NUREG/CR-0169
EGG-2037
Vol. XX

Idaho National Engineering Laboratory
Operated by the U.S. Department of Energy

LOFT Experimental Measurements Uncertainty Analyses Volume XX Fluid Velocity Measurement Using Pulsed Neutron Activation

Gordon D. Lassahn
Douglas J. N. Taylor

August 1982

Prepared for the
U.S. Nuclear Regulatory Commission
Under DOE Contract No. DE-AC07-76IDO1570

EG&G Idaho

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, of any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights.

Available from

GPO Sales Program
Division of Technical Information and Document Control
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

and

National Technical Information Service
Springfield, Virginia 22161

NUREG/CR-0169
EGG-2037
Vol. XX
Distribution Category: R2

LOFT EXPERIMENTAL MEASUREMENTS UNCERTAINTY ANALYSES VOLUME XX FLUID VELOCITY MEASUREMENT USING PULSED NEUTRON ACTIVATION

Gordon D. Lassahn
Douglas J. N. Taylor

Published August 1982

EG&G Idaho, Inc.
Idaho Falls, Idaho 83415

Prepared for the
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
Under DOE Contract No. DE-AC07-76IDO1570
FIN No. A6043

ABSTRACT

Analyses of uncertainty components inherent in pulsed-neutron-activation (PNA) measurements in general and the Loss-of-Fluid-Test (LOFT) system in particular are given. Due to the LOFT system's unique conditions, previously-used techniques were modified to make the volocity measurement. These methods render a useful, cost-effective measurement with an estimated uncertainty of 11% of reading.

NRC FIN No. A6043—LOFT Experimental Instrumentation

SUMMARY

Pulsed neutron activation (PNA) is a technique for measuring fluid flow velocity. Fluid in a short section of pipe is irradiated with a burst of neutrons. Downstream, gamma radiation detectors sense the flow of radioactive fluid. This method has the advantages of being nonintrusive and of giving a mass-weighted average velocity in two-phase flow. However, the measurement results are usually slightly ambiguous, so there are inherent uncertainties in any PNA application on the order of 2% of reading. Although the details of the theory of PNA measurements have been the subject of considerable debate in recent years, it is now generally agreed that the simple theories are applicable only to simple special cases and that there will always be significant uncertainty in real applications of PNA.

The PNA measurement system in the Loss-of-Fluid Test (LOFT) facility is a case in point. It has some unorthodox features due to unusual size and weight limitations. There is also a high level of background radiation. Thus, in addition to the uncertainty inherent in PNA, there are some abnormally large PNA measurement uncertainty components. The most significant of these are:

- Distance from neutron source to detector
- Velocity profile
- Lateral asymmetry
- Radiation randomness
- Turbulence randomness.

Despite these handicaps, the LOFT PNA system gave useful fluid velocity measurements with an estimated uncertainty of 11% reading.

FOREWORD

This document (NUREG/CR-0169, EGG-2037, Volume XX[a]) reports results of an uncertainty analysis for the pulsed neutron activation system for velocity measurements in the Loss-of-Fluid Test (LOFT) system. Measurements uncertainty analyses are performed to evaluate the anticipated performance uncertainty for each experimental measurement in the LOFT system. Results of these analyses are reported in a series of volumes designated NUREG/CR-0169, EGG-2037. Volume I of this series will describe the LOFT experimental measurement systems and the technique used for calculating the uncertainties. The remaining volumes in the series will present detailed results from the uncertainty analysis performed for each experimental measurement system.

The following volumes have preceded Volume XX:

1. G. D. Lassahn, *LOFT Experimental Measurements Uncertainty Analyses, Volume III, Data Acquisition and Recording System*, NUREG/CR-0169, EGG-2037, August 1982.

2. P. A. Quinn, G. L. Biladeau, R. Y. Maughan, *LOFT Experimental Measurements Uncertainty Analyses, Volume V, LOFT External Accelerometer Uncertainty Analysis*, NUREG/CR-0169, TREE-1089, October 1978.

3. G. L. Biladeau, *LOFT Experiment Measurements Uncertainty Analyses, Volume VI, LOFT Linear Variable Differential Transformer Displacement Transducer Uncertainty Analysis*, TREE-NUREG-1089, February 1978.

4. G. D. Lassahn, *LOFT Experimental Measurements Uncertainty Analyses, Volume VII, LOFT Self-Powered Neutron Detector Uncertainty Analysis*, NUREG/CR-0169, TREE-1089, August 1978.

5. G. D. Lassahn and P. A. Quinn, *LOFT Experimental Measurements Uncertainty Analyses, Volume VIII, LOFT Traversing In-Core Probe Uncertainty Analysis*, NUREG/CR-0169, TREE-1089, August 1978.

6. G. L. Biladeau, *LOFT Experimental Measurements Uncertainty Analyses, Volume IX, LOFT Strain Gage Uncertainty Analysis*, TREE-NUREG-1089, June 1978.

7. S. Ploger, *LOFT Experimental Measurements Uncertainty Analyses, Volume X, Absolute Pressure Measurement Uncertainty Analysis*, NUREG/CR-0169, EGG-2037, September 1981.

8. L. D. Goodrich and G. D. Lassahn, *LOFT Experimental Measurements Uncertainty Analyses, Volume XI, Free Field Pressure Transducer*, NUREG/CR-0169, EGG-2037, June 1982.

9. G. D. Lassahn, *LOFT Experimental Measurements Uncertainty Analyses, Volume XII, Differential Pressure Measurements*, NUREG/CR-0169, EGG-2037, August 1981.

10. G. D. Lassahn, *LOFT Experimental Measurements Uncertainty Analyses, Volume XIII, Temperature Measurements*, NUREG/CR-0169, EGG-2037, March 1982.

11. S. Silverman, *LOFT Experimental Measurements Uncertainty Analyses, Volume XIV, LOFT Drag Disc-Turbine Transducer Uncertainty Analysis*, NUREG/CR-0169, TREE-1089, November 1978.

---

a. Volumes VI, IX, XV, and XVI were published prior to implementation of the NUREG/CR numbering system as TREE-NUREG-1089; Volumes V, VII, VIII, and XIV were published as NUREG/CR-0169, TREE-1089 (TREE was the former designation for formal reports prepared by EG&G Idaho, Inc.). The remaining volumes in this series of uncertainty analyses will be published as NUREG/CR-0169, EGG-2037.

12. L. D. Goodrich, *LOFT Experimental Measurements Uncertainty Analyses, Volume XV, LOFT Primary Coolant Pump Speed Measurement Uncertainty Analysis*, TREE-NUREG-1089, April 1978.

13. G. D. Lassahn, *LOFT Experimental Measurements Uncertainty Analyses, Volume XVI, LOFT Three-Beam Gamma Densitometer System*, TREE-NUREG-1089, February 1978.

14. G. D. Lassahn, *LOFT Experimental Measurements Uncertainty Analyses, Volume XVIII, Radiation-Hardened Gamma Densitometer*, NUREG/CR-0169, EGG-2037, September 1980.

15. G. D. Lassahn, *LOFT Experimental Measurements Uncertainty Analyses, Volume XIX, Small-Pipe MCA Densitometer*, NUREG/CR-0169, EGG-2037, August 1981.

CONTENTS

NOMENCLATURE

$b(t)$	Background radiation gamma count rate at time t
B_i	Background radiation gamma counts in the i-th counting interval
$c(t)$	Detected gamma photon count rate at time t
C_i	Number of gamma counts in the i-th counting interval, from time (i-1) Δt to $i\Delta t$. $C_i \approx c(i\Delta t)\,\Delta t$
f_i	i-th digital filter weight
L	The source to detector distance, corrected for pipe irregularities
r	Distance from pipe axis
R	Radius of pipe
$s(t)$	Smoothed $c(t)$
S_i	Smoothed C_i
t	Time after neutron pulse
t_p	Time of occurrence of the peak in $s(t)$
t_o	Correct transit time, $L/\bar{u}$
t_i	$(i-1/2)\,\Delta t$, the time at the center of the i-th counting interval
$T_{1/2}$	Half life of a radioactive species
Δt	Length of a single counting interval
$u(x,y,z,t)$	Local, instantaneous fluid velocity at (x,y,z,t)
$\bar{u}$	Mass-weighted average velocity
$<u>_t$	Time average of u
$<<u>>$	Time and area average of u
x,y,z	Cartesian coordinates, with z along the pipe axis
α	$\frac{ds(t)}{dt}$ evaluated at $t = t_o$
β	$\frac{d^2s(t)}{dt^2}$ evaluated at $t = t_o$
Θ	Angular position around the pipe axis
λ	Decay constant for a radioactive species
μq	Mean value of q, for any quantity q
σq	Standard deviation of q, for any q
$\sigma^2 q$	Variance of q, for any q

LOFT EXPERIMENTAL MEASUREMENTS UNCERTAINTY ANALYSES VOLUME XX FLUID VELOCITY MEASUREMENT USING PULSED NEUTRON ACTIVATION

1. INTRODUCTION

"PNA" is used to refer to either a system or a technique for measuring flow velocities of fluids in pipes. In this technique, the fluid in a short section of the pipe is irradiated with a burst of neutrons and thereby made radioactive, hence, the phrase "pulsed neutron activation," or PNA. The passing of the radioactive fluid is sensed by gamma radiation detectors at some point, a known distance downstream from the neutron source. This gives a transit time for the fluid, from which a velocity can be directly determined. Since the activation of the fluid in any small volume is proportional to the density of that fluid, the calculated velocity is a density-weighted or mass-weighted velocity. This feature is very useful in two-phase flow measurements, since the mass-weighted velocity multiplied by the average density—which is easily measured—gives the mass flow rate, a quantity of prime interest.

PNA data were published for three Loss-of-Fluid Test[1] (LOFT) experiments: L3-2,[2] L3-7,[3] and L6-7/L9-2.[4] The purpose of the present report is to provide estimates of the uncertainties in these data and in possible future LOFT PNA data. The PNA data uncertainty estimates published in References 2 through 4 are rather rough; the estimates in the present report are more well-founded. If PNA is used in future LOFT tests, the measurement system may be somewhat different from the past systems, and the present uncertainty estimates may not be directly applicable to the future data. However, the uncertainty estimates in those future data reports will be based on the present discussions where appropriate.

