PULSED NEUTRON ACTIVATION CALIBRATION TECHNIQUE

by

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Introduction

Fig. 1 shows a schematic diagram of a Pulsed Neutron Activation (PNA) setup for the measurement of two-phase flow: A pulsed source of fast neutrons (E_n = 14 MeV) is used to activate the oxygen in a steam-water mixture by the O^{16} (n,p) N^{16} reaction, and the activity introduced into the flow is measured downstream of the source by a NaI detector. The measured counts are sorted by a multiscaler into different time channels. A counts vs. time distribution typical for two-phase flow with slip between the two phases is shown in Fig. 1. Proper evaluation of this counts/time distribution leads to flow-regime independent equations for the average of the inverse transit time, $\overline{(1/t)}$, and the average density ρ (Fig. 2). After calculation of the average mass flow velocity U_m, the true mass flow is derived as $\dot{\rho} = U_m \rho F$, where F = cross sectional area of the pipe.

Using the PNA technique, the velocity measurement is reduced to measurement of distance and time, and the density measurement is reduced to measurements of ratios of numbers of counts. Measurements of distance and time can be performed absolutely with great accuracy, and the errors normally associated with the measurement of numbers of counts are eliminated by the ratio used for the derivation of density. Sensitivity of the detectors, gain of the electronic equipment and collimation angles of the source and the detectors need not to be known as long as they are kept constant during an experiment. Gain stability of the electronic equipment is assured by locking it on the Cs^{137} peak. Thus using the PNA technique, two-phase mass flow measurements can be reduced to measurements of distance and time only, a feature that makes very attractive the use of PNA techniques for the calibration of other, more indirect two-phase flow measuring devices.

All parameters effecting the registered number of counts can be summarily described by the "K-value", a calibration constant that is derived by measuring the activity A of water flowing at a known average velocity in a completely filled pipe (ρ = 1 g/cm^3). Although the correct determination of the K-value must be performed according to the equations shown in Fig. 2, it can be approximated by the total number of counts, C_o, measured on a water-filled pipe (ρ_o = 1 g/cm^3) in which the water is flowing at a velocity of U_o = 1 m/sec (See Fig. 3). Experimentally determined K-values for various conditions are tabulated in Fig. 3. The detectors used in these tests were NaI scintillation detectors, with dimensions as shown. The TC-655 neutron source has an output of 3 x 10^9 neutrons/pulse. The K-values listed in Fig. 3 are a valuable aid in planning PNA tests, since K-values for other sources and detectors can be estimated from those listed by proportionating them to the new source strengths and detector areas. Once the K-value of a PNA setup is estimated, the total number of counts, C, expected for any flow conditions can be estimated by $C = K \rho/U$. The number of counts, C, should be $C \geq 1000$ if the average density is to be measured with an error of $\leq 3\%$, and the mass flow velocity is to be measured with an error of $\leq 4\%$.

Application of PNA Technique

Figure 4 lists those fields where application of PNA techniques was found to be useful. First of all, the PNA technique is more accurate than any other two-phase flow measuring device for the measurement of mass flow in small pipes (with diameters $D \leq 10$ cm), and can be used for calibration of these devices. The basic equations for velocity and density measurements (Fig. 2) are rigidly valid only if the neutron fluence and the sensitivity of the detectors can be assumed to be constant over the whole cross section of the pipe. These conditions are sufficiently met for pipe diameters $D \leq 10$ cm. For larger pipes, a correction must be applied to the density reading, considering the attenuation of neutrons and gammas in the fluid as well as geometric attenuation ($1/r^2$ law). Although these effects can be easily modeled, and correction factors for the density reading can easily be derived for large pipe diameters, the PNA technique can not be considered as an absolute two-phase flow calibration tool for large pipes. However, relative measurements can be made even on large-diameter pipes, and gain changes of permanently installed flowmeters can be detected and calibrated by portable and non-intrusive PNA equipment.

The PNA technique is a non-intrusive radioactive tracer technique and, therefore, can be used like any other tracer technique for the measurement of flow distributions in large flow systems. We have measured the ECC bypass ratio in the LOFT reactor and plan to measure flow distributions in the 3-D test facility.

A unique capability of the PNA technique is the measurement of slow flows. This capability is usefully applied to tests simulating slow breaks. TMI related PNA flow measurements are planned for the LOFT reactor (EG&G Idaho, Inc.) and for the PKL (Erlangen, Germany).

