TECHNICAL MEMORANDUM ANL-CT-76-17

MASTER

FEASIBILITY OF CALIBRATION OF LIQUID SODIUM FLOWMETERS BY NEUTRON ACTIVATION TECHNIQUES

by

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Components Technology Division

ARGONNE NATIONAL LABORATORY

U of C-AUA-USERDA

Base Technology

July 1976

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LMFBR Instrumentation
and Controls (UC-79m)

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ABSTRACT

Velocities of fluids in pipes can be measured by injecting radioactive tracers into the fluid and recording the activity downstream of the injection point. One convenient method of injecting radioactive tracers is by neutron activation of the fluid itself.

The present report describes a FORTRAN program that can be used for the prediction of the counting rates of fluid flow tests performed with a pulsed neutron source and a scintillation detector. The program models the flow profile and the mixing of the fluid, the attenuation of neutrons and gamma rays in the fluid, and the geometric arrangement of the source and the detector.

Using this program, an experiment for the measurement of the secondary sodium flow of the EBR-II was optimized. A pulsed D,T neutron source and a 5 in. x 5 in. NaI detector will be used in the EBR-II test. Under optimized conditions, the expected accuracy of the flow measurement is about 2%.

FEASIBILITY OF CALIBRATION OF LIQUID SODIUM FLOWMETERS BY NEUTRON ACTIVATION TECHNIQUES

1.0 SUMMARY

Two techniques for the measurement of the flow of liquid sodium, using neutron activation methods, are described in this report. Both techniques involve the activation of sodium flowing through a pipe by a burst of 14-MeV neutrons and the measurement of the resulting radioactivity by a system of scintillation detectors mounted downstream of the neutron source. Since the neutron source,as well as the detectors, are mounted external to the sodium pipes, all of the equipment can be installed and the flow velocity measurement can be performed during normal operation of the system.

The ability to measure flow in pipes without insertion of probes into the pipes and without attachment of electrodes to the pipes is a major advantage of neutron activation techniques, when compared to other flow measuring methods. Another advantage of neutron activation techniques is that in one of the techniques, flow velocity measurements can be reduced to two very basic measurements of a distance (the distance between source and detectors) and a time (the time between the neutron pulse and the arrival of the activated sodium at the location of the detectors). Fluctuations in the strength of the neutron source or in the efficiency of the detectors do not affect the flow velocity measurement. The second technique described in this report requires the measurement of the total number of counts registered during the passage of the activated sodium past the detectors. The third advantage of neutron activation techniques is that, by proper data handling, flow velocity measurements can be made independent of the flow profile in the pipe and independent of the turbulent mixing of the sodium.

The preferred technique requires irradiation of the flowing sodium with a short burst of neutrons and the subsequent registration of the induced activity as a function of elapsed time, and therefore does not provide a continuous flow measurement. This feature, in combination with the complexity of the required instrumentation, limits the practical use of the proposed technique to calibrate other permanently installed and continuously indicating flowmeters.

Another limitation of the proposed technique is the requirement that the background activity of the flowing sodium be low. This precludes measurement of flow velocity in primary sodium loops containing highly activated sodium.

Sodium flow measurement in secondary loops, however, should be easily and accurately performed with the proposed neutron activation technique.

A computer program was written that predicts the accuracy of flow velocity for sodium flowing through a pipe with known average velocity, known flow profile, and known mixing length. The objective was to determine the feasibility of calibrating flowmeters in the secondary loop of the EBR-II by neutron activation techniques. Variable parameters of the experimental setup, such as source strength, size and number of detectors, source-detector spacing, source and detector collimation angles, and the desired number of information channels were optimized for a minimum expected error of the measured flow velocity in the secondary loop of the EBR-II.

It was found that, in the EBR-II, an overall error of the measured flow velocity of less than 1.5% is expected when a neutron source of 10^{10} neutrons per pulse is used, when the sodium is irradiated and measured through a steel wall 1/4 inches thick with six inches of pipe thermal insulation material, and when no background is present.* The fundamental error of the neutron activation technique due to flow profile and flow mixing was found to be negligible. The portion of the error due to inaccuracies in time and distance measurements was also found to be negligible. The main source of the overall error was found to be counting statistics.

Based on these results, an experiment for the verification of the neutron activation flow measuring technique was proposed to be performed on the secondary loop of the EBR-II.

2.0 INTRODUCTION AND BACKGROUND

A summary review of instruments suitable for the continuous measurement of flow velocities of liquid sodium at high temperatures is given in Ref. 1. Of the devices studied in this reference, four have found practical application: permanent magnet flowmeters,[2] eddy current flowmeters,[3] magnetometer flowmeters,[4] and wound coil electromagnetic flowmeters.

2.1 Calibration of Liquid Sodium Flowmeters

Conventional calibration techniques for permanent magnet and eddy current flowmeters require their removal from the flow channel for subsequent evaluation in sodium loops under well-controlled conditions. The "gain" of magnetometer flowmeters can be calibrated in situ, but shutdown of the reactor is necessary for the setting of the "zero" of magnetometer flowmeters. Obviously, calibration techniques that allow for complete in-situ calibration of flowmeters (i.e., gain and zero calibration) without interruption of reactor operations are much more desirable than conventional calibration techniques.

One way to perform in-situ calibration of liquid sodium flowmeters is by use of neutron activation techniques. The equipment required for activation measurements consists of a pulsed neutron source, one (or more) scintillation detectors, and electronic pulse processing instruments, including a multi-channel analyzer. The neutron source, as well as the scintillation detectors, can be mounted externally to the flow channel, and flow measurements can be performed without interruption of reactor operations. A block diagram for the basic setup of a neutron activation measurement system in shown in Fig. 1.

The pulsed neutron source shown in this figure is shielded by lead and polyethylene, receives its power from the generator power supply, and is triggered to emit a single burst of 14-MeV neutrons. The latter are preferred because they can be easily produced by the D(T, n) α reaction, and because the activation cross sections for sodium are large for high neutron energies. Possible reactions of 14-MeV neutrons with sodium are listed in Table 1. This table lists the cross section (in millibarns), the half-life ($T_{1/2}$) of the reaction product, and the energy of the gamma radiation emitted by the reaction product.

Pulses from the scintillation detectors are passed through a preamplifier and a single channel analyzer, and stored in individual time channels of a multichannel analyzer. These data are then permanently stored on magnetic or paper tapes.

Basically, there are two different techniques for reduction of the measured data to obtain flow velocities. The first technique is based on a measurement of induced activity, whereas the second technique is based on the measurement of time. A discussion of the merits and limits of these two evaluation techniques is presented below.

2.2 Calibration of Flowmeters by Activity Measurements

One way to measure flow velocity independent of flow profiles is to introduce a known amount of radioactive material into the flow channel (either by injection or by neutron activation), and then to measure the total activity at a known distance downstream from the injection point.