The detailed uncertainty estimates in this report are not applicable to the L3-2 data. The L3-2 PNA measurements were marginally successful, and it is not certain that the selected peak in the gamma count rate versus time curve is actually the desired velocity indication instead of a random noise peak. If the peaks are correctly interpreted, the uncertainties in the resulting velocity estimates are probably 30 or 40% of reading. These L3-2 data do not seem reliable enough to warrant a detailed uncertainty analysis.

On the other hand, the L3-7 and L9-2 data are clearly valid velocity indicators. The following uncertainty estimates are applicable to the published L3-7 and L9-2 PNA velocity measurement results. For those uncertainty components which are significantly different for different sets of data, the largest applicable uncertainty value is used. Thus, these uncertainty estimates are conservative in that they describe the worst data and overestimate the uncertainty for the better data.

Because PNA is a relatively new and sometimes controversial measurement technique and because there is no published review or summary of past PNA work, the present report includes a substantial amount of background material. A brief history of the development of PNA for velocity measurement is given in Section 2. Section 3 gives a description of the LOFT PNA system, and Section 4 contains the uncertainty analysis. The conclusions and references are in Sections 5 and 6.

2. HISTORY

PNA differs from previous fluid-tagging transit time measurement systems in two significant respects: (a) the use of pulsed neutron activation instead of previously-used tag injection techniques, which is a trivial difference from theoretical viewpoint but of fundamental importance in terms of practical applications engineering; (b) the greater attention to the details of data interpretation which accompanied the development of PNA.

2.1 Neutron Sources

The first neutron source used for PNA was not described in detail,[5] but it was apparently similar to the first sources used by Argonne National Laboratory. Their sources were developed at Sandia National Laboratories in Albuquerque, New Mexico, presumably for purposes other than fluid flow measurement. They were portable enough to be useful in field applications. The major difficulties with these sources were their rather short lifetimes, their classified status, and their lack of general availability. Sandia later developed similar sources more suitable for PNA application.[6-11] Workers at Rensselaer Polytechnic Institute use a large electron accelerator to generate neutrons for PNA research, but such a source is of course not suitable for field applications.

2.2 General Development

Boswell and Pierce[5] were apparently the first workers to use PNA for fluid velocity measurement. They suggest two methods of using neutron activation to obtain a fluid velocity measurement, one of which is the transit time technique of interest in this report. The other technique, which depends on accurate radiation intensity measurements rather than on time measurements, is probably useful in some applications and is occasionally discussed by later workers; but it will not be discussed further in this report. The details of Boswell and Pierce's method for estimating the transit time t_0 are not clear; apparently t_0 is taken to be the time at which the maximum gamma radiation count rate occurs.

Argonne's first report on a use of PNA was by a group at the Argonne National Laboratory facility in Idaho.[12] It included a derivation of an equation for interpreting PNA measurements:

$$\bar{u} = L \frac{\sum_i e^{\lambda t_i} C_i/t_i}{\sum_i e^{\lambda t_i} C_i}. \tag{1}$$

This equation represents an important step in the development of proper PNA data treatment. It is correct for mixed, but not for laminar, fluid flow. In this report, mixed flow is flow which is turbulent enough so that a fluid particle's velocity in the detector region is not correlated with that particle's velocity between the source and the detector. Such mixed flow is often referred to as highly turbulent flow, although the two are not necessarily the same. The Argonne report also included an uncertainty estimate, which was described too briefly to allow an evaluation of its correctness. These workers did apparently recognize the existence of most of the significant, currently-recognized sources of uncertainty in PNA measurement, except for the variations caused by different amounts of turbulence. Reference 13 summarizes this work. Argonne workers later reported another application of PNA, but did not include any discussion of new developments.[14]

Kehler from Argonne in Illinois reported on a computer program to simulate PNA measurement applications, useful for optimizing the parameters in a PNA application and for predicting the measurement errors.[15] This report contains seemingly contradictory statements, one implying that PNA is independent of turbulence and the other implying a recognition of the fact that turbulence might affect the measurement error. The error estimates yielded by this program are probably quite good, assuming that the program accurately represents the actual fluid transport.

The application of PNA to two-phase flow measurements in nuclear reactor safety experiments was suggested, primarily by Paul Kehler, during the Two-Phase Flow Instrumentation Review Group Meeting, January 1977.[16]

The first report with any significant detail in the discussions of data analysis and error estimation was published by Argonne workers in June 1977.[17] The uncertainty analysis contains one significant mistake: although a good estimate is made for the magnitude of the error introduced by the non-zero width of the neutron source and gamma detector regions, the nature of the error is misinterpreted. The error is actually a known, constant error which, in principle, can be removed from the data if certain aspects of the system geometry are known. However, it is treated as a random error, with the result that its magnitude is greatly underestimated (by squaring the magnitude of the relative error) and its qualitative nature is misrepresented as a random error.

This report seems to indicate a clear recognition of the effects of laminar flow and extreme turbulence on PNA data interpretation. A good estimate of the possible error for the wrong assumption (laminar or highly turbulent flow) is given. The authors apparently had the knowledge required to write the equation for interpreting PNA data for laminar flow, but they did not actually write it.

In a November 1977 report, Price et al.,[18] demonstrated that Equation (1) is correct for a plausible, popular representation of highly turbulent flow presented by Taylor,[19] and they asserted (incorrectly) that this equation is correct for both laminar and turbulent flow. In a January 1978 report, Kehler implied that

$$\bar{u} = L \frac{\sum_i e^{\lambda t_i} C_i / t_i^2}{\sum_i e^{\lambda t_i} C_i / t_i} \tag{2}$$

is correct for both laminar and turbulent flow.[20] (It is not correct for turbulent flow.) Thus began a protracted debate on which, if either, was the correct method of interpreting PNA data. An attempt was made to experimentally verify which of the preceding equations was correct. The experiment was conducted at Utah State University in Logan, Utah. The pipes used were 12 in. in diameter and they led from a reservoir to a weigh tank which accurately metered the water flow rate. The experimental results were not conclusive.[21]

Kehler further asserted that the error introduced by using Equation (1) instead of Equation (2) for analyzing previously published data was negligible.[20] In fact, the error is about 4%, which is more than the error estimates which accompanied those data.

Kehler's data allow a rare opportunity for a check on PNA self-consistency, which then indicates a lower bound on PNA measurement uncertainty. The data include two independent PNA measurements for each of several flow conditions. The root-mean-square (rms) value of the difference between these measurements for all-liquid flow is 6.4% of the value which is assumed to be the more accurate (the PNA measurement with the longer source-to-detector distance). The error analysis predicts an rms difference of $\sqrt{(4.0\%)^2 + (0.5\%)^2} = 4.03\%$ for all-liquid flow. For two-phase and all-liquid data combined, the rms difference between the two PNA measurements is 28%. These numbers indicate that Kehler's predictions of PNA accuracy are exaggerated.

In his report, Kehler introduces the concept of an effective spacing between the source and the detector. Such a concept is valid and useful for correcting the effects of non-zero widths of the source and detector region. However, the effective spacing should be calculated from known source and detector geometries; it should not be done by fitting a set of PNA readings to some reference measurement, because the PNA readings may contain other systematic errors that cannot be corrected by using an effective spacing. After an effective spacing correction is applied to one set of data in Kehler's report, the rms difference between the two redundant PNA measurements is 23% for combined two-phase and all-liquid data, and 1.4% for the all-liquid data alone. It is not valid to compare this 1.4% difference with the predicted 4.03% difference, because the predicted difference presumably includes the effects of errors which were removed by the effective spacing correction to obtain the 1.4% difference. The 1.4% may be construed as a representation of part of random variation, excluding all systematic errors, between two highly redundant PNA measurements. There are some additional random variations common to both of the redundant PNA measurements which are not included in the 1.4%.

In November 1977, Forster and Kehler reported an application of PNA without any significant new developments.[22]

Santee et al., did a study using Monte Carlo techniques to predict asymmetry effects, the errors caused by [illegible]mity of the neutron flux and non-uniformity of the detector sensitivity over the fluid flow are[illegible] tudy is interesting and gives some feeling for the magnitude of the problem, but it is not dire[illegible] relevant to different PNA applications.

Workers at Rensselaer started doing PNA work with an electron linear accelerator used to produce neutrons. They suggest fitting the data with a model given by Taylor[19] to obtain the fluid velocity, but they give no clear statement about the success of this procedure.[24] Accuracies as good as 1% are claimed, without explanation or justifying comments. This report also suggests the idea of combining the data from multiple neutron pulses to reduce the random error of PNA measurements of steady flow. This idea was used in later work,[25] but again there is little useful indication of the measurement accuracy. The data do show some fine structure which is apparently associated with slug flow. This is the first clear exhibition of time-dependent flow effects in PNA measurements.

Kehler's March 1978 report[26] is an excerpt from Reference 20. His November 1978 paper presents no significant new developments, it merely summarizes previous work.[27] His February 1979 report presents a derivation which is a little vague about some details but seems to be an essentially correct derivation of Equation (2) for laminar flow.[28] The derivation is only a short step away from giving Equation (1) for highly turbulent flow, but Kehler neglects this point and asserts that Equation (2) is correct for all flow regimes. In his July 1979 report he suggests the possiblity of measurement errors resulting from the activated nuclei (nitrogen 16) leaving the liquid and mixing with the gas phase.[29]

The November 1979 report from Rensselaer discusses studies of slug flow using PNA.[30] It includes conclusions about the rate of exchange of mass between slugs.

In Reference 31, Kehler presents another slightly vague derivation of Equation (2). He also presents a computer simulation of fluid transport which suggests that Equation (2) is approximately correct for the particular conditions represented in the computer program. However, it is not clear whether the range of simulated conditions spans the range of realistic conditions, and there is no quantitative statement of the errors incurred by applying Equation (2) to realistic turbulent flow. Nevertheless, his suggestion that Equation (2) is better than Equation (1), even for realistically turbulent flow, may be valid. The implication that Equation (2) gives no error for any two-phase flow regime is not justified.

The uncertainty analysis in Kehler's report contains the error already mentioned. His report also states incorrectly that asymmetry effects can be made negligible by using several sources and several detectors arranged circumferentially around the pipe.

In their October 1980 report, Perez-Griffo et al., (from Rensselaer) elaborate on their studies of slug flow with PNA.[32] They also find that bubbly flow does not conform to the Taylor model.