Progress in 1979

PNA work performed at the Argonne National Laboratory (ANL) in 1979 is listed in Fig. 5. The PNA technique is now believed to have been developed to a point when it is prudent to disseminate it to other users. A number of publications (Fig. 6) was written with this in mind. ANL assembled PNA equipment is now installed at the LOFT facility for use on the L3-1 test. EG&G Idaho, Inc., will use their own PNA equipment in future small-break tests (L3 series). Another set of ANL assembled PNA equipment will be used at the PKL (at Erlangen, Germany), in the small-break tests planned there for the first quarter of 1980.

Progress was also made in the areas of testing, analysis, and instrumentation development.

Tests

The PNA technique was used for the measurement of the Emergency Core Cooling (ECC) bypass ratio at the LOFT reactor. The geometric arrangement of PNA equipment (Fig. 7) as well as the preliminary results of this test were presented at last year's meeting. After this meeting, a more detailed analysis of the test data was performed, which can be summerized as follows:

Transient flow in the broken cold leg during the L1-5 Loss Of Coolant Experiment (LOCE) lasted for less than 50 sec (Fig. 8). During this time, fluid in the ECC line was activated by pulsed neutrons three times: at the beginning of the ECC flow, well within the flow, and at a time when the ECC flow was mixed with the pressurant that expels it from the storage tanks. Figure 8 shows the ECC flow through the ECC injection line. The times at which the three PNA tests were made are indicated by arrows in Fig. 8. The ECC bypass ratio is defined as that amount of ECC fluid that went out through the broken cold leg (Fig. 7), and was found to be 0.4 for the two PNA measurements taken while liquid was flowing through the ECC line, and 0.8 at the third PNA measurement, where the ECC liquid was mixed with the pressurant. A detailed analysis of the time distribution of the activities measured in the broken col fleg (by the Detectors 1 and 2 in Fig. 7) led to the conclusion that the flow conditions in the reactor vessel were different for each of the three PNA measurements:

The ECC fluid activated by the first neutron burst bypassed the core and left the broken cold leg in one coherent slug (Fig. 9). LOFT instrumentation data support the interpretation that, at this time, the water level in the reactor vessel was below the core barrel, that the ECC fluid went down the downcomer on one side of the core barrel, passed under the barrel, and that about 40% of the liquid went up the downcomer on the other side of the core barrel and out through the broken cold leg. 60% of the ECC fluid went up into the core assembly.

At the time of the second neutron burst, the reactor vessel was partially filled with water. The ECC fluid injected into the vessel fell on the existing water surface, mixed with the surface layers, went around the core barrel on different paths, and 40% of it went out through the broken cold leg in several small and poorly defined slugs (Fig. 9). The remainder mixed with the water in the partially filled vessel and stayed there.

The two-phase mixture flowing is the ECC injection line during the third neutron burst resided in the reactor for a very short time only. At this time, the vessel was almost filled with water, and most of the ECC fluid (80%) only skimmed the surface of the liquid in the vessel and went out, through the broken cold leg in one well defined slug.

PNA tests were also performed at the FAST loop, a large diameter (30 cm) test loop operated by EG&G at the INEL. The objective of this test was to evaluate the performance of a water pump when operating under two-phase flow conditions, and to compare readings from a LOFT spool spiece with PNA measurements. The geometric arrangement of PNA equipment on the loop is shown schematically in Fig. 10. The pump failed when the void fraction went up to 20%. The distribution of counts measured at this void fraction (Fig. 11) indicated that the flow was homogeneous without measurable slip between the velocities of the two phases. The flow regimes found at the lower void fractions were similar to the one shown in Fig. 11.

The detailed analysis of the PNA data taken at the FAST loop is still in progress. This analysis is more complicated due to the need to model two-phase flow for the large-pipe correction of the density readings. The K-value for 30 cm-pipes, needed for test planning for the L3-1 test at the LOFT reactor, was measured experimentally during this FAST-loop test.

Analyses

The K-value of a particular PNA setup depends not only on the diameter of the pipe, but also on its wall thickness. Source characteristics effecting the K-value are neutron output, collimation, and distance from the pipe. Detector size, collimation, nuclear efficiency as well as the distance of the detector from the pipe also enter into the K-value. Even the electronic equipment used for data processing effects the K-value of a PNA setup, through the setting of the gamma ray energy discriminator. All these parameters are constant during a particular PNA test and the K-value of any particular setup can be determined experimentally by performing PNA measurements on a water-filled pipe in which the water is flowing with a known velocity.

In large pipes, the number of counts registered by PNA equipment is effected not only by the parameters mentioned above but also by geometric and nuclear attenuations. These effects can be best formalized by using corrected K-values for large pipes. In the absence of geometric and nuclear attenuations, the K-value should be proportional to the cross sectional area of the pipe, $K \propto D^2$. Deviations from this ideal relation are shown in Fig. 12. Relations between the density readings obtained from non-corrected K-values and the true density, are shown in Fig. 13 for several pipe diameters.