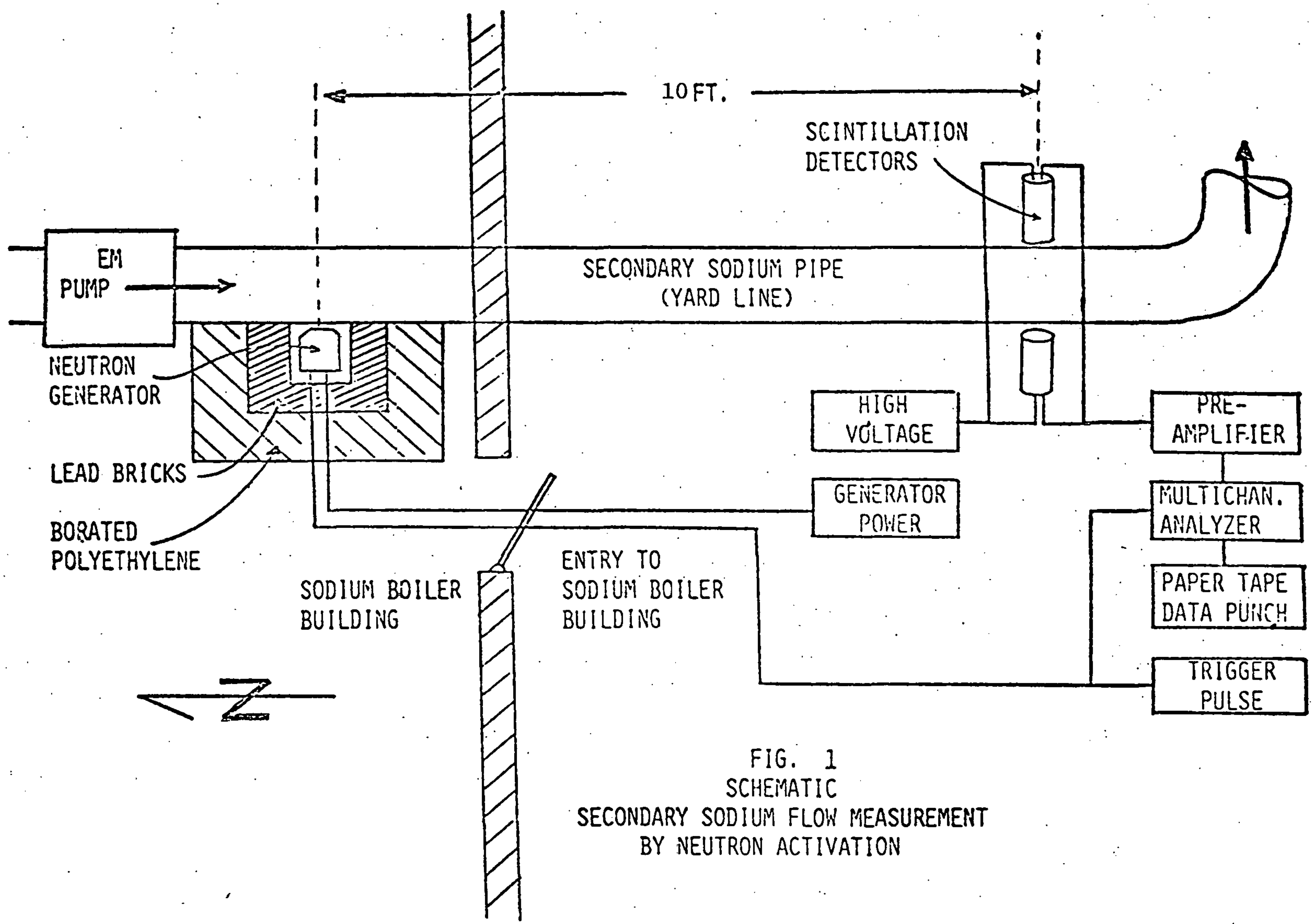

FIG. 1
SCHEMATIC
SECONDARY SODIUM FLOW MEASUREMENT
BY NEUTRON ACTIVATION

Table 1. Fast Neutron Reactions with Sodium

Reaction	Cross Section (mb)	$T_{1/2}$ (sec)	E (MeV)
Na^{23} (n,α) F^{20}	185	11.2	1.6
Na^{23} (n,p) Ne^{23}	42	37.6	0.44; 1.6
Na^{23} (n,2n) Na^{22}	12	8×10^7	1.28
Na^{23} (n,γ) Na^{24}	.2	5×10^4	2.75

When the original activity is A_o and the activity at the detector location is A,

$$A = A_o e^{-\lambda t} , \tag{1}$$

where

λ = decay constant of the radioactive element,

and

t = time elapsed between injection and measurement.

Substituting for t,

$$t = d/v, \tag{2}$$

where

d = distance between injection and measurement location,

and

v = flow velocity,

the activity can be expressed as,

$$A = A_o e^{-\lambda d/v} . \tag{3}$$

When the width of the detector "window" is w, each particle will be "visible" to the detector for a time w/v, and the number of counts N will be proportional to this time and to the activity A and

$$N = \text{const.} \frac{w}{v\ e^{\lambda d/v}} . \tag{4}$$

For a constant window width w,

$$N = \frac{\text{const.}}{v\ e^{\lambda d/v}} . \tag{5}$$

Values for N are plotted in Fig. 2 as a function of the flow velocity v for different source-detector spacings d, and for

$$\lambda = 0.693/T = 0.693/11.2 = 0.0619. \tag{6}$$

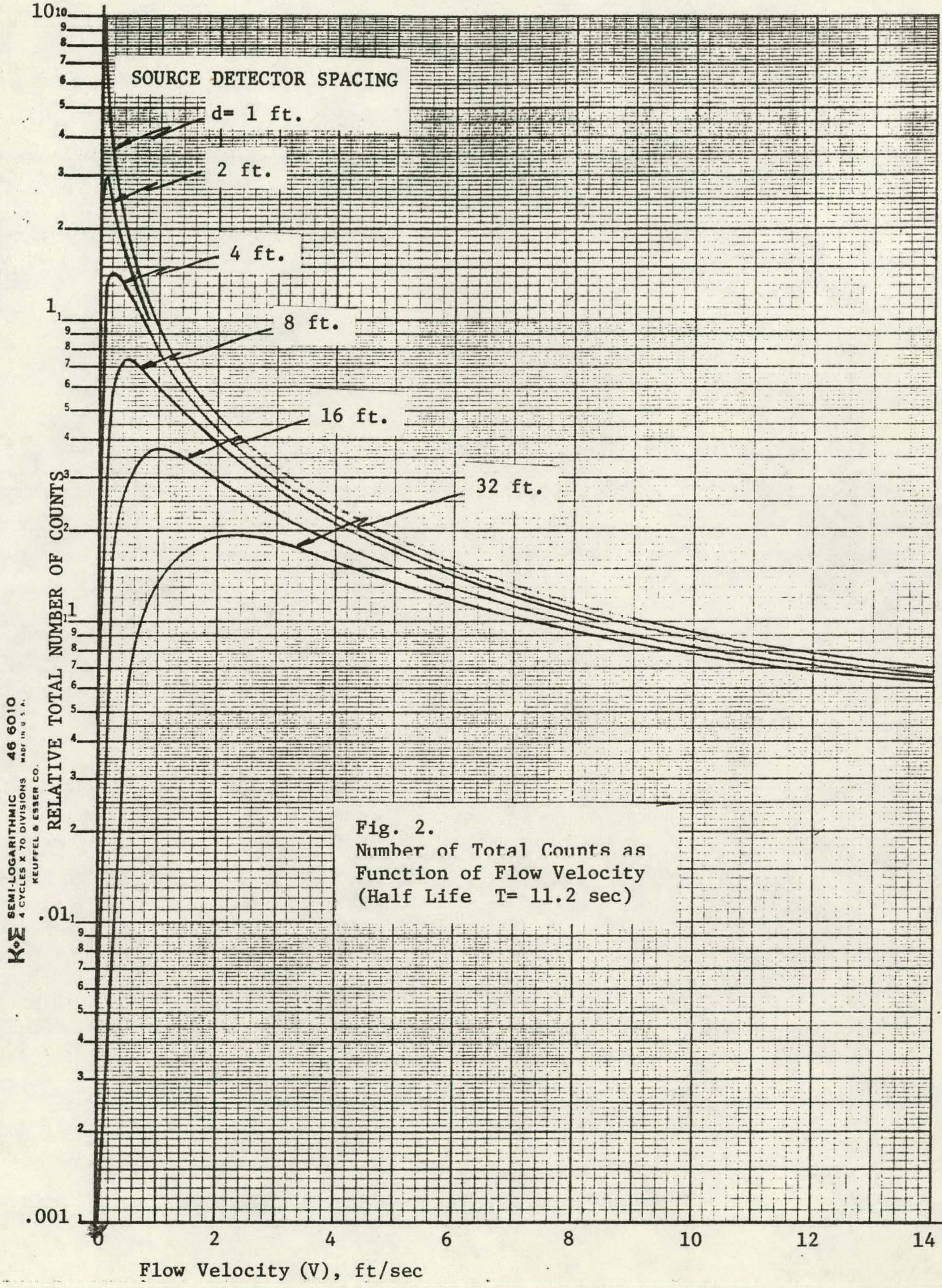

Fig. 2.
Number of Total Counts as Function of Flow Velocity (Half Life T= 11.2 sec)

This figure shows that the total number of counts is an ambiguous function of the flow velocity. This ambiguity is one reason why the total count method is not particularly suited for flow meter calibrations. The other major reason is that an absolute measurement of the induced activity is necessary. Since the number of counts indicating the activity is a function of many variables (such as source and detector collimation, source strength, and detector efficiency) which can be sensitive to temperature and voltage fluctuations (such as the threshold and the gain of the detector system), an absolute measurement of the activity is quite involved. The experimental difficulties of an accurate absolute measurement are somewhat reduced by using two detectors and measuring the ratio of their counting rates as an indication of the decay of the original activity. But the stable operation of two separate detectors again limits the accuracy of this method for flowmeter calibrations.

One advantage of the total count method is its extreme sensitivity to velocity variations in the region of low velocities, where the slopes of the curves shown in Fig. 2 are very steep. The expected accuracy of flow velocity measurements based on this method is estimated in Section 4 and does not compare favorably with the expected accuracy of the alternate method for flow velocity measurement, which is based on the measurement of transit times and is described next.

For these reasons, the verification experiment planned for the EBR-II (Section 4) will primarily utilize the method of transit time measurement. The total count method, however, will be used to double check the measured flow velocities.

2.3 Calibration of Flowmeters by Transit Time Measurements

A more direct way of measuring flow velocities in a pipe is the measurement of the transit time of the activated sodium between the location of activation by fast neutrons and the location of the detectors. Using this method, the flow velocity measurement is reduced to the measurement of the two basic elements of time (transit time between activation and detection) and distance (the distance between the source and the detectors). Were it not for the finite collimation angles of the source and the detectors and for the variation of flow velocities across the diameter of the pipe, flow velocity measurements could be performed by this method with an accuracy that is limited only by the accuracy of the time and the distance measurements. Real conditions, however, introduce additional errors due to source and detector collimation, flow velocity profile, and counting statistics.

The expected accuracy of this calibration method was assessed analytically by Sackett* and found to be under 2.8%. In his analysis, Sackett assumed that the complete time distribution of activity will be measured by a system of detectors downstream of the source by storing counts in a number of time channels with a width of Δt at successive times t_i. The mass averaged flow velocity was then derived by

$$v = D \overline{\left(\frac{1}{t}\right)}, \tag{7}$$

where

D = distance between the source and the detectors,

and

$\overline{\left(\frac{1}{t}\right)}$ = activity weighted average of the inverse of the transit times of the individual time channels.

The average of the inverse times is not equal to the inverse of the average time:

$$\overline{\left(\frac{1}{t}\right)} \neq \frac{1}{\bar{t}} . \tag{8}$$

The activity averaged inverse of the transit times was derived by

$$\overline{\left(\frac{1}{t}\right)} = \frac{\sum_i \left[A(t_i)\ e^{\lambda t_i}\ \Delta t\right]/t_i}{\sum_i \left[A(t_i)\ e^{\lambda t_i}\ \Delta t\right]} , \tag{9}$$

where

$A(t_i)$ = measured activity of the sodium at the time t_i,

and

λ = decay constant of the activated sodium,

Δt = width of the time channel.