Kehler's July 1980 report includes good derivations of Equations (1) and (2) for highly turbulent and laminar flows, respectively, and a repetition of his attempt to justify the use of Equation (2) for realistic turbulent flow.[33] He also suggests the use of

$$\bar{u} = L \frac{\sum_i e^{\lambda t_i} C_i / t_i^{\,n}}{\sum_i e^{\lambda t_i} C_i / t_i^{\,n-1}} \tag{3}$$

with n adjusted to conform to known conditions of laminar or turbulent flow or, in some cases, with n adjusted to force agreement of the PNA data with the right answer known from other information.

In October 1980, Kehler suggested adjusting the value n in Equation (3) to compensate for the effects of the finite extent in the axial direction and the non-uniformity in the lateral directions of the distributions of the neutron activation and the detector sensitivity.[34] He did not mention that this procedure could depend strongly on such factors as the velocity profile, the density profile, the turbulence profile, and the slip (ratio of gas velocity to liquid velocity), and possibly other hard-to-determine parameters. Kehler's October report implies the recognition of some of these factors, but offers no solutions for these very difficult problems.[35]

In November 1980 the Rensselaer group reported on studies of the distribution of the activated fluid in pipes large enough to have significant asymmetry effects.[36] This report also includes derivations of Equations (1) and (2) which contain an easily-corrected minor error in neglecting the spatial dependence of the density of the tagged fluid.

In June 1981 the Rensselaer group reported a new method of treating PNA data, which they call a mechanistic method.[37] Monte Carlo calculations of the source and detector distributions are combined with Taylor's fluid transport model, the flow velocity and other parameters, including the effective diffusion constant, are adjusted to obtain the best fit of the model to the data. This is an improvement over the previously-mentioned fitting technique[24] in that the present mechanistic method includes a realistic representation of the source and detector geometry effects.

The Rensselaer group later reported a further improved data processing method they call the phenomenological model, in which the Taylor model of fluid transport is replaced by a finite difference computer calculation.[38] This report estimates the uncertainties as about 1.08% for the mechanistic method and 2% for the phenomenological method. The results for the two methods applied to one set of data differ by about 5.5%, this suggests that the uncertainty estimates are unrealistically low. This report also gives more detail on the Monte Carlo calculations mentioned earlier, and it repeats the derivations of Equations (1) and (2).

Taylor and Hartwell discuss some difficult problems associated with the application of PNA to the LOFT nuclear reactor, giving primary attention to the problems with high levels of gamma and neutron radiation in the enviornment.[39]

In January 1982 the Rensselaer group published a review of their PNA work.[40] This review contained essentially the same material given in earlier reports but included substantially more detail.

In May 1982, Kehler and Kondic reported another application of PNA which presented no new developments.[41] They also tried to support the general use of Equation (2) with an invalid theoretical argument and with a (probably) valid argument based on the observed lack of mixing of the tagged fluid in some experiments. They failed to include enough details about the experiments to prove the validity of their assumption. There is again the incorrect assertion that Equation (2) has no systematic error.

2.3 Current Status of Theory

Equation (2) is recognized as correct for laminar flow. Equation (1) is recognized as correct for flow with complete mixing, with the reservation that such flow may not occur in practice. Kehler has presented reason to expect that Equation (2) may be better than Equation (1) for real turbulent flow.

Apart from the question of turbulent or laminar flow, both of the analysis methods represented by Equations (1) and (2) allow several errors:

1. Errors or random fluctuations in the count rate for small-time values may cause large errors in the calculated velocity value. Such count rate errors may result from background radiation, even at very low levels.

2. The finite widths of the neutron source distribution and the gamma detector sensitivity distribution, in the direction parallel to the flow, cause a bias error in the calculated velocity.

3. The non-uniformity of the neutron activation and detector sensitivity distributions across the flow area may cause large measurement errors, referred to as asymmetry effects.

The first error is usually avoided by not including the small-time data in the sums. The second error can be eliminated, at least to a good approximation, by the correct use of an effective spacing correction procedure similar to that suggested by Kehler. No reliable method is known for eliminating the third error from the analysis methods represented by Equations (1) and (2), although a rough correction can be done with a procedure like the effective spacing correction.

An alternative to the methods of Equations (1) and (2) is the use of model fitting procedures, such as those used by the Rensselaer group. These procedures are very effective for eliminating, or at least minimizing, the effects of count rate errors and fluctuations (Error 1). Those model fitting procedures which include descriptions of the source and detector distributions automatically eliminate the error associated with the finite distribution widths in the axial direction (Error 2). The model fitting procedures may eliminate asymmetry effects (Error 3) if the model correctly represents the fluid transport, including the velocity profile and the turbulence or molecular diffusion. This is the primary limitation on the accuracy of the model-fitting procedures: they require substantial knowledge of certain characteristics of the fluid flow, which may not be available. Some of this knowledge may in some cases be inferred from the PNA data themselves, but such inference is usually ambiguous and not adequate to ensure accuracy better than a few percent at best. For single phase flow with simple geometry, the required flow characteristics can be predicted fairly well, and the calculated velocity value is not very sensitive to small errors in the predictions. For two-phase flow, the predictions are much more difficult and critical. This requirement for accurate prediction of flow characteristics is a model-fitting disadvantage which, together with the disadvantages of complexity and cost, may more than offset the advantage of eliminating the asymmetry error in many applications.

PNA measurement uncertainties as good as 1% have been quoted. However, most of these quotes underestimate the uncertainty, and the estimates for one application are usually not relevant to other PNA configurations.

3. LOFT PNA SYSTEM DESCRIPTION

The LOFT PNA system consists of pulsed neutron sources, a single gamma radiation detector, extensive radiation shielding for the detector, electronic pulse signal conditioning, a data acquisition system, and a data storage capability. The system was placed on the intact loop hot leg between the reactor vessel and the steam generator (see Figure 1). There is a venturi contraction in this pipe, which complicated the interpretation of the data.

The neutrons from the source activate a slug of the flowing fluid through the reaction ^{16}O (n,p) ^{16}N. The neutron threshold energy for this reaction is 10.2 MeV, and the energy of the excited state of ^{16}N is 6.1 MeV. The ^{16}N decays to its ground state with the emission of a 6.1 MeV gamma which may be sensed by the detector if the nucleus is in the detector sensitivity region when it decays. The half life ($T_{1/2}$) of this decay is 7.12 s.

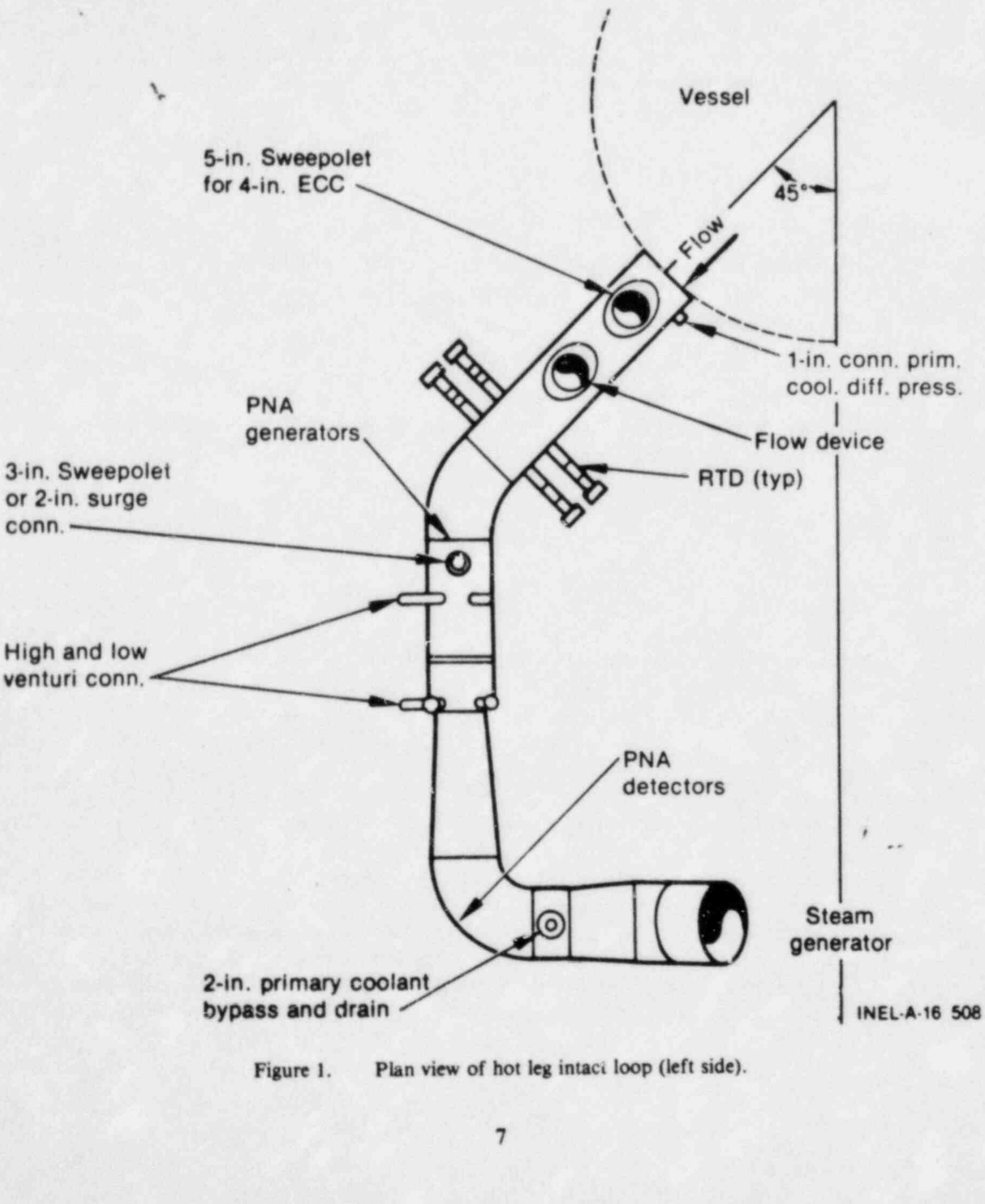

Figure 1. Plan view of hot leg intact loop (left side).

3.1 Neutron Sources

All of the neutron sources for the LOFT PNA system were manufactured by Sandia National Laboratories. Four classified sources were used during the L3-2 and L6-7/L9-2 tests. The nominal yield for each of these neutron generators was 6 x 10^9 neutrons/pulse.