The Figures 12 and 13 were computed by use of the FORTRAN program PNA-SIMulation, which is an advanced version of the program ACTivation OPTimization written previously for single-phase flow (Paul Kehler, "Feasibility of Calibration of Liquid Sodium Flowmeters by Neutron Activation Techniques", ANL-CT-76-17, July 1976). The PNASIM program models all the parameters effecting the K-value as discussed above, as well as various regimes of two-phase flow. Presently, it is written in polar coordinates and models homogeneous and annular flows, with tabulated inputs of velocity and density distributions. Rectangular coordinates will be used to model stratified flow. The accuracy of the models used in PNASIM was verified by experimentally determined K-values (Fig. 3) and flow distributions (Fig. 11). It is planned to improve the PNASIM program by improving its mixing model and by using analytically expressed void and velocity distributions.

Instrumentation Development

The geometric effects on the K-value can be reduced by using a multiplicity of sources and detections, arranged circumferentially around the pipe. A torus detector (Fig. 1) fully encircling pipes with dameters $D \leq 15$ cm, was built to increase the total number of counts and to reduce the geometric effect on the K-value. Using this torus detector, the correction to be applied to the K-value for pipe diameters $D \leq 15$ cm is much smaller than that shown in Fig. 12, which was calculated for input parameters representative of the PNA setup now used on the LOFT reactor. The only variable in Fig. 12 is the diameter of the pipe.

