B, and C.

## PHYSICAL PRINCIPLES (LOFT DENSITOMETER GAMMA BEAM PATH ATTENUATION)

The attenuation of gamma radiation is governed by the narrow beam exponential radiation absorption law:

$$I = I_0 e^{-\left(\frac{\mu}{\rho}\right)(\rho)(x)}$$

where:

$I$ = intensity or flux of the primary or uncollided source photons that pass through the absorber medium thickness (x)

$I_0$ = source or incident intensity before passage through the absorber (x = 0)

$\frac{\mu}{\rho}$ = mass attenuation coefficient of the absorber medium for the monoenergetic source energy $E_0$

$\rho$ = density of the absorber medium

$x$ = thickness of the absorber medium.

For the LOFT experiment, the gamma radiation from an 11-Curie Cobalt-60 source traverses three absorbing mediums (a) the primary coolant pipe walls, (b) the primary coolant fluid, either steam, water, or a two-phase mixture of the two; and (c) air. The metal, fluid, and air path lengths listed in Table I are calculated from the following LOFT primary coolant piping dimensions

$$D_0 = 35.56 \text{ cm and } D_i = 28.397 \text{ cm.}$$

When these values are substituted into the piping geometric equations, the fluid, metal, and air path lengths are (3):

- Fluid path length

$$x_f = \left[D_i^2 - (D_0 + D_s)^2 (\sin^2 \theta)\right]^{\frac{1}{2}}$$

- Metal path length

$$x_m = \left[D_0^2 - (D_0 + D_s)^2 \sin^2 \theta\right]^{\frac{1}{2}} - x_f$$

- Air path length

$$x_a = \left[R - D_0^2 - (D_0 + D_s)^2 \sin^2 \theta\right]^{\frac{1}{2}}$$

where:

$D_s$ = source to detector distance

$D_0$ = pipe outside diameter

$D_i$ = pipe inside diameter.

The source or incident 11-Curie Cobalt-60 gamma beam intensity is calculated from the extensive geometric variables and the source and detector intensive variables. The resulting expression for $I_0$ is (4):

$$I_0 = \frac{\epsilon \gamma A_D S}{4 \pi R^2}$$

where:

$\epsilon$ = detection efficiency or the probability of a photon emitted by the source giving a pulse recorded in the photopeak

$\gamma$ = percentage of the total disintegrations that are gamma radiation

$A_D$ = exposed surface area of the detector (nonshielded area with good collimation)

$S$ = total number of disintegrations per second due to the source ($S$ = number of Curies times $3.7 \times 10^{10}$)

$R$ = source to detector distance.

When the exponential radiation absorption law is applied and that the metal, fluid, and air path length terms are used as the exponent, the final expression for the measured intensity at the detector is:

$$I = \frac{\epsilon\gamma A_D S}{4\pi R^2} \left[ e^{-(\frac{\mu}{\rho})_m (\rho)_m (x)_m + (\frac{\mu}{\rho})_f (\rho)_f (x)_f + (\frac{\mu}{\rho}) (\rho)_a (x)_a} \right]$$

*where the subscripts m, f, and a relate to metal, fluid, and air,* respectively[5]. Since $(\frac{\mu}{\rho})_m$, $(\rho)_m$, and $(x)_m$ remain essentially constant throughout the temperature range of the experiments 333 to 883 K, and the attenuation term due to air is negligible compared with *the metal and fluid attenuation terms, the* measured intensity equation reduces to:

$$I = I_0 e^{-M} e^{-(\frac{\mu}{\rho})_f (\rho)_f (x)_f}$$

where $e^{-M} = e^{-(\frac{\mu}{\rho})_m (\rho)_m (x)_m}$ = constant.

Also, the fluid path length $(x)_f$ remains constant, regardless of the flow regime or steam-water two-phase mixture. The mass attenuation coefficient $(\frac{\mu}{\rho})_f$ is the same for either steam or water because both have the same molecular structure. The only remaining variable is the chordal average density of the coolant fluid $(\rho_f)$. When the natural logarithm of both sides of the equation is taken, the equation becomes

$$\frac{\ln (I/I_0)}{(-M)\ (-)(\frac{\mu}{\rho})_f\ (x)_f} = (\rho)_f .$$

*This final expression is the theoretical basis for relating the* chordal average fluid density to the primary beam, uncollided source flux count rat in terms of known constants and measured count rates

Fluid density is determined from the photopeak window count rate, the pipe full and empty count rates, the subtraction of background radiation count rate and the logarithmic relationship between count rates and density which is (6):

$$\bar{\rho}_c = \rho_\ell - [ (\rho_\ell - \rho_g) \frac{\ln (I_{meas}/I_\ell)}{\ln (I_g / I_\ell)} ]$$

where:

$\bar{\rho}_c$ = chordal average density

$\rho_\ell$ = pipe full water density

$\rho_g$ = pipe empty air density

$I_{meas}$ = measured count rate at any chordal average fluid density

$I_\ell$ = measured count rate with the pipe full of water

$I_g$ = measured count rate with the pipe empty.

