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LOFT ADVANCED DENSITOMETER L1-4 TEST

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ABSTRACT

This report covers the PC-2, C-beam chordal average density measurement made on the loss-of-fluid test (LOFT) primary coolant system hot leg during the L1-4 nonnuclear loss-of-coolant accident (LOCA) test conducted May 3, 1977. The P-2, C-beam, or LOFT advanced densitometer, used was of the pulse height analysis/energy discrimination, or nuclear hardened type to be used for LOFT nuclear tests. The L1-4 test verified the applicability of pulse height analysis/energy discrimination techniques of the nuclear hardened gamma densitometer. Test results show that the reactor coolant fluid chordal average density can be calculated from gamma radiation source signal measured count rate data.

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SUMMARY

Feasibility testing of the pulse height analysis/energy discrimination advanced densitometer on the Loss-Of-Fluid Test (LOFT) L1-4 has been completed. This test included the set-up and checkout of the prototype digital processor modules as well as data collecting during the blowdown.

The advanced densitometer used for the PC-2, C-beam density measurement was of the nuclear hardened pulse height analysis/energy discrimination type currently being developed for the PC-1, -2, -3, BL-1 and BL-2 density measurements required for the LOFT nuclear tests. The nuclear hardened gamma densitometer makes possible the separation of the gamma radiation "source signal", from the reactor generated and nitrogen-16 (N-16) generated gamma radiation background "noise signal" by processing discrete pulses which retain their pulse amplitude information.

For the L1-4 test, a 256 channel spectrum was acquired every 0.1 s from a 30 Curie, Cesium-137 (Cs-137) source. Coolant fluid chordal average density versus time data was accumulated for 70 s. The measured coolant fluid chordal average density went from an average of approximately 0.77 g/cm^3 (48 lbs/ft^3) to approximately 0.03 g/cm^3 (2 lbs/ft^3) during the blowdown. The blowdown excursion lasted less than 1.0 s for the C-beam, which extends through the top section of the pipe.

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LOFT ADVANCED DENSITOMETER L1-4 TEST

1.0 INTRODUCTION

The purpose of using the pulse height analysis/energy discrimination densitometer on the Loss-Of-Fluid Test (LOFT) L1-4 was to demonstrate the feasibility of using this technique for a nuclear hardened densitometer to measure unwanted reactor-generated background radiation and N-16 emitted from the reactor coolant water required when LOFT goes from nonnuclear to nuclear operation^[1]. This report, in addition to the lab testing report^[2], documents the pulse height analysis/energy discrimination method feasibility testing that was done for the LOFT nuclear hardened gamma densitometer.

The primary function of LOFT is to provide test data to support: (a) assessment and improvement of the analytical methods utilized for predicting the behavior of pressurized water reactors (PWR) under LOCA conditions; (b) evaluation of the performance of PWR engineered safety features (ESF), particularly the emergency core cooling system (ECCS); and (c) assessment of the inherent safety margins in ESF performance. The objective of the nonnuclear LOFT experiments is to form an experimental baseline for the ECCS and the reactor plant operation. Because the experiments to date have been nonnuclear, core hydraulic resistance has been simulated by an orifice plate assembly. Thermal energy has been generated by canned rotor-type pumps. The amount of heat internal to the primary coolant system has been modulated by a heat exchanger.

2.0 DISCUSSION

The gamma densitometer measures both collided and uncollided gamma beam fluxes that traverse an attenuating medium. The log of the uncollided flux is proportional to the energy-dependent mass attenuation coefficient of the medium, the medium density, and the path length that the beam traverses in going through the medium. In the densitometer, the mass attenuation coefficient and beam path lengths remain constant, which leaves only the medium density as a variable. It is this relationship between the uncollided gamma beam flux and the density of the attenuating medium which forms the theoretical basis for the densitometer.

LOFT testing to date has been done with a nonnuclear core; hence, there was no reactor-generated background radiation or environment. This leaves the requirement of coolant fluid chordal average density to be measured in a "clean" radiation environment with the only gamma flux incident on the detector being due to the densitometer source. This clean environment eliminates the need of separating gamma source radiation "signal" from reactor generated and coolant water N-16 gamma radiation background noise. Loss-of-coolant accident (LOCA) testing scheduled in the future will be conducted with an operating nuclear core and the inherent reactor and N-16 background gamma radiation. This background must be separated from the uncollided, primary beam densitometer source flux in order to make an accurate chordal average density measurement. The nuclear hardened, pulse height analysis/energy discrimination densitometer provides discrete spectrum data from which the background subtraction can be made.

The pulse height analysis densitometer testing that has been completed includes laboratory tests with test section of LOFT primary coolant pipe, 36.56 cm (14.00 in.) outside diameter (OD); 28.28 cm (11.19 in.) inside diameter (ID); SMLS SST GR 316, SCH 160; and a 44 Curie, Cs-137 source, and in-situ testing during an actual LOFT non-nuclear LOCA test with the same size pipe and a 30 Curie, Cs-137 source.

Definition of the LOFT reactor primary coolant fluid mass flow characteristics during a simulated pipe rupture accident and subsequent coolant loss is necessary to determine the effectiveness of the ECCS and its ability to extract heat from the reactor core. One of the parameters required to define the coolant fluid average cross sectional density is chordal average density. The purpose of the densitometer is to provide a chordal average density measurement which can be folded into a cross sectional coolant fluid, flow regime determination, and to define a subsequent cross sectional average density.