For the L3-7 tests, these classified sources were replaced with two nonclassified sources having a nominal individual yield of 1.2 x 10^{10} neutrons/pulse. These new sources, like the old classified sources, employed a ^3H (d,n) ^4He reaction with a neutron output energy of 14 MeV. The center of the unit was a demountable source tube such that the tritium target together with the deuterium ion source were replaceable. The pulse duration was 1.2 milliseconds, and the maximum pulse repetition rate was 12 pulses/min. At a rate of 1 pulse/min, the lifetime of the tube (before anode and cathode replacement) is in excess of 1000 pulses. However, the tube lifetime is shortened for the 12 pulse/min rate. One generator faced horizontal, and it was symmetric with the pipe diameter; the second vertical neuton generator was centered on a chord which was 10 cm (4 in.) off-center from the diameter of the pipe. In addition, the vertical generator was 7.5 cm (3 in.) downstream from the horizontal generator. The center-to-center distance from the upstream generator to the gamma detector was 1.64 m (64.5 in.). The neutron yield of the vertical source was about 80% of the yield of the horizontal source.

3.2 Detector

It is highly desirable to have many gamma radiation detectors around the pipe to maximize the signal strength. Paul Kehler has proposed and used a massive donut-shaped ring type detector. However, the installation of an adequately shielded array of detectors or a massive ring detector could not be accomplished because of space and weight restrictions on the LOFT assembly. Therefore only a single 12.7 x 7.6 cm (5 x 3 in.) NaI(Tℓ) was used, and it was placed as shown in Figures 1 through 3. This position permitted the maximum amount of shielding to be placed around the detector. The NaI(Tℓ)-photomultiplier was a Harshaw "integral line" detector. This size detector was chosen because it was about 40% efficient for the 6.1 MeV gamma radiation.

3.3 Shielding

The detector was wrapped with a sheet of cadmium 1 mm (0.04 in.) thick, which provided thermal neutron shielding, and was then inserted into a specially-designed detector housing. The housing combined a water cooling jacket with a lead-filled steel box 46 x 20 x 20 cm (18 x 8 x 8 in.). This housing provided about 2.5 cm (1 in.) of linear lead shielding. It was determined in some of the earlier tests that the reason for the inordinate amount of interfering background radiation was due to stray reactor-produced epithermal and fast neutrons which activated the detector crystal. These neutrons came from a streaming path in the gap between the LOFT pressure vessel and its shield tank. The neutrons were then scattered from the material underneath the pressure vessel. Bricks of borated polyethylene, 5 x 10 x 20 cm (2 x 4 x 8 in.), were stacked immediately surrounding the detector housing except for a 5 cm (2 in.) thick by 15 cm (6 in.) diameter space in front of the detector. A lead shield measuring 10 cm (4 in.) in thickness was constructed on all sides of the detector outside of the borated polyethylene except for the shield wall nearest to the reactor vessel where the lead thickness was 20 cm (8 in.) and in the collimation hole in front of the detector where the lead shielding was 0.6 cm (0.25 in.) thick. The detector viewed the primary pipe through a shield collimator. The collimator was 15 cm (6 in.) in diameter and 7.5 cm (3.5 in.) long. Therefore the optical view-angle of the detector to the pipe was 110 degrees. The outside dimensions of the shield were 71 x 86 x 61 cm (28 x 34 x 24 in.). Two sketches of the detector shielding are shown in Figures 2 and 3.

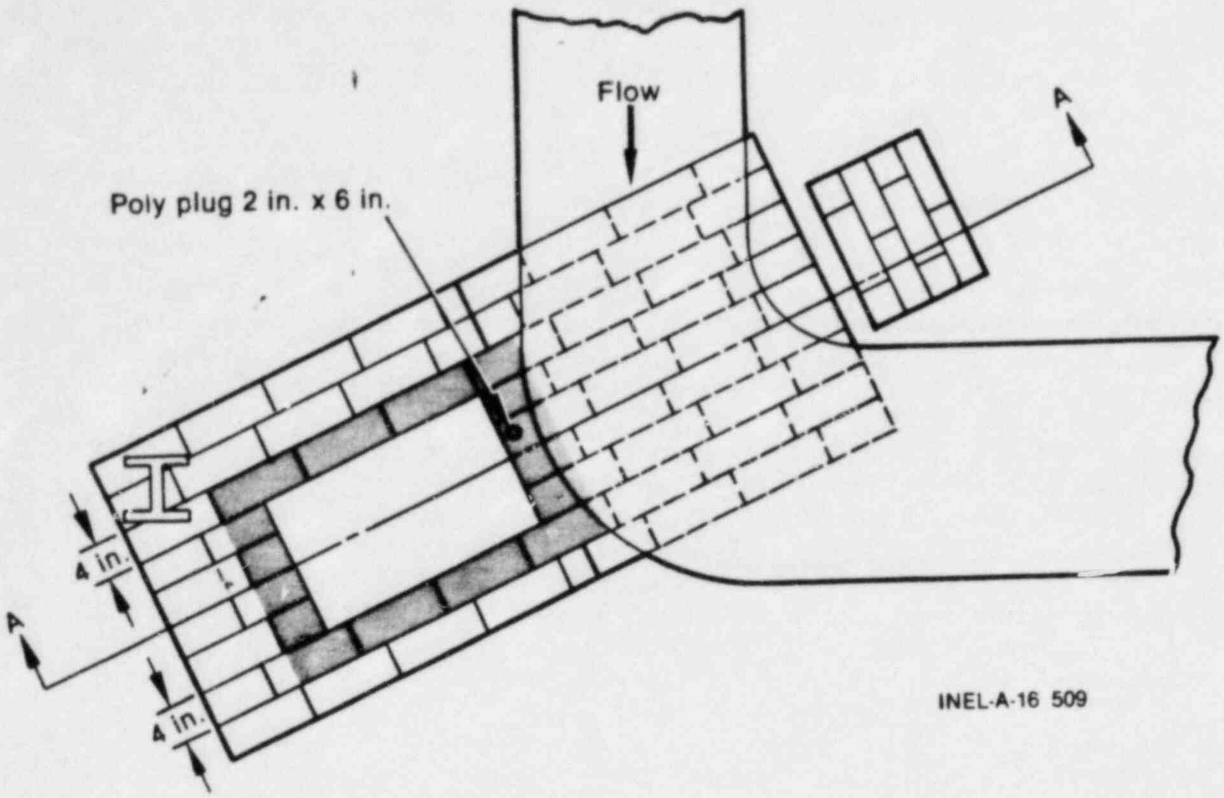

Figure 2. Sketch of downstream detector construction for the L3-7 experiment.

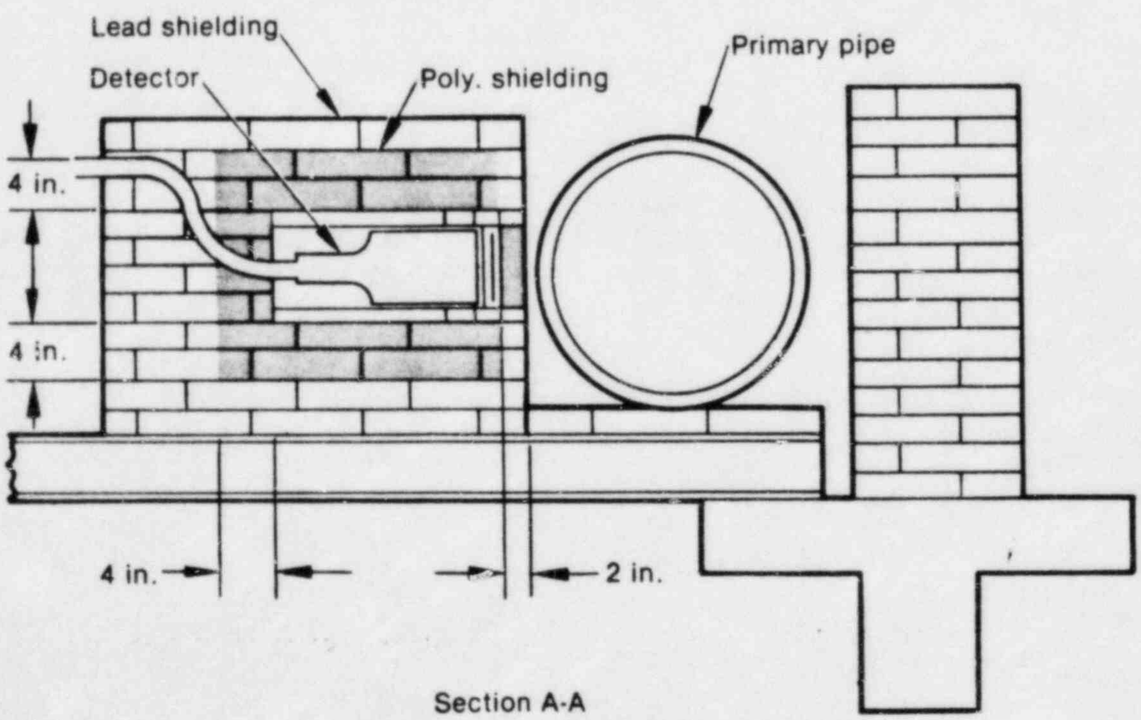

Figure 3. Elevation view of downstream detector structure for Experiment L3-7.

A shadow shield 40 x 71 x 20 cm (16 x 28 x 8 in.) was erected on the opposite side of the primary pipe, and a floor shield 5 cm (2 in.) thick was constructed to decrease the amount of direct and scattered radiation into the 15 cm collimator. To attenuate the streaming neutrons, trays of boric acid crystals were placed in the gap underneath the reactor vessel.

3.4 Electronic Signal Conditioning

The "front end" electronics consisted of a preamplifier, a baseline restorer, and a single channel analyzer.[42] The preamplifier was current sensitive with an output pulse shape determined by the quench time of the NaI(Tℓ) crystal. The quench time, at a fixed temperature of the sodium iodide crystal, was constant for all pulses. The preamplifier output pulse amplitude was proportional to the amount of energy absorbed in the NaI(Tℓ) crystal for each event. The preamplifier had a rate-sensitive-gain compensation circuit which monitored the average current through the photomultiplier tube and compensated for any gain instabilities by applying a corrective high voltage to the dynode resistor chain. The gain stability was held to ±2% over a range of 10^3 to 10^6 counts/s. The baseline restorer was highly symmetric and held the baseline stable to 0.1% of full scale (10 volts) for duty cycles in excess of 90%. The single-channel analyzer had pulse pile-up rejection capabilities and dead time measuring circuits. In addition, it generated gate signals which went to an associated Invert-Delay-Linear gate module. This provided positive output pulses for pulse height analysis as well as logic signal outputs for driving a multichannel time scaling analyzer. These "front end" electronics were able to process count rates in excess of 10^6 counts/s.