## FRONT-END ELECTRONICS

The portion of this system designated as "front-end electronics" includes a gamma-ray proportional detection device, signal conditioning circuits, gamma-ray energy region-of-interest selection circuits, pulse pile-up rejection circuits and live time measuring circuits. These components provide reliable and predictable system performance for detected gamma-ray counting rates ranging from *$10^3$ to 1.2 x $10^6$ count per second (cps). The input to this front* end is gamma radiation. The outputs are region-of-interest pulses, whose pulse amplitudes are proportional to the individual gamma-*ray energies absorbed in the detector, accompanied by appropriate* live time information to allow data *corrections, accounting for* amplifier as well as analog to digital converter (ADC) dead time, and pile-up effects.

Commercially purchased front-end components include an Ortec Model M400N powered Nim Bin, an Ortec Model 456 high-voltage supply, an EMR-541N-01-14 photomultiplier tube and a Bicron 1 x 1 NaI crystal. Components developed by EG&G Idaho, Inc., include a miniaturized preamplifier and count-rate dependent gain stabilization circuitry, a negative restorer with isolated outputs, an invert-delay-linear gate module, and a single-channel analyzer (SCA) with pile-up rejection and live time measuring circuitry.

The system preamplifier-amplifier is a fast current mode amplifier providing 0.2-V/μA current-voltage conversion gain and is housed with the photomultiplier-scintillator inside the tungsten shield. Gas stability versus temperature is 100 ppm/K. Slew rate capability is 100 V/μ second. The output is series 100 Ω terminated. Under operating conditions, the average voltage offset at the preamplifier output is -0.5 V at $10^6$ cps of Cobalt-60. Thus, the calculated average anode current at $10^6$ cps, Cobalt-60, is 2.5 μA.

The count rate gain compensation circuit senses the average voltage offset at the preamplifier output with appropriate time constants and applies a correction voltage to the photomultiplier dynode string at the ground potential end to make a first order rate dependent gain correction allowing less than ±1% gain shift due to rate over an operating range of <$10^5$ to >1.2 x $10^6$ cps. Count rate gain dependence has been found to have more than one time constant. Gain increases as count rate is increased. (The inverse is true of a count rate decrease, although the time *constants involved are somewhat different.)*

The negative restorer, a highly asymmetric restorer with six isolated outputs with each series terminating in 100 Ω, holds the system dc *baseline to less than 0.1% shift up to 90%* duty cycle.

The SCA performs several functions; the most important is to select a region-of-interest in the pulse height distribution from the *negative restorer and provide a gate signal to a linear gate*, allowing only those pulses whose amplitude falls within this region-of-interest to be presented to the analog to digital converter. Figure 2 is a simplified block diagram of the signal conditioning electrons *and shows how the SCA is adjusted to pass only the photopeak* counts through the linear gate. The unit contains a baseline discriminator (BLD), a lower level discriminator (LLD), an upper level discriminator (ULD), a peak detector, and associated emitter-coupled logic circuits to perform pulse pile-up rejection, system and amplifier live time measurements, and input rate measurement.

The peak detector is enabled as an input pulse exceeds the baseline discriminator level. At peak detection time, the conditions of the upper and lower discriminators are strobed into logic circuitry. If the pulse height is such that the LLD is exceeded and the ULD is not exceeded, a gate output is generated if no pile-up was detected and the system is not busy with a previous pulse.

To determine pile-up rejection, LLD and ULD information is strobed at peak detection time for the first peak detected in each baseline excursion. In Figure 3 at the first peak detection time, the proper LLD and ULD conditions were not set; therefore, no output gate was generated, and the four succeeding pulses cannot generate a gate output since BLD had not been reset. Pulse 6 generates a gate output if the rest of the system (ADC or delay discriminator) is not busy. Pulse 7 generated no gate because BLD did not reset between Pulses 6 and 7.

The invert-delay-linear gate module performs the functions indicated by its name. First, the ADC requires positive pulses, so the module accepts negative input pulses and provides positive output pulses. Since the SCA requires approximately 125 ns to determine if a pulse is in the region-of-interest, the module includes a 200-ns stable delay line to delay the input pulse train while the SCA makes its decision finally incorporating a fast linear gate so that an appropriate time slice of the incoming pulse train is presented to the ADC at the command of the SCA.