The chordal average density measurement of metal and coolant fluid path lengths were 9.99 cm (3.93 in.) and 17.94 cm (7.06 in.) respectively. These path lengths were the same for both the lab tests and the primary coolant hot leg densitometer test at LOFT. (See Figures 1 and 2 for a comparison of the LOFT and lab test densitometer beam path geometries.) A 2 x 2 sodium iodide, thallium activated (NaI(Tl)), scintillation crystal coupled to an RCA 6342A photomultiplier tube was used for the gamma flux detector. With this geometry and detector combination, uncollided CS-137 gamma beam flux count rates of 6237 counts/s (pipe empty) and 1256 counts/s (pipe full) were measured. These count rates correspond to coolant fluid densities of 0.001205 g/cm^3 (0.0752 lbs./ft^3) air, to 1.0 g/cm^3 (62.43 lbs./ft^3) water. Using these data points as the calibration of the density measuring system, intermediate stratified water heights in the coolant pipe test section were measured by the count rate technique and compared to measured water height values throughout the 0.00 to 17.94 cm (0.00 to 7.06 in.) pipe ID range.

At LOFT, data accumulation was done in 0.1 s increments which provided a 1 Hz frequency response to the measurement. The photopeak window was set at full width, tenth maximum (FWTM) plus and minus 20 channels, so that only the uncollided CS-137 counts were processed. A 30-Curie source was mounted with the detector on the primary coolant hot leg pipe. All water, all air and intermediate water level chordal average path length densities were measured. The count rate data was then converted into chordal average coolant water densities. The dif-

Fig. 1 LOFT advanced densitometer primary coolant piping beam path geometry.

Fig. 2 LOFT advanced densitometer primary coolant piping lab test, beam path geometry.

ference in the value between measured and theoretical densities ranged from 1.7 to 6.4% of range.

Figure 3 is an example of a Cs-137 spectrum and illustrates the method used for determining fluid density information from the energy spectrum. The fluid density is determined from the photopeak window count rate, the pipe full and empty count rates, and the logarithmic relationship between count rates. The coolant fluid chordal average density is therefore given by:

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

where

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

ρ_ℓ = pipe full water density

ρ_g = pipe empty air density

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

I_ℓ = measured count rate with the pipe full of water

I_g = measured count rate with the pipe empty

A block diagram of the densitometer instrumentation is shown in Figure 4. Operation of the densitometer electronics involved setting a FWTM, plus and minus 20 channel window around the gamma beam source photopeak, see Figure 5, and then counting the pulses that were transmitted in this energy band.

Figure 6 is a plot of the primary coolant fluid chordal average density data versus time as acquired by the densitometer system. As indicated, the coolant fluid chordal average density went from an average of 0.77 g/cm^3 (48 lbs/ft^3) to 0.03 g/cm^3 (2 lbs/ft^3) during the experiment. The major part of the blowdown excursion took less than 1.0 s, while the entire excursion from initiation of the quickly opening

Fig. 3 Background subtraction.

Fig. 4 LOFT nuclear hardened densitometer instrumentation block diagram.

Fig. 5. LOFT nuclear hardened densitometer photopeak window, FWTM $\pm$ 20 channels.

Fig. 6 LOFT advanced densitometer L1-4 LOCA test data primary coolant.

blowdown valves to depressurization of the reactor vessel to 0.4 MPa (60 psia) took approximately 2.5 min.

The nonnuclear LOFT and lab testing has shown that the time dependent, coolant water chordal average density could be determined from the densitometer source uncollided, primary beam count rate; and that this count rate could be determined from the photopeak counts, as measured by the pulse height or energy discrimination densitometer. This method, plus the background radiation subtraction technique will allow the reactor coolant chordal average density to be measured in a nuclear background environment.

3.0 COLLIMATOR DESIGN

3.1 Calculations of Collimator Parameters For PC-2, C-Beam Densitometer

As collimator design is to a certain extent an art rather than a science, the correct criterion for selecting a collimator diameter is largely personal preference based on experiment requirements^[3]. For the L1-4 test, measuring the highest possible gamma source count rate was a primary concern. Hence, the largest diameter collimeter meeting the following design parameters was accepted.

- (1) Length to diameter ratio ($\ell/d > 10$ or $\cos \theta \simeq 1$).

$$\frac{\ell}{d} = \frac{2.4675}{0.25} = 9.87$$

- (2) Mean free path length ($\ell > 10\lambda$)

for tungsten at 0.662 MeV

$$\lambda = \frac{1}{\mu} = 0.507 \text{ cm}$$

for lead at 0.662 MeV

$$\lambda = \frac{1}{\mu} = 0.812 \text{ cm.}$$

Then, for the total collimator length

for tungsten

$$\frac{\ell}{\lambda} = \frac{4.128}{0.507} = 8.142$$

for lead

$$\frac{\ell}{\lambda} = \frac{2.140}{0.812} = 2.635$$

or

$$\frac{\rho}{\lambda} (\text{total}) = 10.776$$

- (3) Pipe ID to collimator diameter ($d_{\text{pipe}}/d_{\text{coll}} > 10$)

$$\frac{d_{\text{pipe}}}{d_{\text{coll}}} = \frac{11.19}{0.25} = 44.76$$

- (4) Collimator diameter versus mean free path length ($d < \lambda$).

$$d = 0.25 \text{ in. (2.54)} = 0.635 \text{ cm}$$

for tungsten

$$0.635 > 0.507$$

for lead

$$0.635 < 0.812$$

- (5) Detector size to collimator size ($d_{\text{xtal}} \geq 2d_{\text{coll}}$).