For each velocity measurement, a single logic pulse triggered both the neutron sources and the multichannel analyzer when operating in the automatic mode. However during manual operation each of the two neutron sources was triggered by its own switch, and the MCA pass could be started by the pulsing of the upstream (horizontal) generator. The pulses with energies in excess of the 3 MeV threshold as fixed by the single-channel analyzer were counted by a ND-100 multichannel analyzer operating in the scaling mode. After each pass, the memory of the MCA was stored on magnetic tape, and then the MCA unit was enabled for the next MCA pass.

3.5 Data Processing

For a single velocity measurement, the raw PNA data were a set of values C_i, $i = 1, 2, 3. . . I$, where I was usually 1024 but sometimes less. Each C_i was the number of gamma photons detected during the time interval from $(i-1)\,\Delta t$ to $i\Delta t$, where Δt was a constant for any one measurement. t_i was defined as the time at the center of the i-th counting interval: $t_i = (i-1/2)\,\Delta t$. The data processing was as follows:

1. A smoothed data set S_i are created from the raw data C_i by two successive applications of a simple moving average, one with 49 and one with 39 data points in the moving window. This smoothing can be represented by

$$S_i = \sum_j f_j \, C_{i+j} \tag{4}$$

where f_j plotted against j is a trapezoid centered at $j = 0$. The smoothing cannot be done well near the ends of the data record, and those few smoothed end points are ignored in later processing steps.

2. The C_i data away from the peak are fitted with a straight line. This linear function is used as the estimate of the trend of the background radiation versus time. B_i is the magnitude of this linear function at time t_i.

3. The peak in the curve of $(S_i - B_i) \exp(\lambda t_i)$ is located, and the time at the peak is called t_p. The quantity $(S_i - B_i)$ is the (estimated) smoothed PNA radiation count rate, and the exponential factor corrects for the decay of the activity in the fluid.

4. The mass-weighted fluid flow velocity $\bar{u}$ is estimated as L/t_p.

Since this LOFT PNA data analysis procedure is different from generally accepted PNA data analysis procedures and since there is no reason to expect this LOFT procedure to be formally correct (although intuition suggests that it should be approximately correct), it seems appropriate to give some explanation and justification of this procedure.

Model-fitting data analysis procedures are not used for LOFT PNA data processing. When applying these methods to LOFT, it would be very difficult to accurately represent the velocity profile and the turbulence of the fluid in the venturi and the elbow. Even a reasonable representation of the detector sensitivity distribution in the elbow region would not be a simple task. It is felt that the possible accuracy impovements, if any, would not be enough to justify the cost of implementing a model-fitting procedure.

The background radiation noise in the LOFT PNA data causes large errors in the results obtained from Equations (1) and (2). The trend of the background radiation can be estimated and removed quite well. However, there is no way to determine which part of the random fluctuation in any one C_i is associated with background radiation and should be removed, as opposed to the part of the fluctuation that is the interesting PNA radiation and should not be removed in the background subtraction. These fluctuations, which remain after the background radiation trend removal, cause major errors in the results obtained from Equations (1) and (2). Smoothing the data before applying Equations (1) or (2) does not help much to reduce these errors. Also, smoothing introduces new errors in the use of those equations. Neglecting the data for small times, when all the radiation can be assumed to be background radiation, does help to reduce the error. However, there is no justifiable, objective criterion for determining how much of the data to delete, and the results obtained from Equations (1) and (2) are rather sensitive to this choice for the noisy LOFT data. Thus, it seems that there is no defensible way to apply Equations (1) and (2) without introducing significant new errors. Those new errors, combined with the inherent errors associated with unknown turbulence and the poorly known detector sensitivity distribution (i.e., the dependence of the detector sensitivity on the position of the radiating nucleus), make the use of Equations (1) and (2) seem very unattractive.

The problem of noise in the LOFT PNA data is quite effectively eliminated by the LOFT data processing procedure. The location of the peak in the smoothed data is sensitive to the trend in the background radiation level, but this trend is removed easily and quite accurately. The location of the peak is affected to some degree by the noise in the data, by unknown turbulence, and by the poorly known detector sensitivity distribution. However, these effects are not extremely large, and the resulting measurement errors are expected to compare favorably with the errors in alternate processing procedures. Of course the ultimate justification (or condemnation) of the LOFT PNA data analysis procedures must rest on the resulting measurement uncertainty, which is estimated later in this report. A valid comparison of the LOFT procedure with alternatives would require careful uncertainty estimates for the alternatives, which are not available.

Figures 4 and 5 show two sets of LOFT PNA data. In those figures, the points are the raw C_i and the continuous curves are the S_i. The data of Figure 4 are the poorest (worst signal to noise ratio) of the data considered in this uncertainty analysis. Figure 5 shows one of the best sets of data, which are of special interest because they were analyzed by the Rensselaer group.[37,38,40]

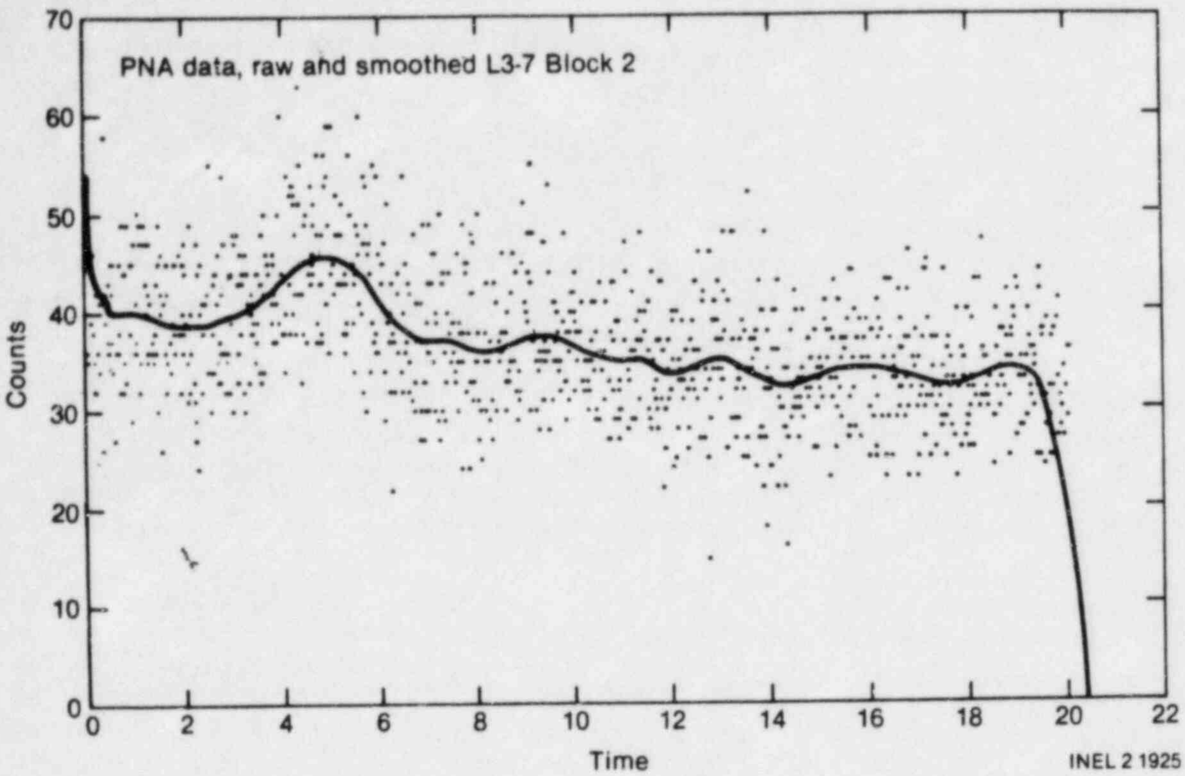

Figure 4. LOFT PNA data with low signal-to-noise ratio.

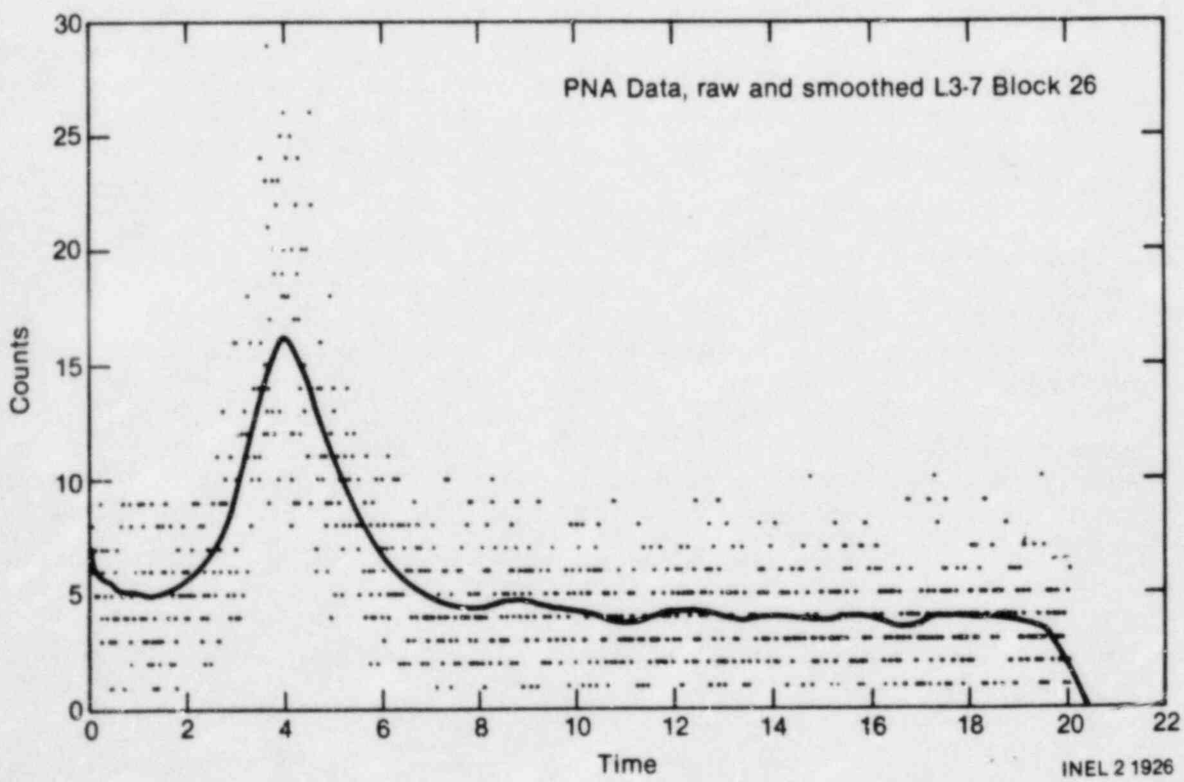

Figure 5. LOFT PNA data with high signal-to-noise ratio.