## DIGITAL PROCESSING AND DATA STORAGE

The digital processor serves the function of the traditional multichannel analyzer (MCA) in nuclear spectroscopy. The major difference between the two is that the digital processor is designed to count and store a discrete pulse throughput rate of up to $1.2 \times 10^6$ Hz. Count rate data that are stored in the memory of the digital system are reduced and converted ultimately to the reactor coolant fluid chordal average density data. Figure 4 shows major components, the front-end processor, the memory controller, the 64 x 8 bit memory, the unloading processor, the tape controller, and the 9 track digital magnetic tape.

The front-end processor accepts an 6 bit word address from the ADC, fetches the appropriate word from the addressed memory location, and then stores it back in the same memory location. The 6 bit word functions as the energy dependent channel number counter that gives the number of times a given 6 bit word received from the ADC is placed in memory.

The 64 x 8 bit memory serves as the counter portion of the densitometer and is identical in purpose to the individual channel counters of a MCA. The 6 bits give 64 possible channels or memory locations that are capable of counting 8 bit or 256 times (really 255 times as "zero" is not considered a count). Each channel is double buffered so that continuous counting or data accumulation can take place. While memory A is counting, memory B is unloading or writing its contents to the digital magnetic tape.

The unloading processor takes the number of counts in one of the 64 memory locations and transfers the data to the magnetic tape interface for data storage on the tape. The tape controller is the interface between the unloading processor and the tape drive.

The 9 track digital magnetic tape drive operates at a transport speed of 125 inches per second (ips) and at a packing density of 1600 bits per inch (bpi).

The memory controller will determine the total counting or data accumulation time at which the system will operate. Incremental sampling or counting time is 0.0125 second. The memory controller also starts and stops the counting process and "zeros" the memory locations.

The following is a summary of the specifications of the digital processor and data storage portion of the densitometer.

| | |
|---|---|
| * Incremental data accumulation time | 0.0125 second |
| * Memory locations per processor ADC | 64 (transmission)<br>512 (background) |
| * Maximum count per memory location | 255 ($2^8 - 1$) |
| * Number of densitometer channels | 16 (expandable to 20) |
| * Mass storage capability | $24 \times 10^6$ bytes |
| * Total data accumulation time | 300 seconds |
| * Tape drive | 125 ips<br>1600 bpi |
| * Computer | PDP 11/04<br>(32 K core memory) |

## DATA ANALYSIS

The data analysis includes three operations on the A, B, and C beam gamma ray spectra: dead time correction, background subtraction, and coincidence correction. The dead time correction and the coincidence correction are also applied to the D beam spectra.

The dead time correction is standard in most spectroscopy applications. The correction consists of multiplying the spectrum by a constant to account for the energy analyzer being "dead", or effectively turned off, during part of the data acquisition time.

The background subtraction is done to separate the desired cobalt radiation from the unwanted nuclear reactor background radiation. The spectrum tail, representing only background (not cobalt) radiation, is extrapolated into the cobalt peak region and subtracted from the total spectrum to obtain the cobalt spectrum. The shape of the extrapolated curve is determined from the D beam spectrum, which contains no cobalt contribution.

The background subtraction by itself would be simple in principle, but it must be done in conjunction with the coincidence correction. The coincidence correction is a spectrum shape correction which must be applied to each spectrum. The correction is necessary because the high count rates – as high as $10^6$ per second – make coincidence events relatively frequent. These are events in which two or more photons are absorbed (or partially absorbed) by a detector with a time separation so small that the detector output pulses overlap and appear to be a single pulse representing one higher energy photon. The general effect of these coincidence events is to decrease the low energy count rate and increase the high energy count rate. Figure 5 shows the predicted effect of coincidence events with a total count rate of $10^6$ per second. As can be seen in Figure 5, the main damaging result of these coincidence effects is that the background part of the observed (uncorrected) spectrum is much larger than it ought to be, which causes a significant error in the background subtraction. Thus, the coincidence correction must be done before the background subtraction.

The computer program that does the coincidence correction requires knowledge of the actual background level. (This is not an inherent property of the coincidence correction, but rather a property of the particular program used in this application because of its efficiency.) Therefore, the use of an iterative, successive approximation scheme is necessary to perform the background subtraction and the coincidence correction simultaneously.