$$d_{\text{xtal}} = 2.0 \text{ in.}$$

$$d_{\text{coll}} = 0.25 \text{ in.}$$

$$2.0 > 0.5$$

- (6) Source to collimator midpoint distance versus collimator diameter ($R/d_{\text{coll}} \geq 100$).

$$\frac{R}{d_{\text{coll}}} = \frac{20.234}{0.25} = 80.94$$

3.2 Calculation of Maximum and Minimum Radiation Count Rates

$$I = \frac{\epsilon \gamma S A_D}{4\pi R^2} e^{-n}$$

where

I = transmitted flux count rate

ϵ = detection efficiency; probability of a photon emitted by the source and incident on the detector giving a pulse recorded in the photopeak

γ = percentage of total disintegration that is gamma radiation of energy interest

A_D = exposed surface area of the detector (unshielded area)

S = total number of disintegrations per second due to the source ($S = \text{no. of Curies} \times 3.7 \times 10^{10}$)

R = source to detector distance

e^{-n} = attenuation coefficient.

(1) Maximum Count Rate^[4,5]

$$I = \frac{(0.25)(0.93)(30 \times 3.7 \times 10^{10})(1.267)}{4\pi(57.785)^2} e^{-n_{\text{empty}}}$$

$$e^{-n_{\text{empty}}} = e^{-\left\{ \left[\left(\frac{\mu}{\rho} \right) (\rho) (x) \right]_{\text{metal}} + \left[\left(\frac{\mu}{\rho} \right) (\rho) (x) \right]_{\text{fluid}} + \left[\left(\frac{\mu}{\rho} \right) (\rho) (x) \right]_{\text{air}} \right\}}$$

where

$\frac{\mu}{\rho}$ = mass attenuation coefficient

ρ = absorber density

x = absorber thickness

hence

$$\begin{aligned}
 e^{-n_{\text{empty}}} &= e^{- (0.0729)(7.83)(9.955)} \\
 &\quad + (0.0773)(0.001205)(17.971) \\
 &\quad + (0.0773)(0.001205)(29.859) \\
 &= e^{- (5.682) + (0.002) + (0.003)} \\
 &= e^{- 5.687} \\
 &= 0.00339
 \end{aligned}$$

then

$$\begin{aligned}
 I_{\text{max}} &= (7.793 \times 10^6)(0.00339) \\
 I_{\text{max}} &= 26417 \text{ counts/s}
 \end{aligned}$$

(2) Minimum Count Rate

$$I = (7.793 \times 10^6) e^{-n_{\text{full}}}$$

where

$$\begin{aligned}
 e^{-n_{\text{full}}} &= e^{- n_{\text{metal}} + \left[\left(\frac{\mu}{\rho} \right) (\rho) (x) \right]_{\text{fluid}} + n_{\text{air}}} \\
 &= e^{- \left\{ [5.682] + \left[(0.0773)(0.75)(17.971) \right] + [0.003] \right\}} \\
 &= e^{- 6.727} \\
 &= 0.00120
 \end{aligned}$$

then

$$\begin{aligned}
 I_{\text{min}} &= (7.793 \times 10^6)(0.00120) \\
 I_{\text{min}} &= 9338 \text{ counts/s}
 \end{aligned}$$

4.0 L1-4 TEST DESIGN

The L1-4 test was conducted to determine the feasibility of using pulse height analysis/energy discrimination techniques for the LOFT nuclear hardened gamma densitometer. An in-house digital processor was developed that could acquire pulse height analysis (PHA) data, and hence photopeak count rate data, for a given counting interval. Details of the operation of the digital processor are given in Appendix C. For the L1-4 test, the counting time interval used was 0.1 s, and was determined by the maximum rate that data could be punched on paper tape in the reference counting system. A block diagram of the experimental digital processing and reference photopeak window counting system is given in Appendix D.

Essentially the two systems were seen in parallel to provide a comparison of the photopeak count rate as a function of the PC-2, hot-leg coolant water density. Data were recorded prior to, during, and immediately after blowdown, so that the chordal average density measurement for the PC-2, C-beam could be determined in the time region of interest. Results of the data are given in Section III.

The following is a list of equipment used in the L1-4 test:

Detector: Bicron 2M2 (2 x 2 in. NaI(Tl) crystal)
Preamplifier: Ortec, Model 276
Power supply: Ortec, Model 456
Pulser: Berkeley Nucleonics, DB2
Amplifier: Ortec, Model 460
Single channel analyzer (SCA): Ortec, Model 455
Frequency to SC converter: Ortec Model 449
Multichannel analyzer (MCA): Tracor Northern, Model 1700
Paper tape punch: Remex 1200

Teletype: RS 242

Analog to digital converter (ADC): Tennelec, Model TC 500

Digital processor: EG&G, Model DEL-1

5.0 TEST RESULTS AND DATA ANALYSIS

PC-2, C-beam densitometer data taken with an accumulation, or counting time, of 0.1 s was acquired on both the experimental digital processor system and a conventional multichannel scaling (MCS) system. Figure 7 is a plot of the blowdown data taken with the experimental digital processor, and Figure 8 is a plot of the same blowdown data taken with the MCS system.

Data indicates that the coolant water density was approximately 0.77 g/cm^3 (48 lb/ft^3) initially and decreased to approximately 0.08 g/cm^3 (5 lb/ft^3) immediately after the blowdown. This excursion occurred in less than 1.0 s. An excursion of this magnitude and short duration was expected from the C-beam which traverses the upper two quadrants of the pipe.