Using this evaluation technique, Sackett found the error to be,

$$\frac{\sigma_v}{v} = \sqrt{\frac{\sigma^2_{\bar{x}}}{\bar{x}^2} + \frac{\sigma^2_{\bar{t}}}{\bar{t}^2} + \left(\frac{\sigma^2_x}{\bar{x}^2}\right)^2 + \frac{\sigma^2_t}{\bar{t}^2 N} + \left(\frac{\overline{\left(\frac{1}{t}\right)} - \frac{1}{\bar{t}}}{2/\bar{t}}\right)^2} , \tag{10}$$

*J. I. Sackett, (EBR-II, Idaho Falls), Private Communication, June 1971.

where σ_v = standard deviation of the measurement of the flow velocity,

$\sigma_{\bar{x}}$ = standard deviation in the measurement of x,

$\sigma_{\bar{t}}$ = standard deviation in the measurement of the transit time,

σ_x = variance of distribution of x,

σ_t = variance of distribution of t,

N = number of counts recorded, and

$\overline{\left(\frac{1}{t}\right)} - \frac{1}{\bar{t}}$ = error induced by fluid mixing.

The distributions of travel distance and transit time for different volume elements of the sodium are due to the finite collimation angles of the source and of the detector, as well as to the flow velocity profile across the pipe. Insertion of estimated values for the errors listed above has resulted in an expected error for the flow velocity of,

$$\frac{\sigma_v}{v} \leq 0.028 = 2.8\% . \qquad (11)$$

This error derived analytically by Sackett, is in very good agreement with the error predicted by a comprehensive computer program that calculates precisely the expected number of counts for each time channel, calculates the mass averaged flow velocity from these counts, and then compares the calculated flow velocity to the true velocity for a determination of the expected accuracy of the flow calibration method. Details of this program called ACTOPT, are discussed in the following section.

3.0 DESCRIPTION OF THE COMPUTER PROGRAM ACTOPT

The computer program ACTOPT is used for the ACTivation technique OPTimization of the flow velocity measurement by the neutron activation technique. The geometry used for these measurements is shown in Fig. 3.

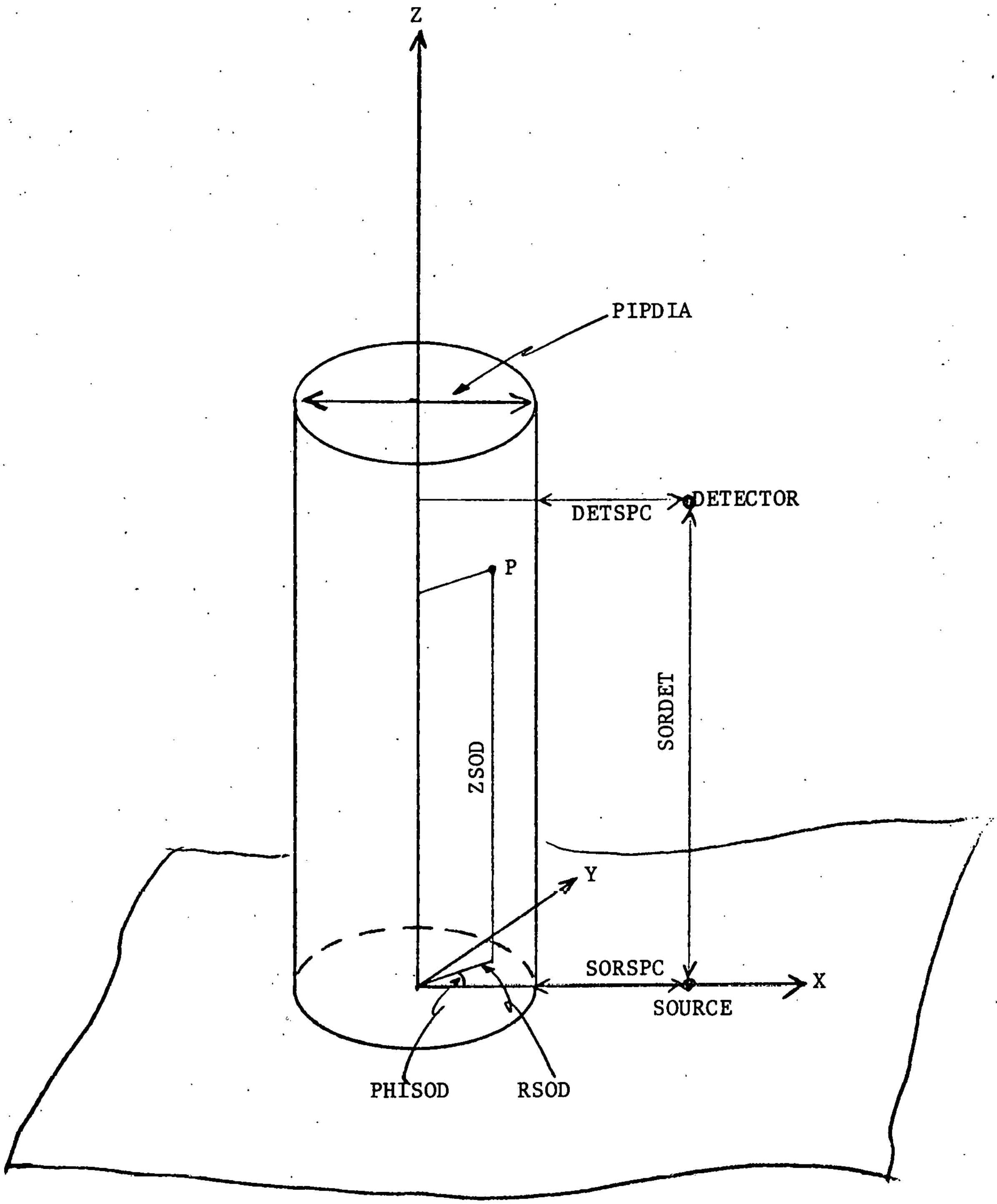

Fig. 3. Geometry used for computation of flow velocity.

Cylindrical and rectangular coordinates are used in this figure. The centerline of the pipe carrying the liquid sodium is the z-axis. The location of volume elements of the flowing sodium is defined by RSOD, PHISOD, and ZSOD, and their size is defined by DELR, DELPHI, and DELZ.

The neutron source is located in the plane z = 0, and its spacing from the wall of the sodium pipe is SORSPC. The spacing of the detector from the sodium pipe is DETSPC. The distance between the source and detector planes is SORDET. The diameter of the pipe is PIPDIA. Other terms used in the computer program are listed in Table 2.

Figure 4 is a flow diagram of the main program which was, for easier presentation, divided into eight subprograms. Three subroutines support the main program. These subprograms and subroutines are discussed briefly. A sample output of the computer program is shown in Table 3.

3.1 Subprogram 1: Input and Initialization

Subprogram 1 reads and prints the input variables for the problem, computes some auxiliary parameters needed for the calculation of the flow profile, and sets the initial conditions (time, counts, etc.) for a new start of the program. The flow diagram shown in Figure 5 and the listing in Table 4 describe fully the details of this subprogram.

The problem to be studied is fully defined by 26 input variables. Dimensions and properties of the pipe are defined by PIPDIA, PIPWAL and RUFNES. The fluid in the pipe is defined by TURBIN, VISKIN, RHOMAT and WTMOLM. The geometric setup, energy, and strength of the neutron source are defined by SORINT, SORSPC, SORCOL, and SIGMAT. The nuclear reaction to be exploited is defined by SIGMAR, TIMHAF, ENERGY, COEFMA and COEFFE. The number, geometric arrangement, and properties of the detector(s) are defined by SORDET, DETEFF, DETDIA, DETLEN, DETSPC, DETCOL, and NNNDET. Measurement accuracies are entered through ERRORX, ERRORT, and BACKGR. The number of radial, circumferential, and longitudinal increments in which the irradiated slug is to be subdivided for the numerical analysis of the problem is defined by NNNPHI, NNNR and NNNZ. Finally, the number of time channels into which the total number of counts is to be stored is defined by NNNCHA.

Table 2. List of Terms used in Program ACTOPT

ABSORP	=	absorbtion of neutrons
ACTIV(i,j,k)	=	activity of volume element
ANUM	=	auxiliary number
BACKGR	=	background counting rate
BNUM	=	auxiliary number
CNTTIM	=	number of counts at time TIME
CNTTOT	=	cumulative number of counts
CNUM	=	auxiliary number
COEFFE	=	linear gamma absorbtion coefficient in iron
COEFMA	=	linear gamma absorbtion coefficient in sodium
COORD(j,k)	=	z coordinate of element (j,k)
CPS	=	counting rate
DELACT	=	number of activated atoms in volume element
DELDET	=	angle between detectors
DELMAT	=	number of atoms in volume element
DELPHI	=	angular increment
DELR	=	radial increment
DELTIM	=	time increment
DELVOL	=	volume of volume element
DELX	=	auxiliary number
DELZ	=	longitudinal increment
DENOM	=	auxiliary number
DETCOL	=	collimation angle of detector(s)
DETDIA	=	diameter of detector(s)
DETEFF	=	efficiency of detector(s)
DETLEN	=	length of detector(s)
DETSPC	=	pipe-detector spacing
DNUM	=	auxiliary number
E1	=	auxiliary number
ENERGY	=	gamma energy of decay product
ENUM	=	auxiliary number
EPSLON	=	small number
ERROR	=	total error of computed velocity

Table 2 (Contd.)