The processing of each A, B, and C beam spectrum results in a single number representing the magnitude of the cobalt radiation contribution to that spectrum. The average density of the fluid in a beam is a linear function of the logarithm of the cobalt radiation magnitude in the corresponding spectrum. The two constants in the linear equation are obtained from two calibration measurements, usually a full pipe and an empty pipe measurement. The chordal average densities, or the fluid densities averaged along the radiation beam paths, are then extrapolated to obtain density profiles for the entire pipe cross section, using techniques described in other reports(7,8).

## CONCLUSIONS

The gamma densitometer used by LOFT allows two-phase density values to be determined from the measured gamma spectrum data. The densitometer is designed so that the measurement will have a 10-Hz frequency response and will accumulate data for 300 seconds. The density measurement accuracy is about ±5% of range. Fluid density data can be extracted from complex spectra data which include unwanted background data using energy or pulse amplitude discrimination techniques. The hardware and software required to operate the LOFT densitometer system has been designed to facilitate its set-up and running.

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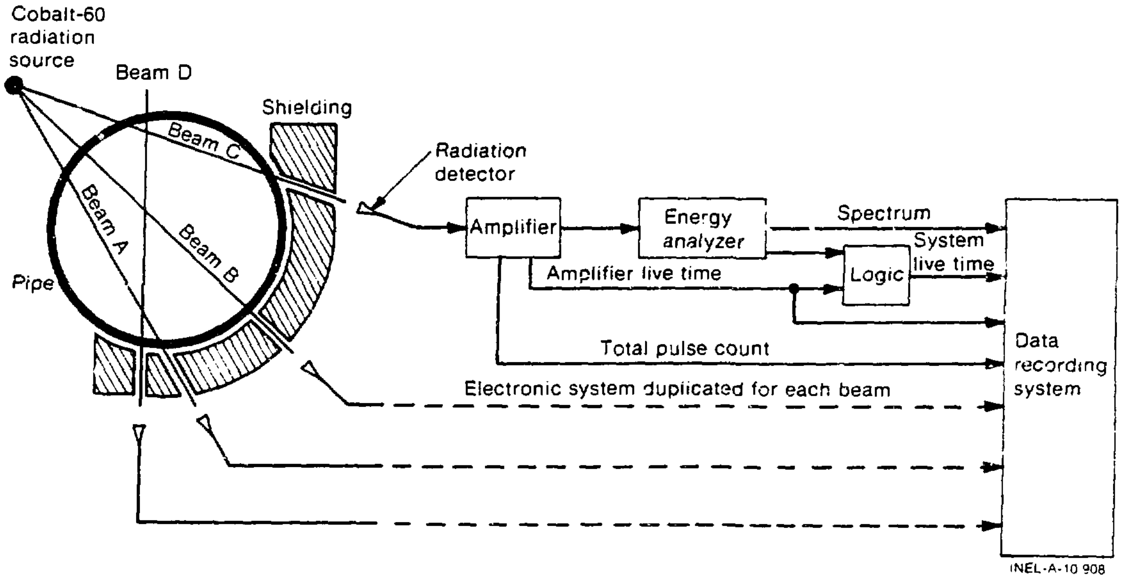
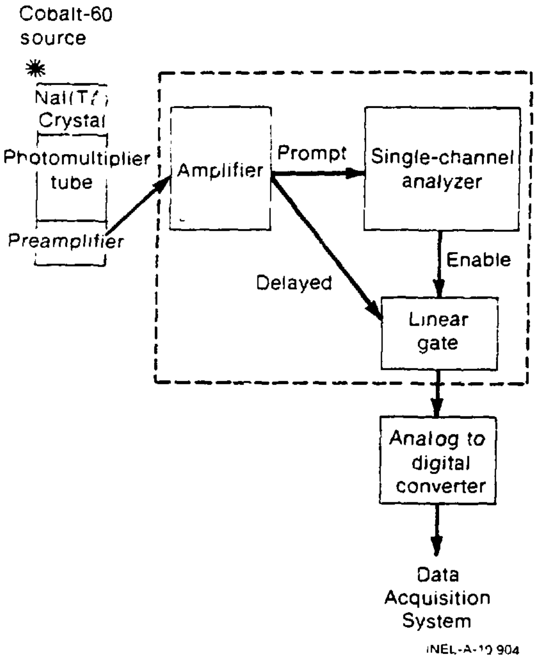
TABLE I

LOFT GAMMA DENSITOMETER
(Metal, Fluid, and Air Transmission Distances)