4. LOFT PNA UNCERTAINTY

Potentially significant uncertainty contributions are expected from the following effects: (a) errors in the estimated effective source-to-detector distance L; (b) systematic differences between the peak position t_p and the correct effective transit time $t_o = L/\bar{u}$; (c) random differences between the observed peak time and the ensemble average peak time. These errors are discussed separately in Sections 4.1 through 4.3, and they are combined in Section 4.4. The available data on LOFT PNA measurement errors are discussed in Section 4.5.

4.1 Effective Length Uncertainty

The physical separation between the source and the detector can be measured quite accurately, probably within a few millimeters. However, the detector is at the upstream end of an elbow in the pipe. This makes it difficult to know the location of the effective center of the detector sensitivity distribution, because the detector sensitivity extends further downstream than upstream and because the details of the fluid flow at the elbow are not known. The effective source position is also difficult to estimate, because there are actually two sources with different orientations and axial positions. These are the major sources of uncertainty in the effective source-to-detector distance L.

A further complication is introduced by the presence of a venturi contraction in the straight length of pipe between the source and the detector. This contraction causes the fluid velocity in the PNA measurement region to be greater than the desired velocity in the full-bore pipe away from the venturi. A correction for the venturi is made by replacing the actual source-to-detector distance by the length of a full-bore pipe which would contain the same fluid volume as is contained between the source and detector. This length is estimated from engineering drawings of the venturi and simple numerical integrations to find fluid volumes.

The combined uncertainty due to the simple length measurement error and the errors caused by the elbow and the venturi are estimated, by engineering judgment, to be roughly 4% of the correct value.

4.2 Systematic Errors in the Peak Position

The time t_p of the peak in the smoothed count rate versus time curve may not be the correct value for use in calculating the average velocity of the fluid. Some error in t_p is related to randomness in the radiation processes and in the fluid flow details; these statistical variations are discussed in Section 4.3. If all these statistical variations were removed—by averaging over many measurements for the same fluid flow conditions, for example—there might still be errors in t_p, associated with the following effects:

1. Fluid velocity profile
2. Fluid turbulence
3. Lateral asymmetry
4. Axial asymmetry
5. Background radiation trend
6. Non-zero counting periods.

4.2.1 Velocity Profile. The velocity profile is the dependence of the time-averaged local velocity $<u>_t$ on the lateral position (x and y or r and Θ coordinates) in the flow area. For a fixed average velocity ū, velocity profile variations can cause variations in t_p, so for at least some velocity profiles there will be errors in t_p (differences between t_p and $t_o = L/\bar{u}$).

For low-velocity, laminar flow, the velocity profile is usually represented by

$$<u>_t = 2 <<u>> . [1-(r/R)^2]. \quad (5)$$

With ideal source and detector distributions, $t_p = t_o/2$ and

$$c(t) = \begin{cases} 0 \text{ for } t < t_p \\ \text{constant}/t \text{ for } t > t_p. \end{cases}$$

Finite width source and detector distributions make c(t) smoother and reduce the error in t_p. For the LOFT PNA geometry, c(t) should be approximately proportional to the curve shown in Figure 6. LOFT PNA data do not have a peak which is this broad, so the parabolic profile of Equation (5) apparently does not occur in these LOFT experiments.

A common representation of turbulent flow is the 1/7 power law profile:

$$<u>_t = <<u>> [1-r/R]^{1/7}/0.8166. \quad (6)$$

Numerical studies show that such a profile with the LOFT PNA geometry and no smoothing of the raw data yields t_p values about 5% too small. The smoothing applied to LOFT PNA data decreases this error very slightly. The c(t) curve obtained with this profile has a shape comparable to typical LOFT PNA data.

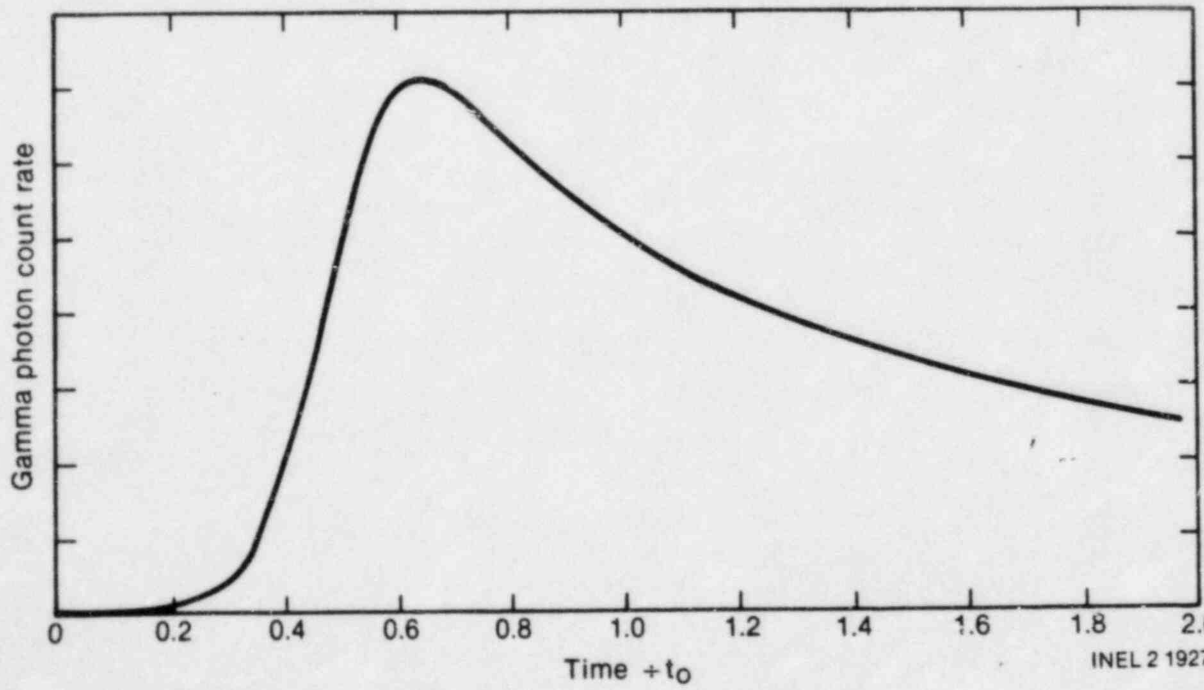

Figure 6. Predicted shape of LOFT PNA peak for parabolic velocity profile.

As an alternate representation of LOFT fluid flow, a flatter velocity profile was tried in numerical studies. The details of the profile were not specified, but the velocity probability density function was assumed to be a Gaussian distribution with an adjustable width. For velocity distribution widths which yielded c(t) curves roughly resembling LOFT data, the errors in t_p were less than 2%, with t_p never greater than t_o.

The Taylor model of mixed flow was represented numerically, and the errors in t_p were less than 2% for peak widths comparable to LOFT data.

These various velocity profile representations are assumed to span the range of velocity profile effects that might have occurred in the LOFT PNA data. These numerical studies lead to the conclusion that velocity profile effects give errors ranging from -5 to 0% in t_p. These errors are represented as an estimated mean error (correct velocity minus measured velocity) of -2.5% of reading and an estimated uncertainty of 2.5% of reading.

4.2.2 Turbulence. In the PNA analysis methods which use Equations (1) or (2), an unknown amount of turbulence is a potential source of measurement error. The situation is somewhat better in the LOFT PNA analysis method. Increasing the turbulence usually makes the c(t) peak more symmetric and decreases the error in t_p. For all the numerical studies mentioned in the previous section except the Taylor model studies, the flow was assumed laminar, and the t_p errors obtained are worst-case errors, relative to variations in turbulence. For the turbulent flow represented by the Taylor model, the t_p errors were smaller than for the laminar flow studies. Thus, the possible errors due to turbulence are already included in the error statement of the previous section.

4.2.3 Lateral Asymmetry. The fluid activation (per unit mass) is not uniform across the entire flow area, because the neutron flux is less for fluid farther from the neutron source. This results from both the $1/r^2$ dependence of the neutron flux (where r is the distance from the source) and from the attention of the neutron flux by the fluid itself. Similarly, the gamma radiation detectors are more sensitive to radiation originating close to the detector than to radiation coming from the activated fluid further from the detector. These non-uniformities in the neutron source distribution and the gamma sensitivity distribution cause the PNA velocity measurements to be biased toward the lower velocity of the fluid near the pipe wall (near the source and detector). Since the magnitude of this asymmetry error depends on the details of the velocity profile and the density profile, which are usually not known very well, it is very difficult to correct the asymmetry error (except perhaps in a few special cases).

For the LOFT geometry with the pipe filled with cold liquid, the neutron flux at the center of the pipe is roughly 70% of the flux at the pipe wall next to the source, and the detector's sensitivity to gamma radiation from the center of the pipe is roughly 70% of the sensitivity to radiation from the fluid closest to the detector. With a parabolic velocity profile [Equation (5)] and laminar flow, the asymmetry error would be roughly 15% of the correct velocity. This error would be smaller for flatter velocity profiles. The 1/7 power law profile [Equation (6)] with laminar flow would give a measurement error of about 4%. Turbulence reduces the error by a factor of 2 M/L, where M is the distance required for substantial mixing of the fluid (in some vaguely-defined intuitive sense) and L is the effective source to detector distance. The presence of the venturi in the LOFT pipe should cause substantial mixing, so 2 M/L should be significantly less than one. The narrowness of the observed c(t) peaks strongly suggests significant turbulent mixing; the peaks are far too narrow to have resulted from the parabolic velocity profile usually associated with laminar flow. Thus, it seems reasonable to expect that the 2 M/L factor should be less than 1 and that 4% of reading is a reasonable upper bound for the error associated with asymmetry effects. Since this error is one-sided, it is represented as a mean error of 2% of reading and an uncertainty component equal to 2% of reading.