ERRORF	=	fundamental error of computed velocity
ERRORM	=	measurement error of computed velocity
ERRORT	=	error in the measurement of time
ERRORX	=	error in the measurement of distance
FPX	=	derivative of FX
FLWATR	=	mass flow at radius R
FLWAVG	=	mass averaged flow velocity
FLWTRU	=	average flow velocity
FRIFAC	=	square root of friction factor
FX	=	friction factor function
i	=	angular label of activated volume element
j	=	radial label of activated volume element
k	=	longitudinal label of activated element
l	=	detector label
NNNCHA	=	number of time channels
NNNDET	=	number of detectors
NNNPHI	=	number of circumferential increments
NNNR	=	number of radial increments
NNNZ	=	number of longitudinal increments
NNTIME	=	auxiliary number
NOUTPT	=	integer determining detail of output
NTIME	=	auxiliary number
NTMIX	=	auxiliary number
PHIDET	=	cylindrical coordinate of detector
PHISOD	=	cylindrical coordinate of element
PHISOR	=	cylindrical coordinate of source
PIPDIA	=	outside diameter of pipe
PIPWAL	=	wall thickness of pipe
PRALEN	=	Prandtl mixing length
R	=	radius
RO	=	radius of pipe
R1	=	auxiliary radial dimension
R2	=	auxiliary radial dimension
R3	=	auxiliary radial dimension
RELRUF	=	relative roughness of pipe wall
REYNLD	=	Reynolds number

Table 2 (Contd.)

RHOMAT	=	density of sodium
RSOD	=	cylindrical coordinate of element
RSOR	=	cylindrical coordinate of source
RUFNES	=	roughness of pipe wall
SIGMAR	=	neutron reaction cross section
SIGMAT	=	total neutron absorption cross section
SIMINT	=	auxiliary number, accumulating SIMINV
SIMINV	=	auxiliary number
SORCOL	=	collimation angle of neutron source
SORDET	=	source-detector spacing
SORINT	=	source intensity
SORSPC	=	source-pipe spacing
TIME	=	time
TIMHAF	=	half life of activated atom
TIMINT	=	auxiliary number accumulating TIMINV
TIMINV	=	auxiliary number = 1/CNTTIM
TIMMIX	=	mixing time for two adjacent elements
TURBIN	=	intensity of turbulence
V1	=	length of source-element vector
V2	=	length of source intersect-element vector
V3	=	length of detector-element vector
V4	=	length of detector intersect-element vector
VELATR	=	flow velocity at R
VELAVG	=	average flow velocity
VELCTR	=	flow velocity at center of pipe
VELWAL	=	flow velocity at wall of pipe
VELGRD	=	gradient of flow velocity
VISKIN	=	kinematic viscosity
VR	=	auxiliary number
WTMOLM	=	molecular weight of sodium
X1	=	rectangular coordinate of volume element
X2	=	rectangular coordinate of detector
X3	=	rectangular coordinate of intersect

Table 2 (Contd.)

XNEW	=	auxiliary number
XOLD	=	auxiliary number
Y1	=	rectangular coordinate of volume element
Y2	=	rectangular coordinate of detector
Y3	=	rectangular coordinate of intersect
Z3	=	rectangular coordinate of intersect
ZDMAX	=	coordinate of detector window
ZDMIN	=	coordinate of detector window
ZSMAX	=	coordinate of irradiated slug
ZSMIN	=	coordinate of irradiated slug
ZSOD	=	cylindrical coordinate of volume element
ZSOR	=	cylindrical coordinate of source

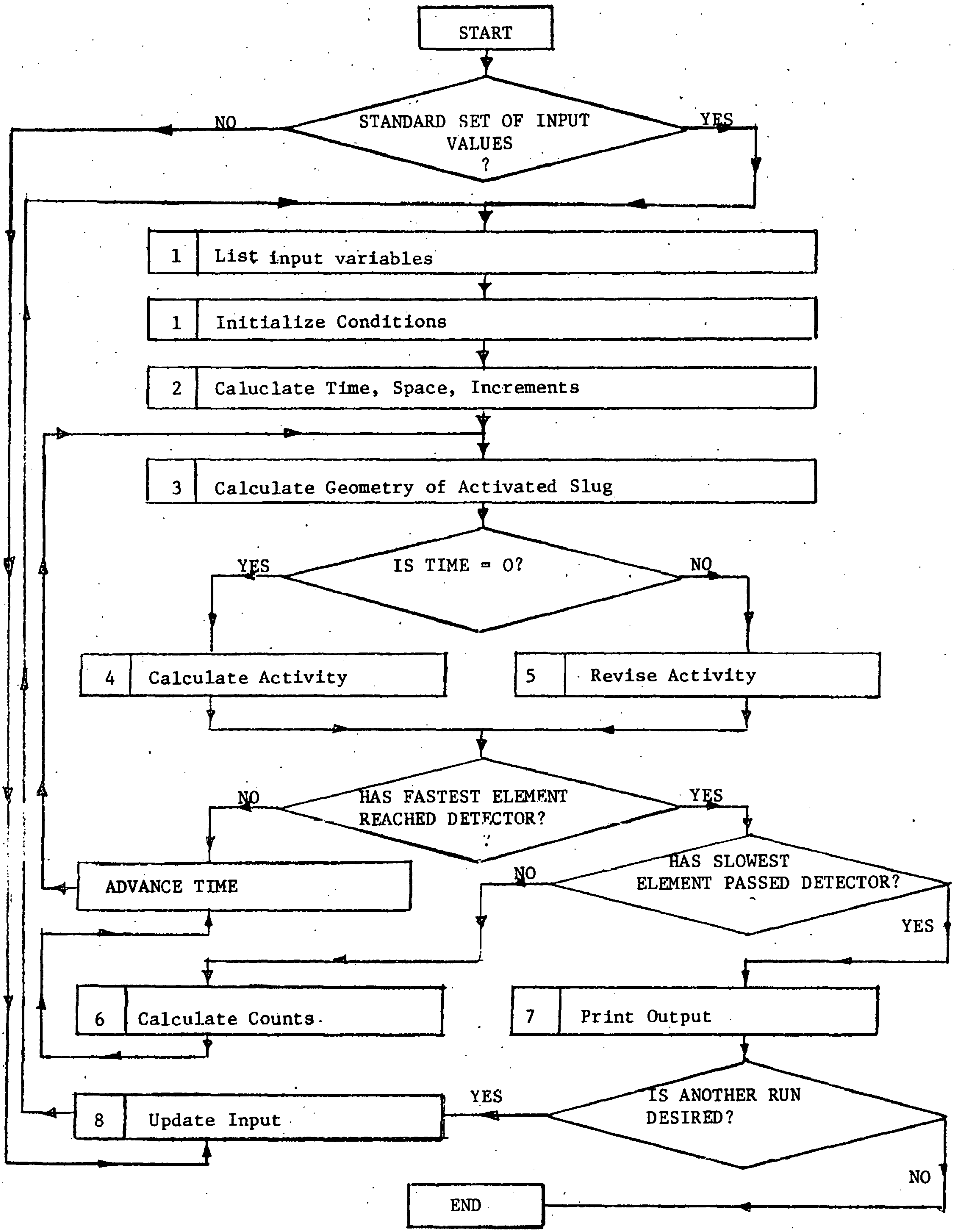

Fig. 4. Flow diagram of main program.

Table 3. SAMPLE OUTPUT

```
PROGRAM ACTOPT


ACCURACY OF FLOW VELOCITY MEASUREMENT
BY THE NEUTRON ACTIVATION TECHNIQUE,
FOR THE FOLLOWING CONDITIONS:


  PIPDIA     PIPWAL     TURBIN     VISKIN     RUFNES
   12.00       0.25       5.00  0.34E-05     0.0010

  SORINT     SORSPC     SORDET     SORCOL     ERRORX
0.10E+11      10.00     240.00     100.00       1.00

  SIGMAR     SIGMAT     TIMHAF     ENERGY     DETEFF
  185.00    1400.00      11.20       1.60      30.00

  DETDIA     DETLEN     DETSPC     DETCOL     ERRORT
    3.00       3.00       8.00     120.00     0.0050

  COEFMA     COEFFE     RHOMAT     WTMOLM     BACKGR
  0.0485     0.3460       0.97      22.99         5.

  NNNCHA     NNNDET     NNNPHI     NNNR      NNNZ
      25          4         12          6         24

  FLWAVG
   15.70

THE SLUG ACTIVITY IS 0.121E-03 CURIES
THE TIME STEP IS 0.0323 SEC
```

Table 3 (Contd.)