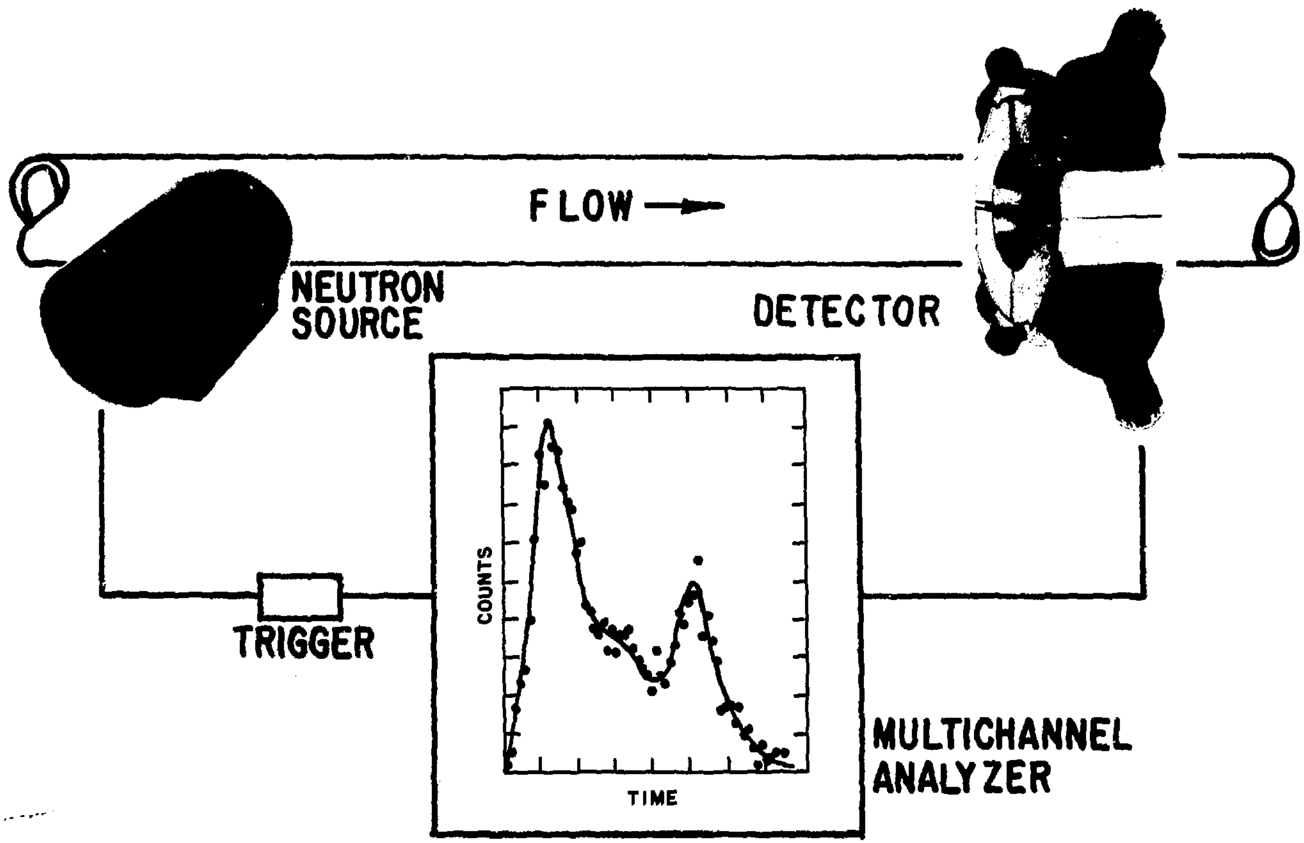

FLOW
NEUTRON SOURCE
DETECTOR
TRIGGER
COUNTS
TIME
MULTICHANNEL ANALYZER

Fig. 1

PNA EQUATIONS

- MASS FLOW VELOCITY U_M FROM THE MASS WEIGHTED AVERAGE OF THE INVERSE OF THE TRANSIT TIME DISTRIBUTION:

$$U_M = \overline{\left(\frac{1}{T}\right)} Z$$

Z = SOURCE - DETECTOR SPACING

$$\overline{\left(\frac{1}{T}\right)} = \frac{\sum \frac{1}{T^2} C\, \varepsilon^{\lambda T}}{\sum \frac{1}{T} C\, \varepsilon^{\lambda T}}$$

C = NUMBER OF COUNTS AT TIME T

λ = DELAY CONSTANT OF ACTIVATED O^{16}

- AVERAGE DENSITY ρ FROM THE TOTAL AMOUNT OF ACTIVITY A INJECTED INTO THE FLUID BY ONE NEUTRON PULSE:

$$\rho = \frac{A}{K}$$

K = CALIBRATION CONSTANT

$$A = \frac{1}{T} \sum C\, \varepsilon^{\lambda T}$$

Fig. 2

EXPERIMENTALLY DETERMINED K-VALUES

$$K = \frac{U_0 C_0}{\rho_0}$$

SOURCE: TC 655	DETECTOR:				
PIPE DIAMETER (CM)	DIAMETER (CM)	HEIGHT (CM)	PIPE DIAMETER (CM)	K	TEST LOCATION
7.5	7.5	7.5	7.5	1280	A/W LOOP
7.5	12.5	7.5	7.5	2480	A/W LOOP
12.5	7.5	7.5	12.5	1050	A/W LOOP
12.5	12.5	7.5	12.5	2670	A/W LOOP
10.0	12.5	7.5	35.0	280	LOFT
35.0	12.5	7.5	35.0	640	FAST

NOTE: WHEN K IS KNOWN, THE TOTAL NUMBER OF COUNTS IS ESTIMATED BY:

$$C = \frac{K\rho}{U}$$

Fig. 3

APPLICATIONS OF PNA TECHNIQUE

- CALIBRATION OF TWO-PHASE FLOW INSTRUMENTATION IN TEST LOOPS.
- IN-SITU RE-CALIBRATION OF TWO-PHASE FLOW INSTRUMENTATION INSTALLED IN LARGE TEST FACILITIES.
- MEASUREMENT OF FLOW DISTRIBUTIONS.
- MEASUREMENT OF SLOW FLOW VELOCITIES (TMI-RELATED SLOW-BREAK TESTS).

Fig. 4

SUMMARY OF PROGRESS

1979

- DISSEMINATION OF PNA TECHNIQUE

  PUBLICATIONS

  TRANSFER OF TECHNOLOGY (LOFT, PKL)

- TESTS

  PERFORMED: LOFT L1-5 (ANALYSIS OF DATA)
  FAST LOOP

  PLANNED:

PLANNED:	LOFT L3-1	Nov.	79
	ORNL	Dec.	79
	PKL	Jan.	80
	3-D		80
	SLAB CORE		80 ?

- ANALYSIS

  PERFORMED: MODELING OF TWO-PHASE, HOMOGENEOUS AND ANNULAR FLOW (PROGRAM PNASIM)

  PLANNED: MODELING OF STRATIFIED FLOW, PHASE CHANGE, IMPROVEMENT OF MIXING MODEL

- DEVELOPMENT OF INSTRUMENTATION

  PERFORMED: TORUS DETECTOR

  PLANNED: GLOBAL GAMMA DENSITOMETER

Fig. 5

PUBLICATIONS SINCE LAST MEETING

1) PAUL KEHLER: "USE OF PULSED NEUTRON SOURCES FOR FLOW MEASUREMENTS IN REACTOR RESEARCH", TRANS. AM. NUCL. SOC. 30, 14 (NOV 1978).