4.2.4 Axial Asymmetry. Asymmetry, in the axial direction, of either the neutron source distribution or the gamma detector sensitivity distribution is normally a potential source of error in a PNA system. This problem is somewhat reduced by the LOFT PNA analysis procedure, which makes the peak more important than the centroid for both distributions. Thus, even though there may be substantial asymmetry in these distributions in the LOFT system, the resulting uncertainty contributions should be quite small. They are already included in the effective source-to-detector uncertainty estimate of Section 4.1.

4.2.5 Background Radiation Trend. If the background radiation trend is not estimated accurately, there could be a residual, time-varying background radiation component in the c(t) data after the background subtraction. If the time derivative of this residual term is not zero at the peak position, the peak position will be biased by an amount approximately equal to

$$\left.\frac{\partial b(t)}{\partial t}\right|_{t=t_p} \div \left.\frac{\partial^2 s}{\partial t^2}\right|_{t=t_p}, \tag{7}$$

where b(t) is the residual background term.

For LOFT data, the second derivative is typically 16, and the first derivative term is expected to be less than 0.05 because the total (uncorrected) background radiation trend normally has a slope on the order of 0.05. On this basis, the uncertainty associated with errors in removing the background radiation trend is estimated to be 0.05/16 = 0.003 s or not more than 0.1% of reading, which is negligible compared with other uncertainty components.

4.2.6 Finite Sample Rate. The raw data are acquired by counting photons for time intervals of length Δt, and the final s(t) curve is represented by discrete points separated by time Δt. The peak in the ideal s(t) curve might lie between the points for which S_i data are available, but the data processing algorithm can only select one of the discrete points for the t_p value. This can result in errors as large as $\Delta t/2$ in t_p. The 2σ value (2 times the root-mean-square error) associated with this error is $2\ \Delta t/\sqrt{12} \sim 0.577\ \Delta t$. For the largest Δt of 0.04 s, this uncertainty component is 0.024 s, which is typically a negligible 0.6% of reading.

4.3 Random Fluctuations in the Peak Position

If such quantities as the distributions of the neutron flux and the gamma sensitivity, the velocity profile, the turbulence profile, and the density profile were all known, the errors and uncertainties discussed in the preceding sections could (at least in principle) be eliminated. However, there would still remain two uncertainty contributions associated with statistical fluctuations which vary randomly from one PNA measurement to the next, even with constant flow conditions. These uncertainties are caused by randomness in the radiation processes and by the random nature of turbulence in the fluid flow. In some two-phase flow applications, there could be an additional large uncertainty component associated with randomness in instantaneous fluid density distributions, but this error is neglected here because the LOFT data are believed to represent single-phase or very nearly all-liquid flow.

4.3.1 Radiation Process Fluctuations. The observed value of C_i, the number of gamma counts acquired in the i-th counting interval, is not generally equal to the ensemble average value. It has a root-mean-square error equal to the square root of the ensemble average value. These errors in the C_i propagate into the smoothed S_i values and they may cause errors in the location of the peak in the S_i versus t curve.

The magnitude of the t_p error can be estimated by assuming that the S_i values are discrete values from a continuous function s(t) which is approximately parabolic near the peak. Then

$$s(t) \sim s(t_o) + (t - t_o)\ \alpha + 1/2\ (t - t_o)^2\ \beta \tag{8}$$

in the peak region, where α and β are the first and second derivatives of s(t) evaluated at $t = t_o$. The value of t_p is found by setting the derivative of s(t) equal to 0:

$$0 = \left.\frac{\partial s}{\partial t}\right|_{t=t_p} = \alpha + (t_p - t_o)\,\beta , \tag{9}$$

or

$$t_p = t_o - \alpha/\beta . \tag{10}$$

Since t_o is a constant,

$$\sigma^2\,(t_p) = \sigma^2(\alpha/\beta) \sim \sigma^2(\alpha)/\beta^2 . \tag{11}$$

This last step is justified by noting that $\sigma\beta << \beta$. If $\sigma\beta$ were comparable to β, then the observed β would be negative and the s(t) peak would be inverted in a significant fraction (about 16% if $\sigma\beta = \mu\beta$) of the measurements. That is, the signal-to-noise level would be so small that the peak could not be reliably distinguished from random noise, and the measurement would be useless. For the LOFT data being considered, $\sigma\beta$ is clearly small compared to β.

If α is approximated by the finite difference representation, $\sigma^2\alpha$ can be estimated in terms of known quantities:

$$\alpha \sim \frac{S_{i+1} - S_i}{\Delta t} = \frac{1}{\Delta t}\left[\sum_j f_j\, C_{i+1+j} - \sum_j f_j\, C_{i+j}\right]$$

$$= \frac{1}{\Delta t}\left[\sum_k f_{k-i-1}\, C_k - \sum_k f_{k-j}\, C_k\right] \tag{12}$$

with i equal to the largest integer not greater than $t_o/\Delta t$. Then

$$\sigma^2\,\alpha = \sum_n \left(\frac{\partial \alpha}{\partial C_n}\right)^2 \sigma^2\, C_n$$

$$= \sum_n \left(\frac{f_{n-i-1} - f_{n-i}}{\Delta t}\right)^2 C_n \tag{13}$$

where C_n is used as the best available estimate of $\sigma^2\, C_n$. Because of the f values, the terms in this sum are non-zero only near the peak, and a reasonable approximation results from replacing all the C_n values by the value of S at the peak. Then this S value can be factored out of the sum, and the sum then contains only known quantities. In this LOFT PNA system, the sum is about $2.136 \times 10^{-5}/(\Delta t)^2$. Finally,

$$\sigma^2 t_p = \frac{2.136 \times 10^{-5} S_{peak}}{\beta^2 (\Delta t)^2} , \qquad (14)$$

Typical values for S_{peak} and β yield $\sigma t_p \sim 0.052$ or $\sigma t_p \sim 1.3\%$ of t_p. The uncertainty would be 2 σt_p for a typical data set, but the larger value of 5% of reading must be used as the uncertainty estimate to allow for atypical data.

4.3.2 Turbulence Fluctuations. Because of the random local velocity fluctuations associated with turbulence, the fluid that is activated in any one PNA measurement may not travel to the detector region with a velocity equal to the desired ensemble average fluid velocity. In fact, in any one measurement, some of the activated fluid may have different velocity fluctuations than other parts of the activated fluid, so that both the shape and the position of the s(t) peak may be changed randomly by turbulence. These effects are negligible if the fluid is very turbulent so that it is mixed in a small fraction of the distance L, and of course there are no turbulence effects in laminar flow. It is the realistic case of intermediate turbulence that can yield PNA measurement errors.

It is very difficult to obtain a rigorous estimate of the magnitude of the t_p uncertainty associated with turbulence. In this work, the shapes of the s(t) peaks for similar flow velocities were compared to obtain estimates of how much the $t_p - t_o$ varied for constant flow conditions. This variation is expected (intuitively) to give at least a rough indication of the standard deviation of t_p caused by the combinations of turbulence and radiation process randomness. The $t_p - t_o$ variation are generally within ±0.2 s. Variations about half this large are expected from radiation process randomness alone, so the remaining $\sqrt{(0.2)^2 - (0.1)^2} = 0.17$ s is used as the estimate of random variations of t_p due to turbulence. The uncertainty component is twice this, which is typically about 8% of reading. This uncertainty component estimate is very rough and should be regarded with some skepticism.

4.4 Predicted Uncertainty Summary

The various estimated uncertainty components and estimated mean errors (sometimes called bias or systematic errors) are summarized and combined in Table 1. The total estimated mean error is negligible compared to the random errors represented by the uncertainty. Some of the estimates of individual uncertainty components may have substantial errors; the total uncertainty could be as small as 8% or as large as 13 or 14% of reading.

It is generally not possible to make a quantitative comparison of this uncertainty estimate with most published PNA uncertainty estimates, because the uncertainty is strongly dependent on the details of the particular PNA system. An exception is found in the Rensselaer group's estimates of uncertainty in the results of their processing some of these LOFT PNA data.[40]

The peak position uncertainty, associated with radiation process randomness, is estimated as 10% by the Rensselaer group and as 2.6% by the procedures of Section 4.3.1 (for Data Blocks 24 and 26 only). This discrepancy is resolved by noting that the Rensselaer estimate is not claimed to be rigorous, and is furthermore based on a data-smoothing procedure different from that used by LOFT.

The Rensselaer uncertainty statements of 1.0 or 2.2% (for Data Blocks 26 and 24, respectively) using the mechanistic method and 2% with the finite difference method are not estimates of the total measurement uncertainty. They do not include the uncertainty in the source-to-detector distance, for example. Thus, it is not legitimate to compare those Rensselaer values with the present uncertainty estimate of 10.7%. These Rensselaer uncertainties should, however, be comparable with the combination of a certain subset of the uncertainty components estimated in this report; the subset probably would include all the uncertainty components in Table 1 except the source-to-detector distance and the turbulence components. For the particular data being considered, the combination of these components from Table 1

Table 1. LOFT PNA uncertainty components

Mean Errors	Percent of Reading
Velocity profile	-2.5
Lateral asymmetry	+2.0
Overall known error	-0.5
Uncertainties (2σ)	**Percent of Reading**
Source to detector distance	4.0
Velocity profile	2.5
Lateral asymmetry	2.0
Background radiation trend	0.1
Finite sample rate	0.6
Radiation randomness	5.0
Turbulence randomness	8.0
Overall uncertainty	10.74[a]

a. Because the estimates of individual uncertainty components contain considerable variation, the total uncertainty could be as low as 8% or as high as 14% of readings.

is about 4.1% of reading. This is substantially larger than the Rensselaer estimates. However, the difference between the results of the two Rensselaer methods applied to the same data is about 5.6%, which is larger than the sum of their uncertainty estimates for the two methods. This strongly suggests that the Rensselaer estimates of the uncertainties in their data processing methods are substantially too small and that the actual uncertainties in their methods may be at least as large as the uncertainty estimates in this report.

Thus, it seems that the LOFT PNA uncertainty predictions are consistent with other applicable uncertainty estimates.

4.5 Comparison of PNA with Venturi

Prior to L6-7, a direct comparison of the LOFT PNA measured flow velocity was made with a velocity determined by a venturi reading. For fluid velocities in the PNA application range, the agreement between the PNA and venturi velocities was good. At 3 m/s, PNA was 3% low, and at 4 m/s it was 7% low. At 6 m/s, PNA measured 21% low, and at 8 m/s is was 31% high. This disagreement at the higher flow velocities is due to the fact that the flow peak was barely discernible, and in one case (at 8 m/s), there was a double peak. Good agreement was not expected at these high velocities, which are outside the PNA application range. The observed PNA measurement errors of 7% or less seem consistent with the predicted uncertainties.