COUNTS AND COUNT RATES ARE

TIME,SEC	COUNTS	CPS
0.9034	0.0	0.0
0.9356	0.13	4.00
0.9679	0.89	27.46
1.0001	3.12	96.61
1.0324	8.34	258.64
1.0647	17.55	544.09
1.0969	31.04	962.24
1.1292	46.71	1447.73
1.1615	60.97	1889.76
1.1937	70.94	2198.91
1.2260	73.79	2287.17
1.2583	70.96	2199.37
1.2905	64.77	2007.60
1.3228	58.63	1817.24
1.3550	56.34	1746.41
1.3873	55.87	1731.72
1.4196	56.15	1740.46
1.4518	54.32	1683.54
1.4841	47.51	1472.46
1.5164	37.15	1151.62
1.5486	25.06	776.84
1.5809	14.53	450.26
1.6131	6.71	207.95
1.6454	2.64	81.86
1.6777	0.70	21.75
1.7099	0.15	4.71

THE NUMBER OF NET COUNTS IS 865.0

THE NUMBER OF BACKGROUND COUNTS IS 4.0

THE TRUE FLOW IS 15.70 FT/SEC

THE AVERAGE VELOCITY IS 15.44 FT/SEC

THE MEASURED FLOW IS 15.26 FT/SEC

THE FUNDAMENTAL ERROR,
DUE TO FLOW PROFILE, FLOW MIXING,
AND TO FINITE COLLIMATION ANGLES
OF THE SOURCE AND THE DETECTORS,
IS -2.79 PERCENT

THE MEASUREMENT ERROR,
DUE TO COUNTING STATISTICS
AND TO ERRORS IN TIME AND DISTANCE MEASUREMENTS,
IS 4.86 PERCENT

THE TOTAL ERROR IS 5.61 PERCENT

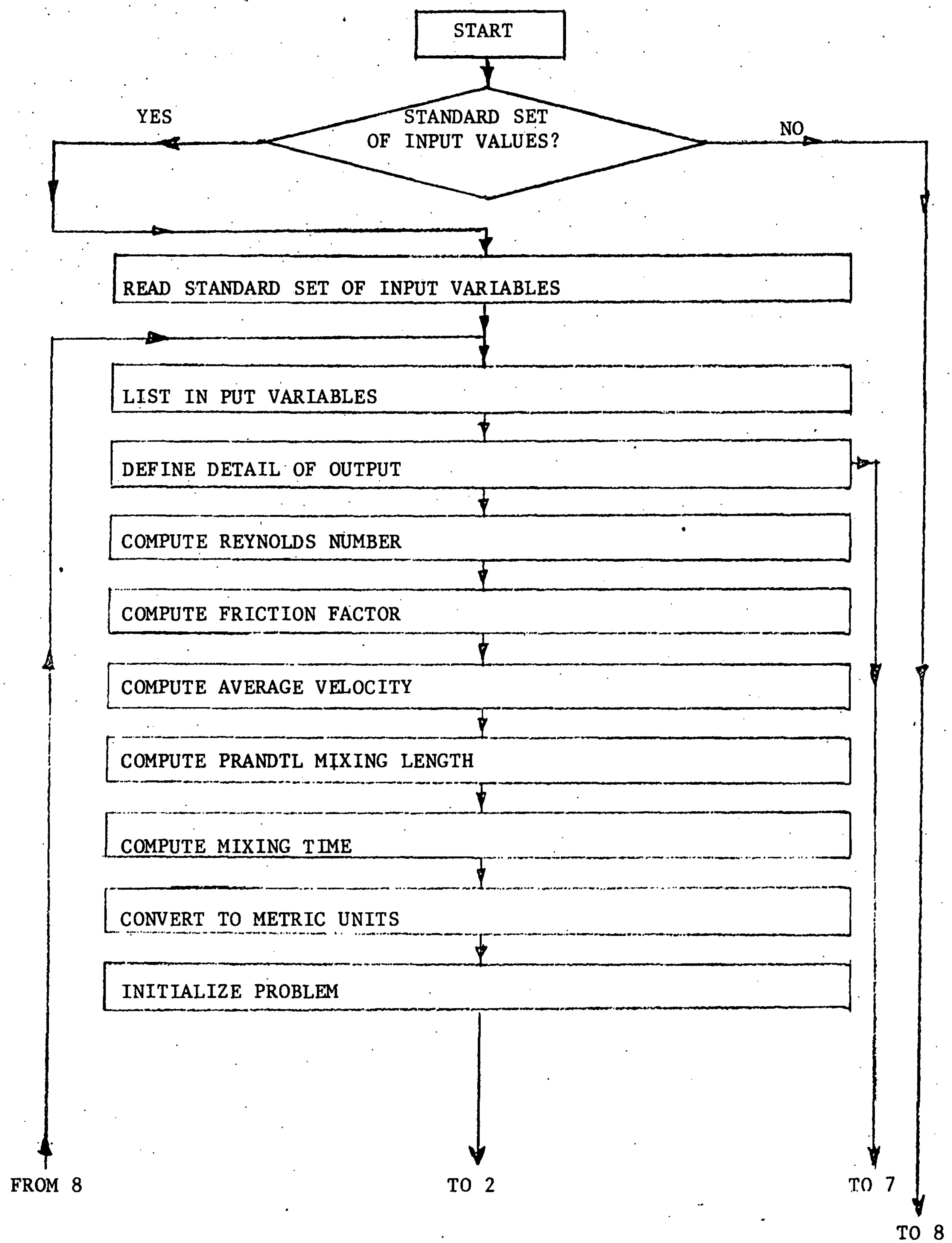

Fig. 5. Flow diagram of Subprogram 1.

Table 4. Subprogram 1

```
C PROGRAM ACTOPT
C      OPTIMIZATION OF FLOW MEASUREMENT
C      BY THE NEUTRON ACTIVATION TECHNIQUE.
C      THIS PROGRAM IS FULLY INTERACTIVE.
C      A SET OF STORED INPUT DATA,
C      OR VARIATIONS FROM THESE DATA, CAN BE USED.
C SUBPROGRAM 1    SUBPROGRAM 1    SUBPROGRAM 1
C STORAGE OF STANDARD INPUT VARIABLES, WITH THE DIMENSIONS:
C     PIPDIA(INCHES),PIPWAL(INCHES),FLWAVG(FT/SEC),VISKIN(FT2/SEC),
C     RUFNES(INCHES),TURBIN(PERCENT),SORINT(NEUTRONS PER PULSE),
C     SORSPC(INCHES),SORDET(INCHES),SORCOL(DEGREES),ERRORX(INCHES),
C     SIGMAR(MILLIBARN),SIGMAT(MILLIBARN),TIMHAF(SEC),ENERGY(MEV),
C     DETEFF(PERCENT),DETDIA(INCHES),DETLEN(INCHES),DETSPC(INCHES),
C     DETCOL(DEGREES),ERRORT(SECONDS),DELTIM(SECONDS),COEFMA(1/CM),
C     COEFFE(1/CM),RHOMAT(G/CM3),BACKGR(1/SEC)
      DIMENSION ACTIV(24,12,24), COORD(12,24)
      PIPDIA = 12.0
      PIPWAL = .25
      TURBIN = 5.0
      VISKIN = .341E-05
      RUFNES = .001
      SORINT = .1E+11
      SORSPC = 10.0
      SORDET = 240.0
      SORCOL = 100.0
      ERRORX = 1.0
      SIGMAR = 185.0
      SIGMAT = 1400.0
      TIMHAF = 11.2
      ENERGY = 1.6
      DETEFF = 30.0
      DETDIA = 3.0
      DETLEN = 3.0
      DETSPC = 8.0
      DETCOL = 120.0
      ERRORT = .005
      COEFMA = 0.0485
      COEFFE = 0.346
      RHOMAT = 0.97
      WTMOLM = 22.99
      BACKGR = 5.0
      NNNCHA = 25
      NNNDET = 4
      NNNPHI = 12
      NNNR   = 6
      NNNZ   = 24
      FLWAVG = 15.7
      GO TO 801
  105 WRITE(6,1016)
      READ(5,*) NOUTPT
C WRITING OF INPUT VARIABLES
      WRITE(6,1043)
      WRITE(6,1017)
      WRITE(6,1018)
      WRITE(6,1019)
      WRITE(6,1028)
      WRITE(6,1020)
```