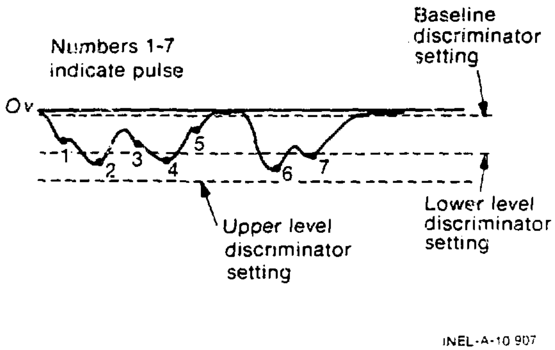
| Beam | $X_{pipe}$ (cm) | $X_{fluid}$ (cm) | $X_{air}$ (cm) | $R_{source\ to}$ detector (cm) |
|---|---|---|---|---|
| A | 8.024 | 24.455 | 25.352 | 60.371 |
| B | 7.142 | 28.418 | 23.279 | 61.379 |
| C | 9.955 | 17.971 | 29.878 | 57.785 |



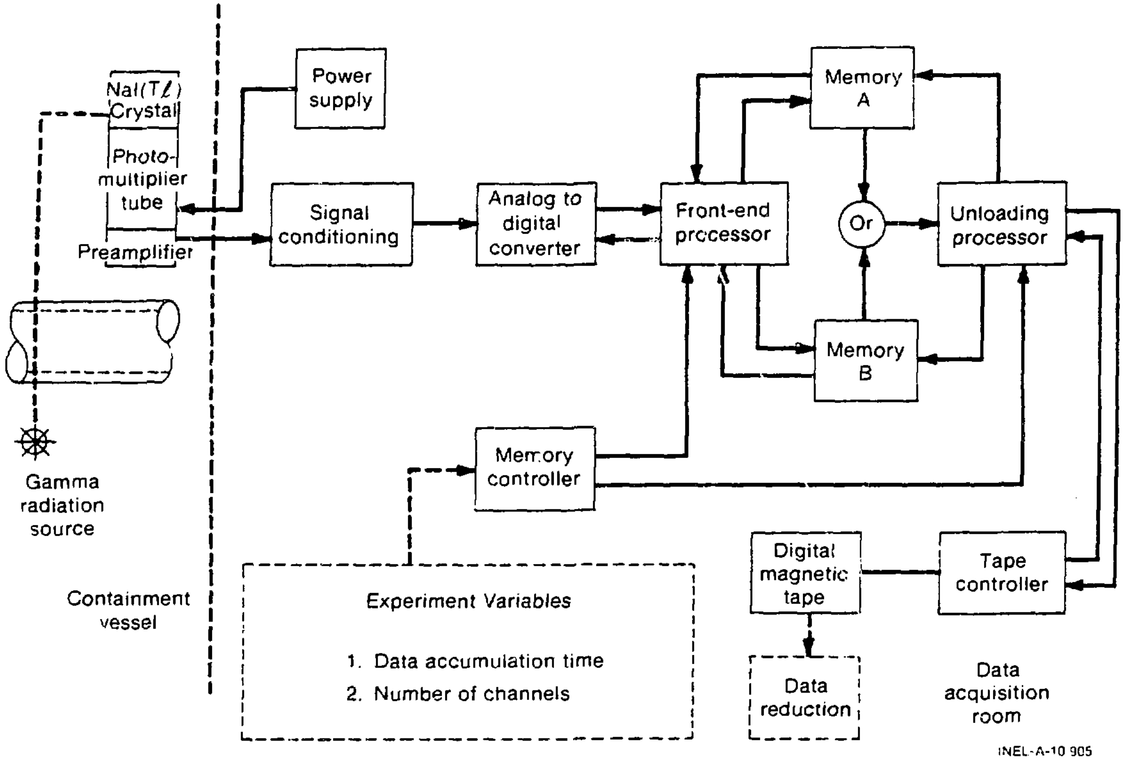
"*Figure 1 - Schematic diagram of LOFT nuclear-hardened densitometer system.*"



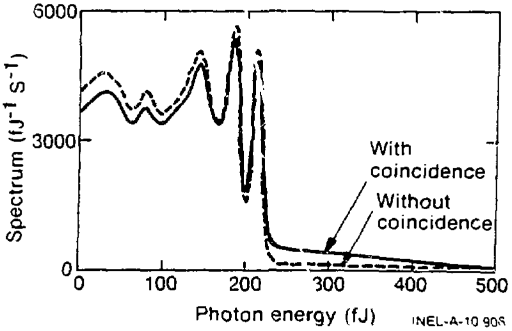
"Figure 2 - LOFT densitometer front-end electronics."



"Figure 3 - LOFT densitometer front-end electronics settings for pulse pile-up rejection."



"Figure 4 - Block diagram of LOFT nuclear-hardened densitometer instrumentation."



"Figure 5 - Coincidence effects."