Figure 9 is an expansion of the blowdown data for a short duration of the major excursion. Of particular interest is the fact that there are only 5 data points during the excursion. These data points represent counting times of 0.1 s, or a frequency response of 1.25 Hz, which is not enough to describe any oscillations that might have taken place during the blowdown. The time scales on all the curves plotted have an arbitrary starting time ($t = 0$), because there was no time synchronization between the two data acquisition modes for the L1-4 test. Figure 10 is a spectral plot of the Cs-137 photopeak and the corresponding voltage and energy scale calibrations. As can be seen, the 256-point spectrum was more than adequate for good photopeak resolution.

Fig. 7 L1-4, C-beam, MCS, blowdown data.

Fig. 8 L1-4, C-beam, PHA, blowdown data.

Fig. 9 LOFT advanced densitometer data L1-4, blowdown test, PC-2, C-beam; MCS output.

Fig. 10 Densitometer spectrum calibration.

6.0 CONCLUSIONS AND RECOMMENDATIONS

Results of the PC-2, C-beam densitometer data showed that the pulse height analysis/energy discrimination techniques could be applied to the LOFT nuclear hardened gamma densitometer. However, the data also indicated that the counting accumulation time would have to be much less than 0.1 s in order to have an acceptable response to the blowdown phenomenon. The data for L1-4 was the C-beam measurement, which requires the highest response, but probably a 1.25 Hz response would not be enough for the A- or B-beam measurements either.

In conjunction with a decrease in data accumulation time, there would have to be a corresponding increase in the count rate in order to have an acceptable number of counts in a data sample for good statistics.

Continuously acquiring data by implementing two memory modules in the processor will ensure that data will be recorded continuously, rather than in a sampling sequence to obtain the required frequency response.

7.0 REFERENCES

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APPENDIX A.

DERIVATION OF THE MEASURED CHORDAL AVERAGE DENSITY EQUATION

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DERIVATION OF THE MEASURED CHORDAL AVERAGE DENSITY EQUATION^[A-1]

The following is a derivation of the mathematical expression used to calculate a chordal average density of the primary system coolant fluid at the Loss-of-Fluid Test (LOFT) Facility. Assumptions implicit in this derivation are:

- (1) Mono energetic gamma source
- (2) Gamma radiation emission follows Poisson statistics (decay probability time independent)
- (3) Well-collimated gamma radiation beam ("good" geometry, no scattering, point source, only uncollimated primary photons contribute to the measured transmitted flux)
- (4) Homogeneous attenuating medium (interaction probability independent of penetration depth)
- (5) Mass attenuation coefficient constant with material and independent of the steam/water phase (microscopic cross section is a property of the atom)

$$\frac{\mu}{\rho} = \frac{N_o \sigma_c}{A}$$

where

μ = attenuation coefficient

ρ = attenuating medium density

N_o = Avogadro's number

A = atomic weight

σ_c = atomic cross section (interaction probability,
function of photon energy)

(6) Symmetric pipe and consistent wall thickness

(7) Gamma beam perpendicular to attenuating medium layers
(no streaming)

where the subscripts

l refers to the liquid or water phase

g refers to the gas or steam phase .

The exponential radiation attenuation equation is

$$I = I_0 e^{-n} \quad (1)$$

where

I = beam intensity after transmission through the medium

I_0 = intensity of the γ -ray beam incident on the attenuating medium

n = attenuation coefficient

$$\left[n = \sum \left(\frac{\mu}{\rho} \right)_i (\rho)_i (x)_i \right]$$

Since the γ -ray beam transmission is really through three media: metal (pipe walls), fluid, and air; the exponential attenuation coefficient is really

$$n = \left(\frac{\mu}{\rho} \right)_m (\rho)_m (x)_m + \left(\frac{\mu}{\rho} \right)_f (\rho)_f (x)_f + \left(\frac{\mu}{\rho} \right)_a (\rho)_a (x)_a \quad (2)$$

But the attenuation due to the transmission through air is much less than the attenuation due to the transmission through the pipe walls and the coolant fluid, at high energy so it can be neglected. The attenuation coefficient for density measurement purposes then becomes

$$n \cong \left(\frac{\mu}{\rho} \right)_m (\rho)_m (x)_m + \left(\frac{\mu}{\rho} \right)_f (\rho)_f (x)_f \quad (3)$$

For the all gas or steam condition define, $I = I_g$ so that

$$I_g = I_0 e^{-n_g} \quad (4)$$

where

$$n_g = \left(\frac{\mu}{\rho}\right)_m (\rho)_m (x)_m + \left(\frac{\mu}{\rho}\right)_g (\rho)_g (x)_g \quad (5)$$

The attenuation due to transmission through the gas or steam medium is a chordal (beam path) average density measurement such that the term

$$\left(\frac{\mu}{\rho}\right)_g (\rho)_g (x)_g$$

should really be written as

$$\left(\frac{\mu}{\rho}\right)_g \int_0^L \rho_g dl$$

Then the attenuation coefficient becomes

$$n_g = \left(\frac{\mu}{\rho}\right)_m (\rho)_m (x)_m + \left(\frac{\mu}{\rho}\right)_g \int_0^L \rho_g dl \quad (6)$$

Using an identical analogy for the water or liquid phase part of the measurement

$$n_l = \left(\frac{\mu}{\rho}\right)_m (\rho)_m (x)_m + \left(\frac{\mu}{\rho}\right)_l \int_0^L \rho_l dl \quad (7)$$