Table 4 (Contd.)

```
      WRITE(6,1038) PIPDIA,PIPWAL,TURBIN,VISKIN,RUFNES
      WRITE(6,1022)
      WRITE(6,1025) SORINT,SORSPC,SORDET,SORCOL,ERRORX
      WRITE(6,1023)
      WRITE(6,1021) SIGMAR,SIGMAT,TIMHAF,ENERGY,DETEFF
      WRITE(6,1024)
      WRITE(6,1034) DETDIA,DETLEN,DETSPC,DETCOL,ERRORT
      WRITE(6,1032)
      WRITE(6,1033) COEFMA,COEFFE,RHOMAT,WTMOLM,BACKGR
      WRITE(6,1026)
      WRITE(6,1027) NNNCHA,NNNDET,NNNPHI,NNNR,NNNZ
      WRITE(6,1039)
      WRITE(6,1021) FLWAVG
C CALCULATION OF AUXILIARY PARAMETERS
C COMPUTATION OF REYNOLDS NUMBER
      REYNLD=FLWAVG*(PIPDIA-2.0*PIPWAL)/(12.0*VISKIN)
      IF(NOUTPT.EQ.3) WRITE(6,1042) REYNLD
C COMPUTATION OF FRICTION FACTOR
      RELRUF = RUFNES / PIPDIA
      EPSLON = .001
      XOLD = .1
  102 FX=1.0/XOLD+2.0*ALOG10(2.51/(REYNLD*XOLD)+0.54*RELRUF)
      FPX=(-1.0)/XOLD**2
      FPX=FPX-1.09/(2.51*XOLD+0.54*REYNLD*RELRUF*XOLD**2)
      DELX = FX /FPX
      XNEW = XOLD - DELX
      IF(XNEW.LT.0.0) XNEW = 0.1*ABS(XNEW)
      IF(ABS(DELX/XOLD).LT.EPSLON) GO TO 103
      XOLD = XNEW
      GO TO 102
  103 FRIFAC = XNEW
      ANUM = FRIFAC**2
      IF(NOUTPT.EQ.3) WRITE(6,1040) ANUM
C COMPUTATION OF THE AVERAGE VELOCITY
      R1 = 0.0
      R0 = (PIPDIA-2.0*PIPWAL) / 2.0
      DELR = R0 /NNNR
      FLWTRU = 0.0
      DO 10 I = 1,NNNR
      R2 = R1 + DELR
      R3 = R1 + DELR/2.0
      VELATR = FRIFAC*(2.15*ALOG10((R0-R3)/R0)+1.43)+1.0
      VELATR = VELATR * FLWAVG
      FLWATR = 3.141 * (R2**2-R1**2) * VELATR
      FLWTRU = FLWTRU + FLWATR
      R1 = R1 + DELR
   10 CONTINUE
      FLWTRU = FLWTRU / (3.141*R0**2)
      VELAVG = FLWAVG**2 / FLWTRU
C COMPUTATION OF PRANDTL MIXING LENGTH AND MIXING TIME
      VELCTR=FRIFAC*(2.15*ALOG10((R0-DELR/2.0)/R0)+1.43)+1.0
      VELCTR=VELCTR*VELAVG
      VELWAL=FRIFAC*(2.15*ALOG10(DELR/(2.0*R0))+1.43)+1.0
      VELWAL=VELWAL*VELAVG
      VELGRD = (VELCTR-VELWAL) / (DELR*(NNNR-1))
      PRALEN = TURBIN * VELAVG / (VELGRD*100.0)
      IF(NOUTPT.EQ.3) WRITE(6,1041) PRALEN
      TIMMIX = PRALEN / (VELAVG*NNNR)
C TIMMIX IS THE TIME OVER WHICH ADJACENT RADIAL ELEMENTS MIX
```

Table 4 (Contd.)

```
C CONVERSION FROM ENGLISH TO METRIC UNITS
      R0 = R0 * 2.54
      VELCTR = VELCTR * 12.0 * 2.54
      VELWAL = VELWAL * 12.0 * 2.54
      VELAVG = VELAVG * 12.0 * 2.54
      PIPDIA = PIPDIA * 2.54
      PIPWAL = PIPWAL * 2.54
      DELR = DELR * 2.54
      SORSPC = SORSPC * 2.54 + PIPDIA/2.0
      SORCOL = SORCOL * 6.28 / 360.0
      DETDIA = DETDIA * 2.54
      DETLEN = DETLEN * 2.54
      DETSPC = DETSPC*2.54 + DETLEN/2.0 + PIPDIA/2.0
C DETSPC IS THE DISTANCE OF THE DET CENTER FROM  ZERO
      DETCOL = DETCOL * 6.28 / 360.0
      DETEFF = DETEFF / 100.0
      SORDET = SORDET * 2.54
      ERRORX = ERRORX * 2.54
C INITIALIZATION
      TIME = 0.0
      TIMINT = 0.0
      SIMINT = 0.0
      CNTTOT = 0.0
      BACKTT = 0.0
      CNTTIM = 0.0
      BACKTM = 0.0
      CPS = 0.0
      ENUM = 0.0
      DENOM = 0.0
      NTIME = 1
      NNTIME = 1
      NTMIX = 1
 1016 FORMAT(' DEFINE OUTPUT, 1(SHORT), 2(LONG), OR 3(DETAIL)')
 1017 FORMAT(//////////,' ACCURACY OF FLOW VELOCITY MEASUREMENT ')
 1018 FORMAT(' BY THE NEUTRON ACTIVATION TECHNIQUE,')
 1019 FORMAT(' FOR THE FOLLOWING CONDITIONS:')
 1020 FORMAT(/,3X,'PIPDIA   PIPWAL   TURBIN   VISKIN   RUFNES')
 1021 FORMAT(5F9.2)
 1022 FORMAT(/,3X,'SORINT   SORSPC   SORDET   SORCOL   ERRORX')
 1023 FORMAT(/,3X,'SIGMAR   SIGMAT   TIMHAF   ENERGY   DETEFF')
 1024 FORMAT(/,3X,'DETDIA   DETLEN   DETSPC   DETCOL   ERRORT')
 1025 FORMAT(1E9.2,4F9.2)
 1026 FORMAT(/,3X,'NNNCHA   NNNDET   NNNPHI   NNNR    NNNZ')
 1027 FORMAT(5I9)
 1028 FORMAT(////)
 1029 FORMAT(/)
 1032 FORMAT(/,3X,'COEFMA   COEFFE   RHOMAT   WTMOLM   BACKGR')
 1033 FORMAT(2F9.4,2F9.2,1F9.0)
 1034 FORMAT(4F9.2,1F9.4)
 1038 FORMAT(3F9.2,1E9.2,1F9.4)
 1039 FORMAT(/,3X,'FLWAVG')
 1040 FORMAT(' THE FRICTION FACTOR IS',1F8.5)
 1041 FORMAT(' THE PRANDTL MIXING LENGTH IS',1F7.2,' INCHES')
 1042 FORMAT(/,' THE REYNOLD NUMBER IS',1E11.4)
 1043 FORMAT(///////,' PROGRAM ACTOPT')
```

After the definition and the listings of the input variables, the desired detail of the output is determined by entering an integer for NOUTPT into the program (requested by the program, which is written in fully interactive mode.). For NOUTPT = 1, only the computed flow and the expected error are printed in Subprogram 8. For NOUTPT = 2, the counts accumulated in the individual time channels are additionally printed out as shown in Table 3.

In calculating the mass flow through the pipe, the flow profile across the diameter of the pipe is considered. According to Ref. 5, this flow profile can be easily derived when the friction factor, f, is known. The friction factor for smooth pipe flow was given by von Karman as

$$\frac{1}{\sqrt{f}} = 1.74 - 2 \log (18.6/R \sqrt{f}), \tag{12}$$

where R is the Reynolds number. For pipes with rough surface flow, the friction was determined by Prandtl and by von Karman as

$$\frac{1}{\sqrt{f}} = 1.74 - 2 \log (2 e/d), \tag{13}$$

where

e = pipe roughness,

and

d = pipe diameter.

For unknown or transitional flow conditions, Colebrook combined both equations empirically into a new equation given as

$$\frac{1}{\sqrt{f}} = -2 \log \frac{2.51}{R\sqrt{f}} + \frac{2e}{3.7d} . \tag{14}$$

Friction factors calculated by this equation are plotted in Reference 6 and reproduced in Fig. 6. In Subprogram 1, the Reynolds number is computed by

$$\text{REYNLD} = \frac{\text{FLWAVG (PIPDIA - 2.0 + PIPWAL)}}{\text{VISKIN}}. \tag{15}$$

Using this Reynolds number and the relative roughness

$$r = e/d = \text{RELRUF} = \text{RUFNES/PIPDIA}, \tag{16}$$

the friction factor is calculated according to Eq. (14) and Newton's Method for solution of equations using the substitution $x = \sqrt{f}$ and the algorithm ,

$$x_{k+1} = x_k - \frac{f(x)_k}{f'(x)_k}, \tag{17}$$

with

$$f(x) = \frac{1}{x} + 2 \log \left(\frac{2.51}{Rx} + 0.5405r\right), \tag{18}$$

and

$$f'(x) = -\frac{1}{x^2} - \frac{1.09}{2.51x + 0.5405\ Rr\ x^2}. \tag{19}$$

The iterative calculation of x or $\sqrt{f}$ is interrupted as soon as the relative difference between two successive solutions for x is less than EPSLON = .001. In the program, $\sqrt{f}$ is called FRIFAC.

For calorimetric considerations, only the averaged mass flow measured in gal/min is of interest. Flowmeters, on the other hand, usually measure the linear flow velocity in ft/sec. The mass averaged linear flow velocity, obtainable from the averaged mass flow and the pipe diameter, is called FLWAVG in this program. The mass flow at the distance R from the centerline of the pipe is called FLWATR. The flow profile across the diameter of the pipe is expressed in terms of flow velocities instead of terms of mass flow. The average flow velocity is called VELAVG in the program and the flow velocity, at a distance R from the flow velocity distribution in a circular pipe, is expressed by

$$\text{VELATR} = \text{VELAVG x FRIFAC} \left(2.15 \log \frac{\text{RO-R}}{\text{RO}} + 1.43\right) + 1,$$