2) PAUL KEHLER: "TWO-PHASE FLOW MEASUREMENT BY PULSED NEUTRON ACTIVATION TECHNIQUES", MEASUREMENTS IN POLYPHASE FLOW, P. E. STOCK EDITOR, ASME PUBLICATION H001211 (DEC 1978).

3) PAUL KEHLER: "PULSED NEUTRON MEASUREMENT OF SINGLE- AND TWO-PHASE LIQUID FLOW", *IEEE TRANS. NUCL. SC.* NS-26 (1), 1627 (FEB 1979).

4) M. KONDIC, P. KEHLER, S. NAFF: "REACTOR VESSEL BLOWDOWN: DETERMINATION OF EMERGENCY CORE COOLING PARAMETERS", ASME PUBLICATION 79-HT-83 (JUNE 1979).

5) PAUL KEHLER AND C. W. SOLBRIG: "MEASUREMENT OF THE EMERGENCY CORE COOLANT BYPASS FLOW ON THE LOFT REACTOR", NUREG/CR-0208 (IN PRINT).

6) PAUL KEHLER: "ACCURACY OF TWO-PHASE FLOW MEASUREMENTS BY PULSED NEUTRON ACTIVATION TECHNIQUES", PRO. 2ND MULTI-PHASE FLOW AND HEAT TRANSFER SYMP. WORKSHOP, MIAMI BEACH, FL (APRIL 79).

7) PAUL KEHLER: "TWO-PHASE FLOW MEASUREMENT BY PULSED NEUTRON ACTIVATION TECHNIQUES", PROC. (Y. Y. HSU, EDITOR), REVIEW GROUP MTG. ON TWO-PHASE FLOW INSTRUMENTATION, NUREG/CP-0006 (MAY 1979).