Dividing the intensity of the transmitted flux measured when the coolant fluid is in the steam or gas phase by the intensity of the transmitted flux for the water or liquid phase measurement

$$\frac{I_g}{I_l} = \frac{I_o e^{-n_g}}{I_o e^{-n_l}} = e^{n_l - n_g} \quad (8)$$

for the unknown coolant density condition where the attenuation coefficient is represented by n , such that

$$I = I_0 e^{-n}$$

And dividing the two-phase intensity by the liquid phase attenuated intensity,

$$\frac{I}{I_l} = \frac{I_0 e^{-n}}{I_l e^{-n_l}} = e^{n_l - n} \quad (9)$$

To define an unknown intermediate coolant density in terms of the known steam and water attenuated intensities, take the natural log of both Equations (8) and (9), and then divide Equation (9) by Equation (8) so that

$$\frac{\ln(I/I_l)}{\ln(I_g/I_l)} = \frac{\ln \left[e^{(n_l - n)} \right]}{\ln \left[e^{(n_l - n_g)} \right]} \quad (10)$$

or

$$\frac{\ln(I/I_l)}{\ln(I_g/I_l)} = \frac{n_l - n}{n_l - n_g} \quad (11)$$

$$\frac{\ln(I/I_l)}{\ln(I_g/I_l)} = \frac{\left[\left(\frac{\mu}{\rho} \right)_m (\rho)_m (x)_m + \left(\frac{\mu}{\rho} \right)_0 \int_0^L \rho_l dl \right] - \left[\left(\frac{\mu}{\rho} \right)_m (\rho)_m (x)_m + \left(\frac{\mu}{\rho} \right)_l \int_0^x \rho_l dl + \left(\frac{\mu}{\rho} \right)_g \int_x^L \rho_g dl \right]}{\left[\left(\frac{\mu}{\rho} \right)_m (\rho)_m (x)_m + \left(\frac{\mu}{\rho} \right)_l \int_0^L \rho_l dl \right] - \left[\left(\frac{\mu}{\rho} \right)_m (\rho)_m (x)_m + \left(\frac{\mu}{\rho} \right)_g \int_0^L \rho_g dl \right]} \quad (12)$$

The attenuation factors due to the metal (pipe wall) path length cancel leaving

$$\frac{\ln(I/I_g)}{\ln(I_g/I_1)} = \frac{\left(\frac{\mu}{\rho}\right)_1 \int_0^L \rho_1 dl - \left(\frac{\mu}{\rho}\right)_1 \int_0^x \rho_1 dl - \left(\frac{\mu}{\rho}\right)_g \int_x^L \rho_g dl}{\left(\frac{\mu}{\rho}\right)_1 \int_0^L \rho_1 dl - \left(\frac{\mu}{\rho}\right)_g \int_0^L \rho_g dl} \quad (13)$$

but

$$\left(\frac{\mu}{\rho}\right)_1 = \left(\frac{\mu}{\rho}\right)_g = \frac{\mu}{\rho}$$

because the mass attenuation coefficient, for a Compton scattering process, is a constant with material and independent of phase.

Then

$$\begin{aligned} \frac{\ln(I/I_g)}{\ln(I_g/I_1)} &= \frac{\frac{\mu}{\rho} \left[\int_0^L \rho_1 dl - \int_0^x \rho_1 dl - \int_x^L \rho_g dl \right]}{\frac{\mu}{\rho} \left[\int_0^L \rho_1 dl - \int_0^L \rho_g dl \right]} \\ &= \frac{\left[\int_0^L \rho_1 dl - \int_0^x \rho_1 dl - \int_x^L \rho_g dl \right]}{\int_0^L \rho_1 dl - \int_0^L \rho_g dl} \quad (14) \end{aligned}$$

where

$$\int_0^x \rho_1 dl + \int_x^L \rho_g dl$$

is the sum of the water and steam components along the beam path, which is a chord traversing the pipe. Defining the chordal average density as $\bar{\rho}_c$ then

$$\int_0^L \bar{\rho}_c \, dl = \int_0^x \rho_l \, dl + \int_x^L \rho_g \, dl \quad (15)$$

$$\frac{\ln(I/I_1)}{\ln(I_g/I_1)} = \frac{\int_0^L \rho_l \, dl - \int_0^L \bar{\rho}_c \, dl}{\int_0^L \rho_l \, dl - \int_0^L \rho_g \, dl} \quad (16)$$

Since the integral of $\int_0^L dl$ is just L , Equation (17) becomes

$$\frac{\ln(I/I_1)}{\ln(I_g/I_1)} = \frac{(\rho_l - \bar{\rho}_c)L}{(\rho_l - \rho_g)L} = \frac{\rho_l - \bar{\rho}_c}{\rho_l - \rho_g} \quad (17)$$

Finally, solving for the experimental chordal average density as a function of the chordal average measured count rate I , and the liquid (water) and steam (air) count rates

$$\begin{aligned} \frac{\ln(I/I_1)}{\ln(I_g/I_1)} &= \frac{\rho_l - \bar{\rho}_c}{\rho_l - \rho_g} \\ \rho_l - \bar{\rho}_c &= (\rho_l - \rho_g) \frac{\ln(I/I_1)}{\ln(I_g/I_1)} \\ \bar{\rho}_c &= \left[\rho_l - (\rho_l - \rho_g) \frac{\ln(I/I_1)}{\ln(I_g/I_1)} \right] \quad (18) \end{aligned}$$

Equation (18) is the desired result since all the terms on the right hand side of the equation are either definable or can be measured during densitometer calibration. Specifically, I_1 is the measured count rate when the density of the attenuating medium is ρ_l , and I_g is the measured count rate when the density of the attenuating medium is ρ_g . For the LOFT densitometer calibration, these are all water and all air conditions respectively. (The assumption has been made that $(\mu \div \rho)_{\text{steam}} \approx (\mu \div \rho)_{\text{air}}$ at 0.662, 1.17 and 1.33 MeV.)