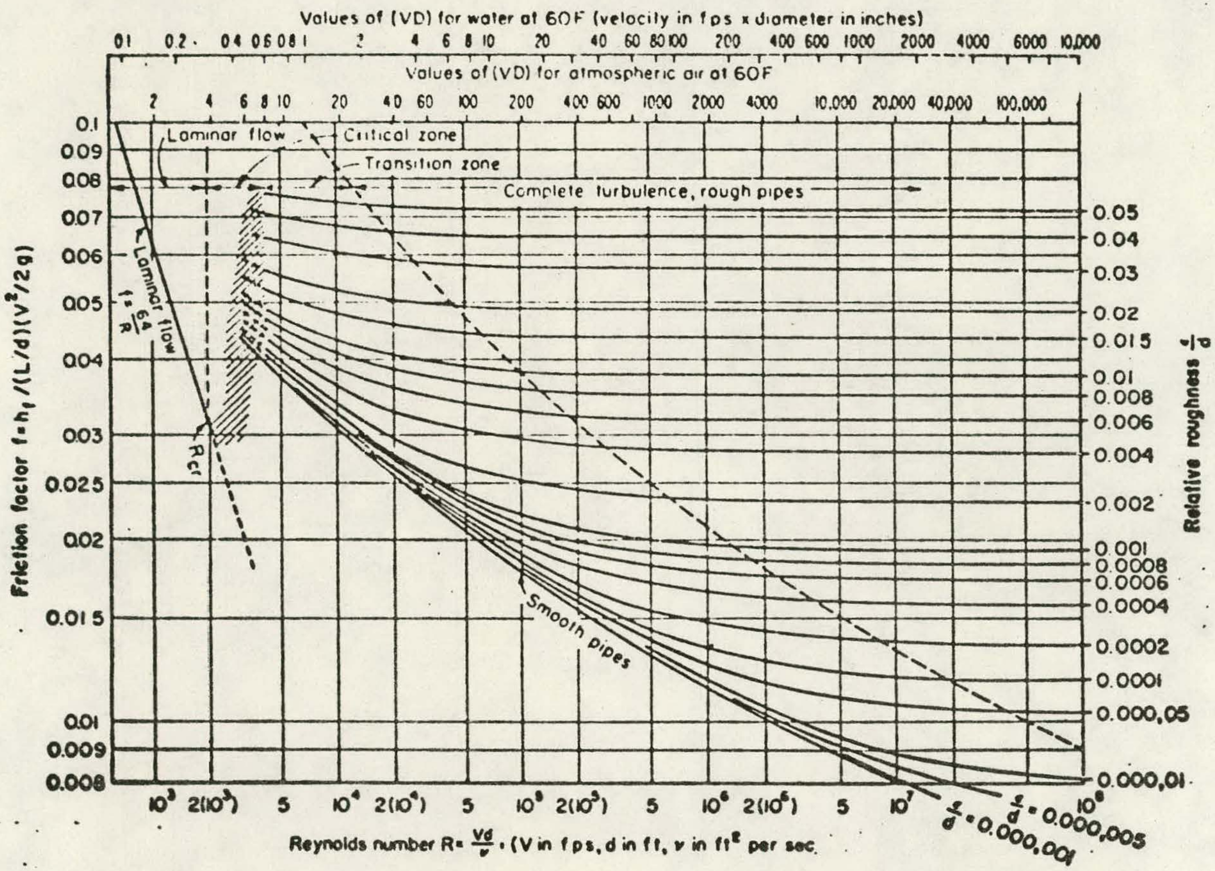

Fig. 6. Friction factors (Reproduced from Ref. 6).

where

RO = radius of the pipe.

An initial value of VELAVG = FLWAVG is assumed for the calculations of the flow distribution. With this flow distribution, the true mass flow FLWTRU, is then calculated by

$$\text{FLWTRU} = \frac{\Sigma\ \text{VELATR x} \left[(\text{R} + \text{DELR})^2 - \text{R}^2 \right]}{\text{RO}^2} . \tag{21}$$

Since this FLWTRU must be equal to FLWAVG, the originally assumed value for the average flow velocity (VELAVG = FLWTRU) is then corrected to read

$$\text{VELAVG} = \text{FLWAVG}\ \frac{\text{FLWAVG}}{\text{FLWTRU}} . \tag{22}$$

This corrected value of VELAVG is then utilized later in the program whenever the calculation of the flow profile in the pipe is desired.

A flow velocity gradient along the radius of the pipe will cause friction and mixing between adjacent layers of the flowing medium. Based on theories related to the kinetic theory of gases, a Prandtl mixing length can be determined that has a meaning similar to the average free path length in a gas. According to Ref. 6, the Prandtl mixing length can be expressed by

$$\ell = \sqrt{(v')^2_{av}} \Bigg/ \frac{dv_{av}}{dx} , \tag{23}$$

where

v' = random fluctuating turbulent velocity component,

v_{av} = average velocity, (24)

and

$v = v_{av} + v'$ = total velocity.

The turbulent velocity component v' is expressed by the intensity of turbulence t as

$$t = \frac{\sqrt{(v')^2_{av}}}{v_{av}} .$$

In Subprogram 1, the turbulent velocity component is derived from the intensity of turbulence (TURBIN) and the average velocity (VELAVG). From this turbulent velocity component and the velocity gradient across the pipe (VELGRD), the Prandtl mixing length (PRALEN) is then calculated. The Prandtl mixing length, in turn, is used for the computation of TIMMIX, the average time over which two adjacent flow elements mix:

$$\text{TIMMIX} = \text{PRALEN}/(\text{VELAVG})\ (\text{NNNR}). \qquad (25)$$

3.2 Subprogram 2: Time and Space Increments

Subprogram 2 defines the geometric arrangement of the source and the detector(s) relative to the pipe, and determines the length of the time steps to be used in the computer program. Also, it calculates the angle between the detectors, if more than one detector is used, as well as the dimensions of the volume elements used for the flow calculation. Subprogram 2 is listed in Table 5.

Figure 7 illustrates how the length of the irradiated sodium slug (BNUM) is calculated from the source collimation angle (SORCOL), the source spacing (SORSPC) and the diameter of the pipe (PIPDIA). This figure also illustrates the size of the detector window (ANUM), as derived from the detector spacing (DETSPC) and the detector collimation angle (DETCOL). The edges of the detector window have the z coordinates ZDMAX and ZDMIN. The irradiated sodium slug is located between the z-coordinates ZSMAX and ZSMIN. The length of the time steps is derived by dividing the difference between the longest time of arrival of an activated volume element in the detector window, (ZDMAX-ZSMIN)/VELWAL, and the shortest time of arrival, (ZDMIN-ZSMAX)/VELCTR, by the number of channels NNNCHA into which the total number of counts is to be stored.

3.3 Subprogram 3: Geometry of Sodium Slug

Subprogram 3, listed in Table 6, computes the z-coordinate of each of the elements of the activated sodium slug at the time of activation as well as for later times as the elements move along the pipe with velocities that vary with the distance from the centerline of the pipe.

Table 5. Subprogram 2.

```
C SUBPROGRAM 2    SUBPROGRAM 2    SUBPROGRAM 2
C CALCULATION OF SODIUM SLUG, DET WINDOW, DELPHI, DELDET, DELTIM
      ZSMAX = SORSPC * TAN(SORCOL/2.0)
      ZSMIN = (-ZSMAX)
      ZDMAX = SORDET + DETSPC * TAN(DETCOL/2.0)
      ZDMIN = SORDET - DETSPC * TAN(DETCOL/2.0)
      ANUM = (ZDMAX-ZDMIN) / 2.54
      BNUM = (ZSMAX-ZSMIN) / 2.54
      IF(NOUTPT.EQ.3) WRITE(6,2000) BNUM
      IF(NOUTPT.EQ.3) WRITE(6,2001) ANUM
      DELTIM = (ZDMAX - ZSMIN + ZSMIN/NNNZ) / VELWAL
      DELTIM = DELTIM - (ZDMIN - ZSMAX + ZSMAX/NNNZ) / VELCTR
      DELTIM = DELTIM / NNNCHA
      DELPHI = 6.282 / NNNPHI
      DELZ = (ZSMAX - ZSMIN) / NNNZ
      DELDET = 6.282 / NNNDET
 2000 FORMAT(/,' THE IRRADIATED SLUG IS',F7.2,' INCHES LONG')
 2001 FORMAT(' THE DETECTOR SEES',1F7.2,' INCHES')
```