Fig. 6

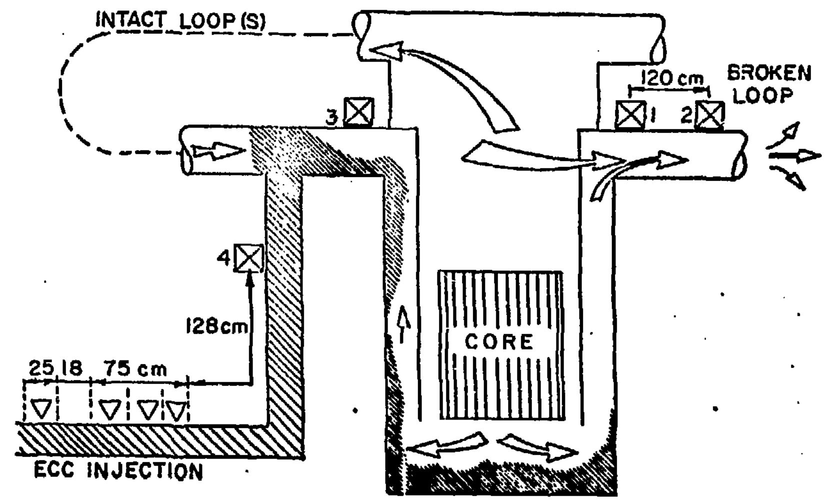


Fig. 7

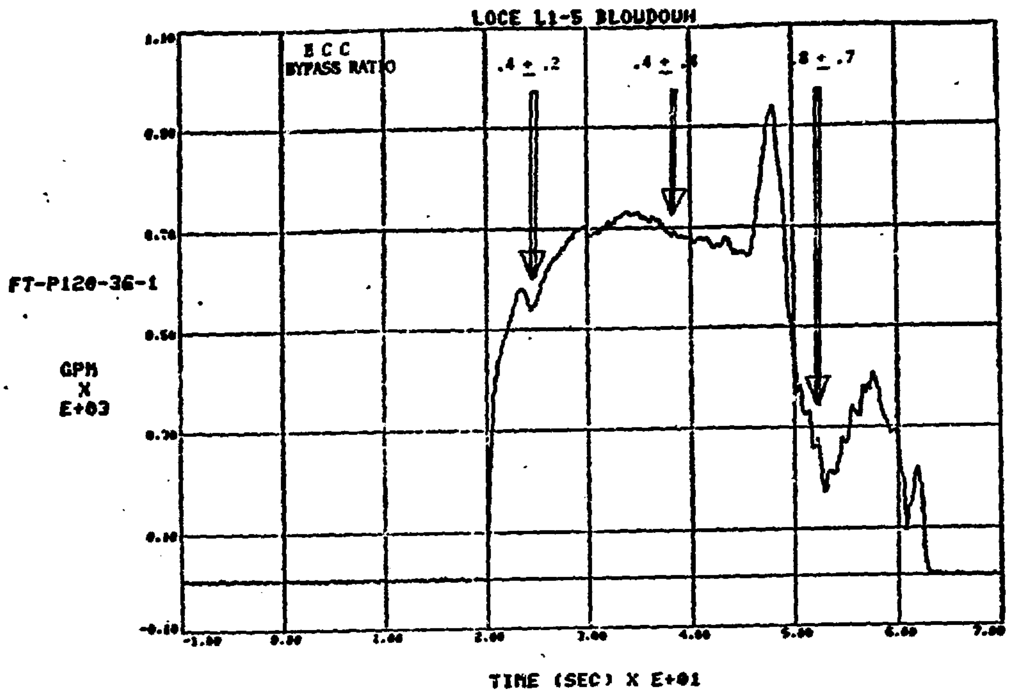


Fig. 8

L1-5 TEST DATA

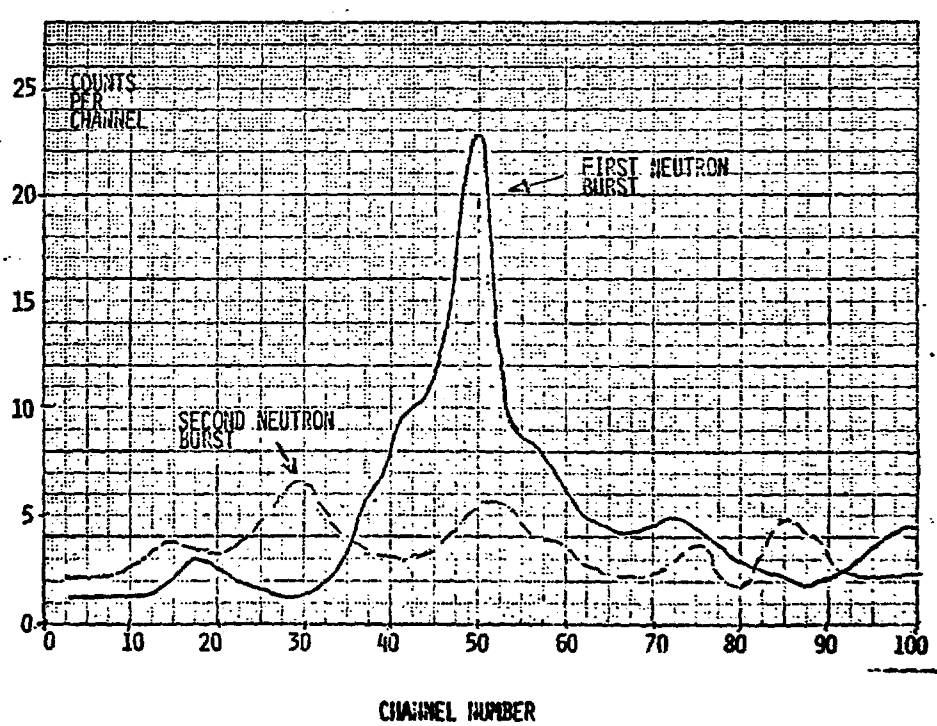
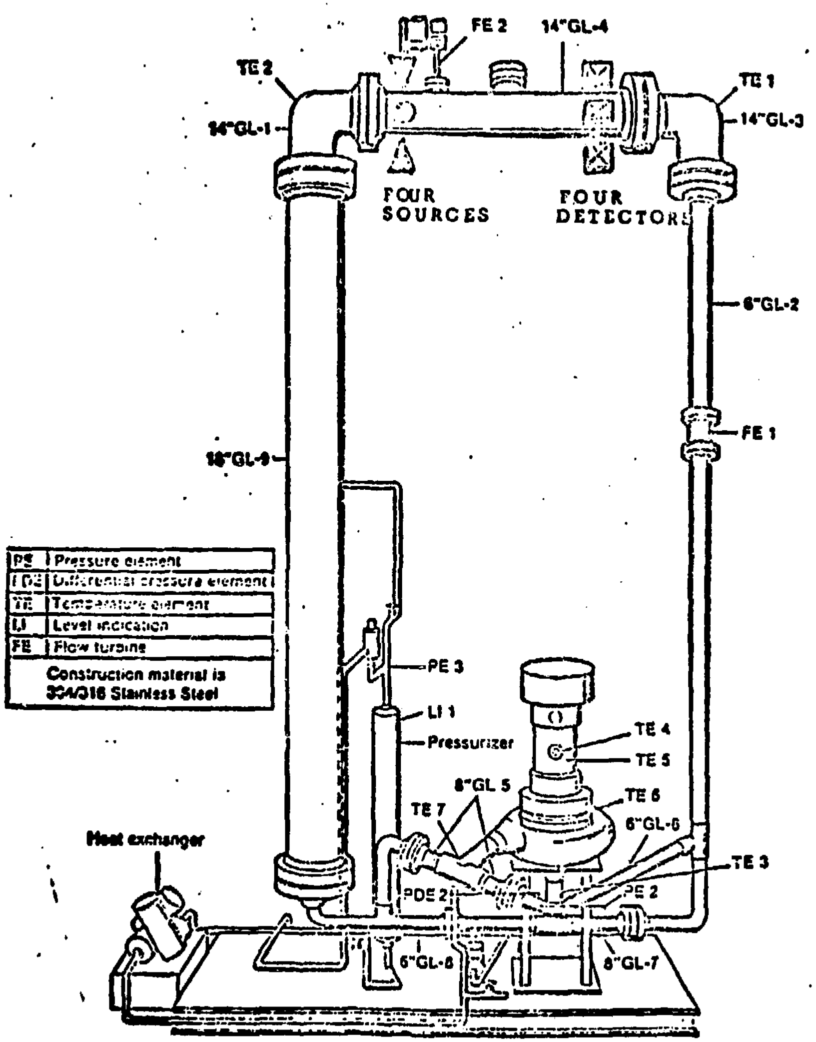
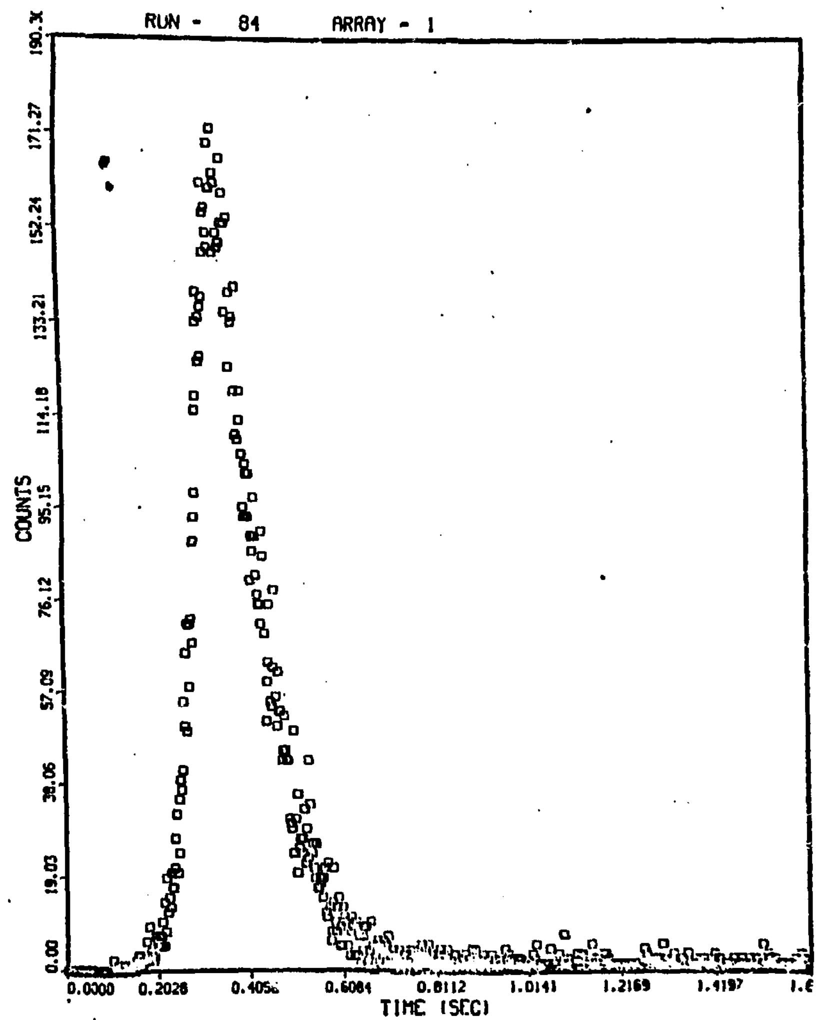


Fig. 9



FE 2
14"GL-4
TE 2
TE 1
14"GL-1
14"GL-3
FOUR SOURCES
FOUR DETECTORS
6"GL-2
FE 1
18"GL-9
PE 3
LI 1
Pressurizer
TE 4
TE 5
8"GL 5
TE 6
TE 7
6"GL-6
TE 3
PDE 2
PE 2
Heat exchanger
6"GL-8
8"GL-7
Construction material is 304/316 Stainless Steel