REFERENCES

- A-1 Y. Y. Hsu and R. W. Graham, Transport Processes in Boiling and Two-Phase Systems, Washington, D. C.: Hemisphere, 1976.

APPENDIX B

BEAM INTENSITY VARIATION

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BEAM INTENSITY VARIATION

The geometrical factors that enter into the A- B- and C-beam chordal average density measurements are shown in Figure B-1. The metal and fluid path lengths for each of the three beams is calculated from the following relationships^[B-1]:

$$X_f = D_i^2 - (D_o + D_s)^2 \sin^2 \theta^{1/2}$$

$$X_m = D_i^2 - (D_o + D_s)^2 \sin^2 \theta^{1/2} - X_f$$

where

- X_f = fluid path length
- X_m = pipe or metal path length
- D_i = inside diameter of pipe
- D_o = outside diameter of pipe
- D_s = twice the source to pipe wall distance
- θ = beam angle.

For the LOFT piping and densitometer application:

$$D_i = 28.418 \text{ cm (11.188 in.)}$$

$$D_o = 35.56 \text{ cm (14.0 in.)}$$

$$D_s = 22.86 \text{ cm (9.0 in.)}$$

Thus, for A-Beam

$$\theta_A = 14.35^\circ (14^\circ 21')$$

$$\sin \theta_A = 0.2478$$

$$\sin^2 \theta_A = 0.0614$$

$$X_f = [807.583 - (35.56 + 22.86)^2 0.0614]^{1/2}$$

$$X_m = 8.024 \text{ cm (3.159 in.)}$$

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Fig. B-1 LOFT densitometer beam geometries.

B-Beam

$$\theta_B = 0^\circ$$

$$X_f = 28.418 \text{ cm (11.188 in.)}$$

$$X_m = 7.142 \text{ cm (2.812 in.)}$$

C-Beam

$$\theta_C = 22.117^\circ (22^\circ 7')$$

$$X_f = 17.971 \text{ cm (7.075 in.)}$$

$$X_m = 9.995 \text{ cm (3.912 in.)}$$

See Table B-I for a summary.

TABLE B-I
GEOMETRICAL FACTORS

<u>Densitometer Beam</u>	<u>θ</u>	<u>X_m</u>	<u>X_f</u>
A	14.35°	8.024 cm (3.159 in.)	24.455 cm (9.628 in.)
B	0°	7.142 cm (2.812 in.)	28.418 cm (11.188 in.)
C	22.117°	9.955 cm (3.912 in.)	17.971 cm (7.075 in.)

REFERENCES

- B-1 A. G. Stephens, Determination of Flow Regime Characteristics of Photo Attenuation, doctoral thesis for Pennsylvania State University (1975).

APPENDIX C

LOFT DENSITOMETER DIGITAL DATA ACQUISITION SYSTEM FOR L1-4

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LOFT DENSITOMETER DIGITAL DATA ACQUISITION SYSTEM FOR L1-4

FUNCTIONAL:

The Digital Data Acquisition System (DDA) (Figure C-1) will take a 10 or 12 bit digital word from a Tennelec No. 500 analog to digital converter (ADC) and map it to an appropriate 8-bit word. Using this 8-bit word as an (Figure C-2) address, it will fetch a 12-bit word from the addressed memory location, increment it by one (1) and store it back in the same memory location. This 12-bit word is a counter that will count the number of times a given 8-bit address is mapped from the word received from the ADC. The maximum count for a given address is 4095. The time during which counting takes place (data accumulation time) may be varied from 10 ms to 990 ms in 10 ms intervals.

There are 256, 12-bit words for each ADC. There may be from 1 to 15 ADC channels. At the end of the data accumulation time the 256, 8-bit words from each of the channels will be written on digital magnetic tape. The format will be the least significant 8 bits of word 1, the most significant 4 bits of word 1 concatenated with the least significant 4 bits of word 2, the most significant 8 bits of word 2, and so on. Each channel is double buffered, i.e., Memory A is counting during data accumulation time while Memory B is writing its contents to tape. During the next data accumulation time, Memory B is counting while Memory A is writing to tape. (See Figure C-3.)

Each double buffer memory is 100% redundant as is the unloading processor and the tape unit (Figure C-4 and -5). The redundancy in the front-end processors and ADCs lies in the fact that there can be up to 15 of them. There will be three separate power supplies for the total system.

The tape drive will have the option of writing with a density of 800 bits per inch (BPI) or 1600 BPI. It will be capable of running at 75 inches per second (IPS) or 125 IPS. The internal compatibility of

The 3 bins are standard CAMAC 25 slot bins. Each bin has a separate power supply.

There are 6 card types:

Control board	(CB)
Memory board	(MB)
Sync clock	(SC)
Reg control	(RC)
State machine	(SM)
Dump sequence	(DS)

Physical layout L1-4

The above configuration will be used for L1-4 along with one (1) power supply and one (1) tape unit.

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Fig. C-1 Densitometer digital data acquisition system physical layout.