5. CONCLUSIONS

The LOFT PNA velocity measurement uncertainty is estimated to be about 11% of reading for the poorest published data, and somewhat smaller (perhaps 8%) for the better data.

Although 11% of reading seems at first glance like a rather large uncertainty, it is not unusually large for a global velocity measurement with the LOFT constraints and the low flow (1 m/s or less) conditions. The LOFT PNA hardware is carefully engineered and probably cannot be significantly improved using existing technology without violating size and weight limits. The LOFT PNA data processing procedures are believed to compare well with the alternatives (for which realistic uncertainty estimates have not been published). Alternatives to PNA—such as turbines, drag bodies, or pitot tubes—are not expected to work very well in the low flow conditions of interest, and they require a rather uncertain extrapolation from local measurements to global velocity estimates.

In summary, the LOFT PNA system is a useful and competitive global velocity measurement system with an uncertainty of about 11% of reading or less.

6. REFERENCES

1. D. L. Reeder, *LOFT System and Test Description (5.5-Ft Nuclear Core 1 LOCEs)*, NUREG/CR-0247, TREE-1208, July 1978.

2. M. L. McCormick-Barger et al., *Experiment Data Report for LOFT Nuclear Small Break Experiment L3-2*, NUREG/CR-1311, EGG-2016, April 1980.

3. G. E. McCreery, *Quick-Look Report on LOFT Nuclear Experiment L3-7*, EGG-LOFT-5192, June 1980.

4. B. D. Stitt and J. M. Divine, *Experiment Data Report for LOFT Anticipated Transient Experiment L6-7 and Anticipated Transient with Multiple Failures Experiment L9-2*, NUREG/CR-2277, EGG-2121, September 1981.

5. C. R. Boswell and T. B. Pierce, "Flowrate Determination by Neutron Activation Analysis," *Modern Developments in Flow Measurement*, PPL Conference Publication 10, London: Peter Peregrinus, Ltd., 1972, pp. 264-272.

6. R. C. Dougherty et al., *Newton Generator for Two-Phase Flow Calibration: Annual Progress Report*, NUREG/CR-0480, SAND78-2030, November 1978.

7. G. E. Rochau, "Development of a Pulsed Neutron Generator for Two-Phase Flow Measurements," *Review Group Conference on Advanced Instrumentation for Reactor Safety Research*, NUREG/CP-0007, October 1979, pp. III.10-1 through III.10-23.

8. G. E. Rochau, "A Pulsed Neutron Generator for Use with Pulsed Neutron Activation Technique," *Review Group Conference on Advanced Instrumentation Research for Reactor Safety*, NUREG/CP-0015, December 1980, pp. IV.2-1 through IV.2-14.

9. G. E. Rochau et al., "A Pulsed Neutron Generator for Mass Flow Measurement Using the Pulsed Neutron Activation Technique," *IEEE Transactions on Nuclear Science, NS-28*, 2, April 1981, pp. 1658-1660.

10. G. E. Rochau, *Neutron Generator for Use With Pulsed Neutron Activation Techniques: Final Report*, NUREG/CR-1905, SAND81-0197, June 1981.

11. G. E. Rochau, "A Pulsed Neutron Generator for Use with Pulsed Neutron Activation Techniques," *Eight Water Reactor Safety Research Information Meeting, 2*, NUREG/CP-0023, March 1982.

12. C. C. Price et al., "Flow Measurements in the EBR-II Secondary System, Using the Pulsed-Neutron Technique," *Reactor Development Program Progress Report, February 1976*, ANL-RDP-48, March 31, 1976, pp. 1.15-1.19.

13. C. C. Price, P. Kehler, and J. I. Sackett, "Fluid Flow Measurements at EBR-II Using Pulsed-Neutron Activation," *Transactions of the American Nuclear Society, 23*, June 1976, pp. 117-118.

14. C. C. Price, R. N. Curran, P. Kehler, and J. I. Sackett, "Flow Measurements in the EBR-II Secondary System, Using the Pulsed-Neutron Technique," *Reactor Development Program Progress Report, April 1976*, ANL-RDP-50, June 9, 1976, pp. 1.4-1.6.

15. P. Kehler, *Feasibility of Calibration of Liquid Sodium Flowmeters by Neutron Activation Techniques*, ANL-CT-76-17, July 1976.

16. Y. Y. Hsu (ed), *Two-Phase Flow Instrumentation Review Group Meeting*, NUREG-0375, March 1978.

17. P. Kehler et al., *Measurement of Liquid Sodium Flow in the Secondary System of the EBR-II by a Neutron Activation Technique*, ANL-CT-77-25, June 1977.

18. C. C. Price et al., *Application of the Pulsed-Neutron-Activation Technique for Flow Measurements at EBR-II*, ANL-77-52, November 1977.

19. G. Taylor, "Dispersion of Soluble Matter in Solvent Flowing Slowly Through a Tube," *Proceedings of the Royal Society of London, Series A, 219*, October 7, 1953, pp. 186-203.

20. P. Kehler, *Two-Phase Flow Measurement by Pulsed Neutron Activation Techniques*, ANL-NUREG-CT-78-17, January 1978.

21. R. N. Curran, "Results of Utah State University Attempt to Experimentally Verify the Correct Method for Interpretation of PNA Data," private communication, Argonne National Laboratory, Idaho Falls, ID, June 1980.

22. G. A. Forster and P. Kehler, *Sodium Flow Calibration Using a Pulsed Neutron Activation Technique on a 400 mm (16 inch) Pipe at LMEC*, ANL-CT-78-9, November 1977.

23. G. E. Santee, Jr., C. C. Price, and A. E. Wilson, "Asymmetry Effects in Fluid Flow Measurement Using Pulsed Neutron Activation." *Transactions of the American Nuclear Society, 27*, November-December 1977, pp. 217-218.

24. R. C. Block et al., "^{16}N Tagging of Water for Transient Flow Measurements," Idem Reference 23, pp. 682-683.

25. M. L. Perez-Griffo, R. C. Block, and R. T. Lahey, Jr., "^{16}N Tagging for Two-Phase Mass Flow Measurements," *Transactions of the American Nuclear Society, 30*, November 1978, pp. 500-501.

26. P. Kehler, "Two-Phase Flow Measurement by Pulsed Neutron Activation," *Review Group Meeting on Two-Phase Flow Instrumentation*, NUREG/CP-0006, April 1979, pp. I.9-1 through I.9-28.

27. P. Kehler, "Use of Pulsed Neutron Sources for Flow Measurement in Reactor Research," Idem Reference 25, pp. 141-142.

28. P. Kehler, "Pulsed Neutron Measurement of Single and Two-Phase Liquid Flow," *IEEE Transactions on Nuclear Science, NS-26*, 1, February 1979, pp. 1627-1631.

29. P. Kehler, "Pulsed Neutron Activation Techniques for the Measurement of Two-Phase Flow," Idem Reference 7, pp. III.9-1 through III.9-29.

30. M. L. Perez-Griffo, R. C. Block, and R. T. Lahey, Jr., "Determination of Mass Exchange Rates in ^{16}N Tagged Slug Flow," *Transactions of the American Nuclear Society, 33*, November 1979, pp. 984-986.

31. P. Kehler, "Accuracy of Two-Phase Flow Measurements by Pulsed Neutron Activation Techniques," *Multiphase Transport: Fundamentals, Reactor Safety, Application 5*, Washington, D.C.: Hemisphere Publishing Corporation, May 1980, pp. 2483-2506.

32. M. L. Perez-Griffo, R. C. Block, and R. T. Lahey, Jr., "Basic Two-Phase Flow Measurements Using ^{16}N Tagging Techniques," *Proceedings of the 1980 International Topical Meeting on Nuclear Reactor Thermal-Hydraulics*, NUREG/CP-0014, Vol. 2, October 1980, pp. 923-933.

33. P. Kehler, "Measurement of Slow Flow Velocities by the Pulsed Neutron Activation Technique," Idem Reference 8, pp. IV.1-1 through IV.1-37.

34. P. Kehler, "Pulsed Neutron Activation Techniques in Water Reactor Safety Research," Idem Reference 11, March 1982.

35. P. Kehler, "Two-Phase Flow Measurements by Pulsed Neutron Activation Techniques," *Ninth Water Reactor Safety Research Information Meeting, 1*, NUREG/CP-0024, March 1982.

36. M. L. Perez-Griffo, R. C. Block, and R. T. Lahey, Jr., "Non-Uniform Tagging and Flow Structure Effects in PNA Measurements," *Transactions of the American Nuclear Society, 35*, November 1980, pp. 637-640.

37. M. L. Perez-Griffo, R. C. Block, and R. T. Lahey, Jr., "A Mechanistic Analysis of LOFT Pulsed Neutron Activation Data," *Transactions of the American Nuclear Society, 38*, June 1981, pp. 750-751.

38. M. L. Perez-Griffo, R. C. Block, and R. T. Lahey, Jr., "Measurement of Flow in Large Pipes by Pulsed Neutron Activation (PNA)," to be published in *Nuclear Science and Engineering*.

39. D. J. N. Taylor and J. K. Hartwell, "The LOFT Pulsed Neutron Activation System of Fluid Flow Measurement," presented at *ASME Symposium on Measurements in Polyphase Flows, St. Louis, Mo.*, June 7-11, 1982.

40. M. L. Perez-Griffo, R. C. Block, R. T. Lahey, Jr., *Analysis of the Pulsed Neutron Activation Technique*, NUREG/CR-2471, EGG-2160, January 1982.

41. P. Kehler and N. Kondic, "Pulsed Neutron Activation (PNA) Technique Application to Fluid Velocity Determination in Nuclear Plant Simulators", *Instrumentation in the Aerospace Industry 28, Advances in Test Measurement 19*, 2 *Proceedings of the 28th International Instrumentation Symposium, Las Vegas, Nevada*, May 3-6, 1982, pp. 291-306.

42. L. O. Johnson, "A High Rate NaI Detector System," Idem Reference 28, pp. 465-475.

120555078877 1 ANR2
US NRC
ADM DIV OF TIDC
POLICY & PUBLICATIONS MGT BR
PDR NUREG COPY
LA 212
WASHINGTON DC 20555

EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, Idaho 83415