Fig. 10



RUN - 84
ARRAY - 1
COUNTS
TIME (SEC)
0.00
19.03
38.06
57.09
76.12
95.15
114.18
133.21
152.24
171.27
190.3
0.0000
0.2028
0.4056
0.6084
0.8112
1.0141
1.2169
1.4197

Fig. 11

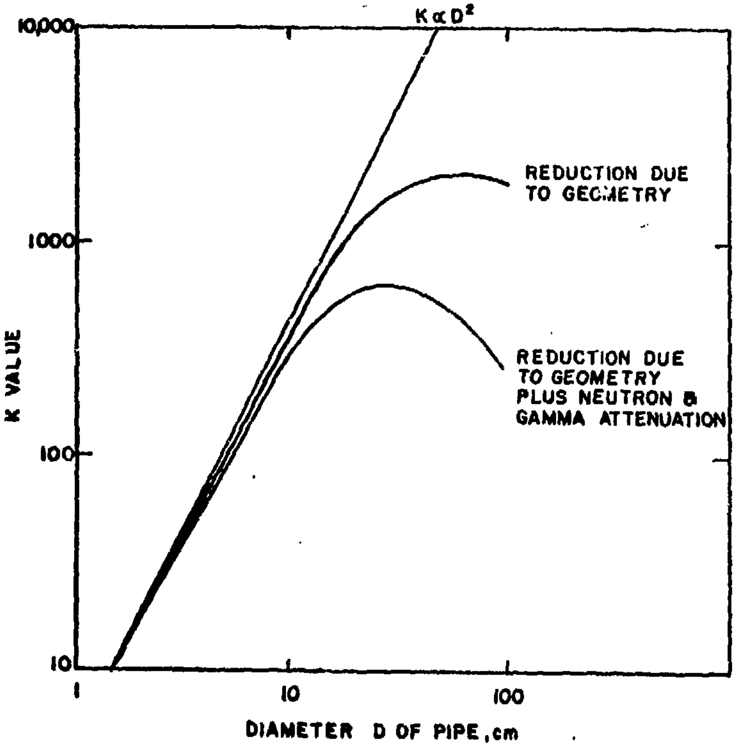

K ∝ D²
10,000
1000
100
10
K VALUE
1
10
100
DIAMETER D OF PIPE, cm
REDUCTION DUE TO GEOMETRY
REDUCTION DUE TO GEOMETRY PLUS NEUTRON & GAMMA ATTENUATION

Fig. 12

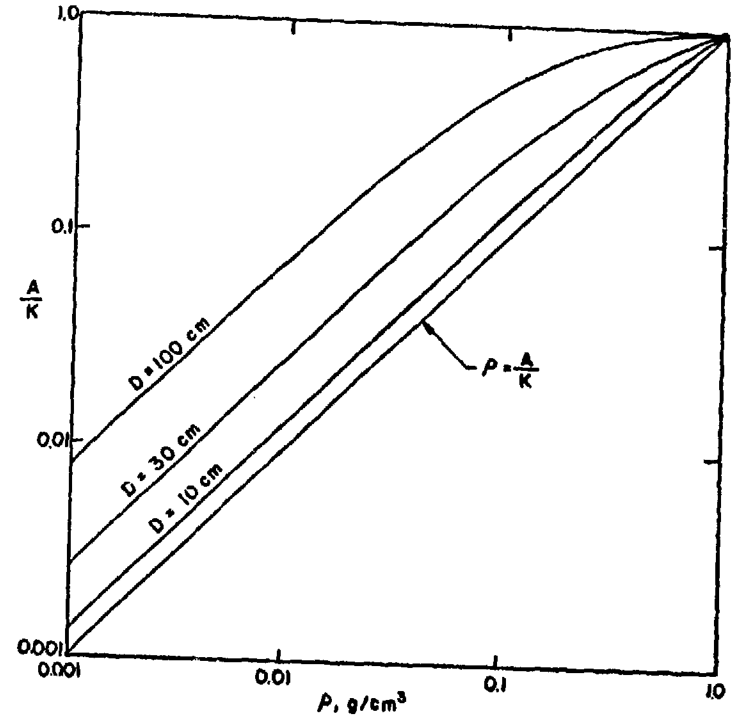

1.0
0.1
0.01
0.001
A/K
0.001
0.01
0.1
1.0
ρ, g/cm³
D = 100 cm
D = 30 cm
D = 10 cm
ρ = A/K

Fig. 13