Fig. C-2 Densitometer digital data acquisition system.

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Fig. C-3 Densitometer high speed processor.

Fig. C-4 Densitometer front end processor.

INEL-A-7442

Fig. C-5 Densitometer unloading processor.

the DDA will be determined by the appropriate selection of the number of channels, data accumulation time, and tape speed and density. The selection of these parameters will also determine the effective total data capacity and total data acquisition time.

The DDA will have three states: stop, run and reset (see state diagrams). The stop state is the quiescent state (Figures C-6 through C-11). The DDA enters the run state only from the stop state and only on the start command either from LOFT or local push button. The DDA enters the reset state from either the run or stop state only on command from the local reset push button. After a reset has been initiated, the DDA will complete the reset sequence and return to the stop state. No external signal can interrupt the reset sequence. The DDA enters the stop state at the end of a reset sequence. It also enters the stop state from the run state upon command from the local stop button or at the end of the magnetic tape.

A form of digital filtering or digital discrimination can be performed by using one of the 256 memory locations as a trap location. Any of the 2^{10} or 2^{12} input words from the ADC can be mapped by the address translator to the trap location. This could count the number of traps up to 4096. In any case, the count of this location will be stored on tape but may be ignored during data reduction. If the number of traps is greater than 4096, the counter counts around in modulo 4096. In fact all the memory locations are modulo 4096 counters.

INTERFACE: ADC

The Digital Data Acquisition System (DDA) must interface with the Tennelec No. 500 analog to digital converter. The maximum input rate to DDA from the ADC is one per 3.0 μ s. The maximum ADC busy time due to DDA (time from data ready to not busy) is 1.0 μ s. This implies that the ADC may start processing the next pulse while the DDA completes counting the present one.

$\wedge$ = Logical and
V = Logical or

Fig. C-6 Densitometer state diagram.

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Fig. C-7 Densitometer control sequence.

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Fig. C-8 Densitometer system go.

Fig. C-9 Densitometer system reset.

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Fig. C-10 Densitometer system stop.

Fig. C-11 Densitometer dump sequence.

Due to double buffering the maximum rate can be sustained throughout the test by the DDA. Actual data input rate is a function of the input to the ADC and the time it requires to digitize.

INTERFACE: LOFT

Two signals will be sent from LOFT to the DDA.

- (1) A start signal which will start the DDA taking data.
- (2) An Inter-Range Instrumentation Group (IRIG) Clock pulse with a period of 1 ms and a pulse width of 1 μ s.

The DDA will send a start acknowledge signal to LOFT to indicate that it has started taking data.

DENSITOMETER DIGITAL DATA ACQUISITION SYSTEM DESIGN
PARAMETERS SUMMARY

<u>Parameter</u>	<u>Value</u>
ADC max input rate	333,333 pulses/s
Data accumulation time	10-990 ms by 10 ms
Address translation	10 to 8 bits or 12 to 8 bits
Memory locations per processor	256
Maximum count per memory location	4095
Number of channels	1 - 15
Mass storage requirement	1, 2400 ft-9 tract tape
Tape drive	75 or 125 IPS 800 or 1600 BPI

NOTE: Total data storage and data collection time are a function of

- (1) number of channels
- (2) data accumulation time
- (3) tape speed
- (4) tape density

Spares are as follows:

<u>P/N</u>	<u>QTY-L1-4</u>	<u>QTY Spares</u>
CB	3	1
MB	3	4[a]
SC	1	1
OS	1	1
RC	1	0[b]
SM	1	0[b]

[a] Three of the spares will be used for redundancy check out.

[b] For check out and L1-4 these cards will be wire-wrapped; there will be no spare.

DENSITOMETER DDA

SUMMARY OF EQUATIONS FOR CALCULATING TRANSFER RATES AND DATA ACCUMULATION TIMES

Required Transfer Rate

$$RR = \frac{384 (C + 1)}{DAT}$$

Where C = Number of Channels $1 \leq C \leq 15$

DAT = Data Accumulation Time $10 \text{ ms} \leq DAT \leq 990 \text{ ms}$ in increments of 10 ms.

Effective Transfer Rate

$$ER = \frac{(RL) (BPI) (IPS)}{RL + RG}$$

where

$$RL = \frac{C (384)}{BPI}$$

BPI = 800 or 1600

RG = 0.6

IPS = 75 or 125

Therefore

$$ER = \frac{C (384) (IPS) (BPI)}{C (384) + 0.6 (BPI)}, \text{ Bytes/s}$$

$$ER > RR$$

Data Accumulation Time

$$ER > RR$$

$$\frac{(384) (C) (IPS) (BPI)}{(384) (C) + (0.6) (BPI)} > \frac{384 (C + 1)}{DAT}$$

$$\text{DAT} > \frac{384C^2 + 384C + 0.6 (\text{BPI}) (C + 1)}{C (\text{IPS}) (\text{BPI})}, \text{ seconds}$$

Number of Records

$$\text{NR} = \frac{28800 (\text{BPI})}{384 (C) + 0.6 (\text{BPI})}$$

Storage Capacity

$$\text{CAP} = \frac{28800 (\text{BPI}) (384) (C)}{384 (C) + 0.6 (\text{BPI})}$$

Test Time

$$\text{TT} = \frac{28800 (\text{BPI}) (\text{DAT})}{23040 (C) + 35 (\text{BPI})}, \text{ minutes}$$

APPENDIX D

PC-2 "C BEAM" DENSITOMETER FOR L1-4 TESTS

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Fig. D-1 LOFT advanced densitometer L1-4 test instrumentation.

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APPENDIX E

INSTALLATION AND CALIBRATION OF THE LOFT ADVANCED DENSITOMETER
FOR THE L1-4 TEST

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INTEROFFICE CORRESPONDENCE

date April 20, 1977
to P. Y. Hsu
from D. B. Wood *ABW*
subject INSTALLATION AND CALIBRATION OF THE LOFT ADVANCED
DENSITOMETER FOR THE LI-4 TEST - Wood-2-77.

The attached report describes the experimental LOFT Advanced Densitometer to be used on the primary coolant hot leg (PC-2, "C Beam"), during the LI-4 test.

Included is a block diagram of the system and the calibration data taken which will be used to determine the primary coolant fluid chordal average density during blowdown.

Attachment -
as stated

ct

cc: A. E. Arave
R. L. Chaney
M. R. Clements
J. L. Edson
L. D. Goodrich
D. E. Larsen
J. C. Lucero *RL*
T. C. Robb
B. V. Thornton
Central File
D. B. Wood File

1. Containment Vessel

The modified PC-2, "C Beam" detector cask has been installed in its designated location on the primary coolant hot leg pipe along with a sodium iodide crystal, photomultiplier tube, and pulse height preamp, detector. The type T thermocouple used to monitor detector temperature, and to insure cooling water is being circulated, has been relocated in the detector cask cavity next to the lead sleeve.

The advanced densitometer detector is mounted with the standard "C Beam" geometry and except for the pulse height preamp, and a 1/4 inch diameter (in place of 3/4 inch diameter) collimation hole, is identical to the previous detector used. The external dimensions of the detector cask remain unchanged.

2. Rm 219 Advanced Densitometer Electronics

Figure 1 is a block diagram of the experimental LOFT Advanced Densitometer at the PC-2, "C Beam" location.

The standard NIM nuclear spectroscopy modules are either rack or bench mounted. The two additional cables for preamp power and test pulser (standard high voltage and signal cables are also being used) are routed through position #4, cables 1 and 2, on the 3Q penetrator.

The PC-2, "C Beam," densitometer signal to the DAVDS is brought into the cabling in Rm. 219 at the input to the control amplifier.

3. Primary Coolant Density Measurement. (Densitometer Calibration)

Six measurements have been taken with the primary coolant hot leg pipe full and empty and are being used for the densitometer calibration. These are listed below:

- 3.1 all air, pipe empty (air or all steam condition)
- 3.2 all water, pipe full (water at 70°F, 80 psig)
- 3.3 all water, pipe full (water at 350°F, 1000 psig)
- 3.4 all water, pipe full (water 520°F, 2000 psig)
- 3.5 all water, pipe full (water at 250°F, 1500 psig)
- 3.6 all air, pipe empty (air condition)

Looking at the photopeak count rates and corresponding measured water densities in more detail, the measured water density is calculated from the equation

$$\bar{\rho}_{\text{meas}} = \rho_1 - [(\rho_1 - \rho_g) \frac{\ln(I_{\text{meas}}/I_1)}{\ln(I_g/I_1)}]$$

where

$\bar{\rho}_{\text{meas}}$ = measured chordal path density

ρ_1 = water density, pipe full of water (70°F, 00 psig)

ρ_g = air or steam density

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

I_1 = measured count rate at all water, pipe full, 70°, 0.0 psig

I_g = measured count rate at all air condition

3.1 - all air

$$I_g = 5491 \text{ counts/sec}$$

$$\rho_g = 0.0752 \text{ \#/ft}^3$$

3.2 - all water

$$I_1 = 1162 \text{ counts/sec}$$

$$\rho_1 = 62.4 \text{ \#/ft}^3$$

3.3 - all water, (350°F, 1000 psig)

$$I_{\text{meas}} = 1425 \text{ counts/sec}$$

$$\rho_{\text{meas}} = 62.4 - [(62.4 - 0.0752) \frac{\ln(1425/1162)}{\ln(5491/1162)}]$$

$$\rho_{\text{meas}} = 54.235 \text{ \#/ft}^3$$

$$\bar{\rho}_{\text{theoretical}} (350^\circ\text{F}, 100 \text{ psig}) = 55.83 \text{ \#/ft}^3$$

$$\% \text{ difference} = \frac{\rho_{\text{th}} - \rho_{\text{meas}}}{\rho_{\text{th}}}$$

$$= \frac{55.83 - 54.235}{55.8}$$

$$= 2.8$$

3.4 - all water (520°F, 2000 psig)

$$I_{\text{meas}} = 1773 \text{ counts/sec}$$

$$\rho_{\text{meas}} = 45.44 \text{ \#/ft}^3$$

$$\rho_{\text{th}} = 48.54 \text{ \#/ft}^3$$

$$\% \text{ difference} = 6.4$$

3.5 - all water (250°F, 1500 psig)

$$I_{\text{meas}} = 1295 \text{ counts/sec}$$

$$\rho_{\text{meas}} = 58.1$$

$$\rho_{\text{th}} = 59.1 \text{ \#/ft}^3$$

$$\% \text{ difference} = 1.7$$

3.6 - all air

$$I_{\text{g}_{\text{end}}} = 5500 \text{ counts/sec}$$

$$I_{\text{g}_{\text{start}}} = 5491 \text{ counts/sec}$$

$$\% \text{ difference} = 0.2$$

Fig. E-1 LOFT advanced densitometer experimental PC-2, C-beam instrumentation block diagram.