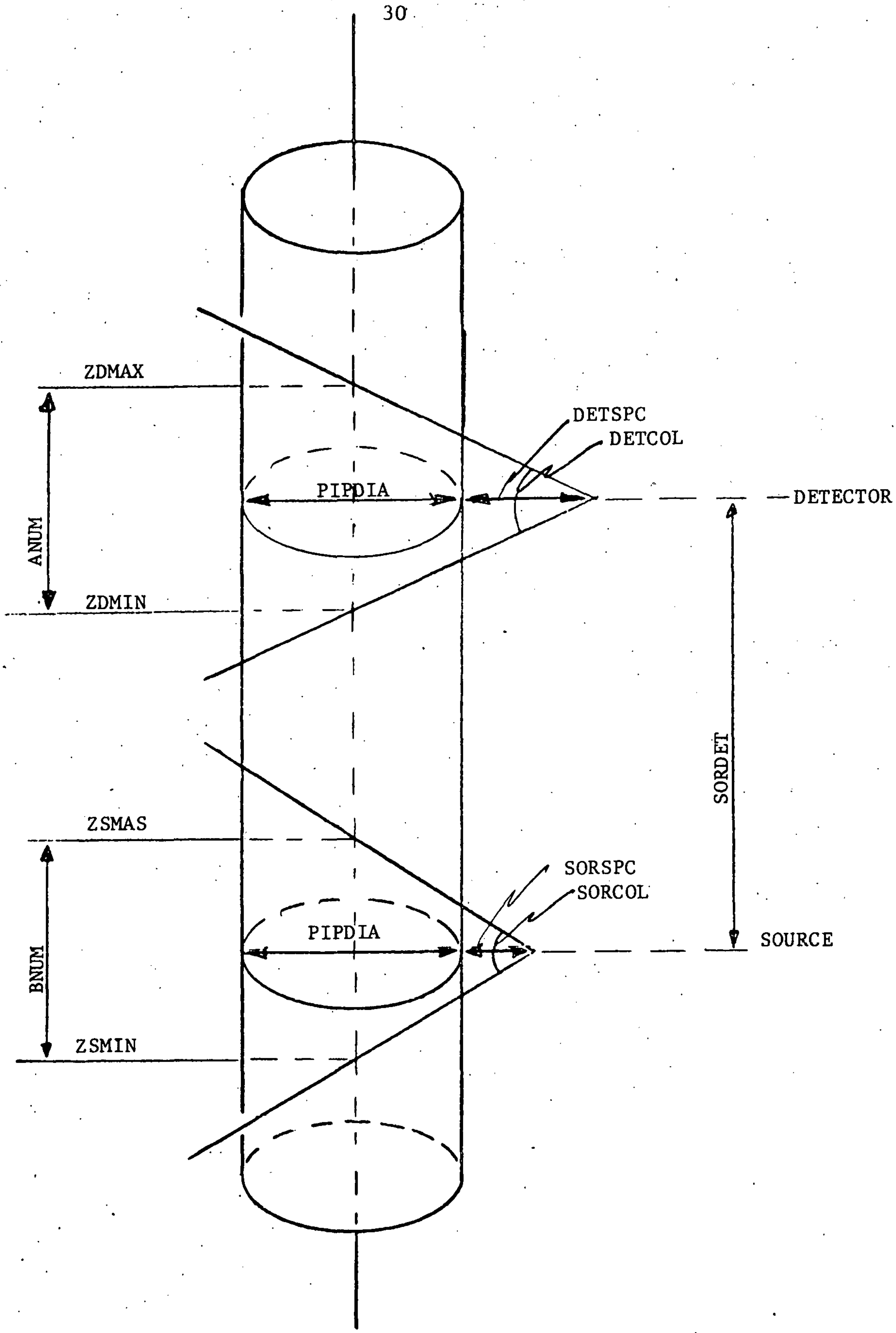

Fig. 7. Geometric arrangement of source and detector.

Table 6. Subprogram 3.

```
C SUBPROGRAM 3     SUBPROGRAM 3     SUBPROGRAM 3
C CALCULATION OF  GEOMETRY OF IRRADIATED SODIUM SLUG
  300 DO 30 J = 1,NNNR
      VR = J * DELR - DELR/2.0
      VELATR = FRIFAC*(2.15*ALOG10((R0-VR)/R0)+1.43)+1.0
      VELATR = VELATR * VELAVG
      DO 30 K = 1,NNNZ
      COORD(J,K) = (ZSMIN+K*DELZ-DELZ/2.0) + VELATR*TIME
   30 CONTINUE
      IF(TIME.GT.0.0) GO TO 500
```

3.4 Subprogram 4: Initial Activity

The distribution of the initial activity in the irradiated sodium slug is calculated by Subprogram 4. The geometry used for this calculation is shown in Fig. 8 and the subprogram is listed in Table 7.

Initially, the cylindrical coordinates of each element are converted to their rectangular coordinates X1, Y1, and COORD (j,k) by use of the subroutine POLREC. Then, using the subroutine VECTOR, the length of the vector V1 between the volume element and the source, with the rectangular coordinates X2, Y2, 0, is computed. Following this, the activity DELACT (in decays/sec) that would be caused by a non-attenuated source in each volume element is computed by

$$\text{DELACT} = \frac{\text{DELMAT} \times \text{SORINT} \times \text{SIGMAR}}{4\pi\ (\text{V1})^2}, \qquad (26)$$

where

DELMAT = number of atoms in the volume element,

SORINT = source intensity,

and

SIGMAR = reaction cross section.

After this, the point of intersection of the vector V1 with the pipe is computed by the subroutine INSECT, and the length at that portion of V1 that passes through sodium called V2 is computed by the subroutine VECTOR. The attenuation ABSORB of the original beam of neutrons emitted from the source towards the volume element is then computed by

$$\text{ABSORB} = \exp\left(\frac{6.02 \times 10^{23} \times \text{RHOMAT} \times \text{SIGMAT} \times \text{V2}}{\text{WTMOLM}}\right), \qquad (27)$$

where

RHOMAT = the density of sodium,

and

WTMOLM = the molecular weight of sodium.

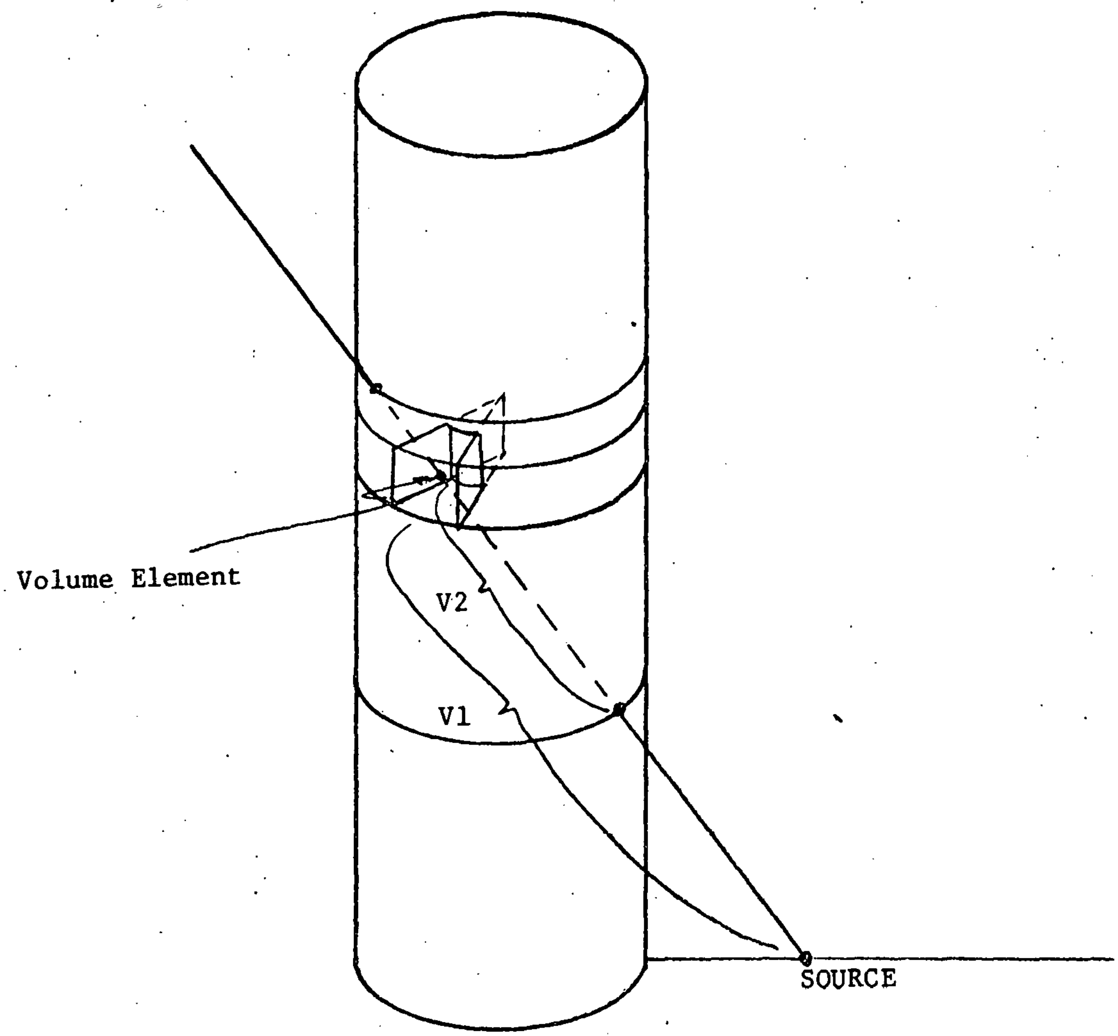

Fig. 8. Model for calculation of initial activity.

Table 7. Subprogram 4.

```
C SUBPROGRAM 4     SUBPROGRAM 4     SUBPROGRAM 4
C CALCULATION  OF INITIAL ACTIVITY  (DECAYS PER SEC)
      DO 40 K = 1,NNNZ
      DO 40 J = 1,NNNR
      DO 40 I = 1,NNNPHI
      RSOD = J*DELR - DELR/2.0
      PHISOD = (I-1) * DELPHI
      CALL POLREC(RSOD,PHISOD,X1,Y1)
      RSOR = SORSPC
      PHISOR = 0.0
      ZSOR = 0.0
      CALL POLREC(RSOR,PHISOR,X2,Y2)
      CALL VECTOR(X1,Y1,COORD(J,K),X2,Y2,ZSOR,V1)
      R2 = J * DELR
      R1 = R2 - DELR
      DELVOL = 3.141*(R2**2-R1**2)*DELPHI*DELZ / 6.282
      DELMAT = 6.022E+23 * DELVOL * RHOMAT / WTMOLM
      DELACT=.1E-26*SIGMAR*DELMAT*SORINT/(4.0*3.141*V1**2)
      CALL INSECT(X1,Y1,COORD(J,K),X2,Y2,ZSOR,R0,X3,Y3,Z3)
      CALL VECTOR(X1,Y1,COORD(J,K),X3,Y3,Z3,V2)
      ABSORB=EXP(.1E-26*SIGMAT*RHOMAT*6.02E+23*V2/WTMOLM)
      ACTIV(I,J,K) = DELACT*0.693 / (TIMHAF*ABSORB)
   40 CONTINUE
      DNUM = 0.0
      DO 43 I = 1,NNNPHI
      DO 43 J = 1,NNNR
      DO 43 K = 1,NNNZ
      DNUM = DNUM + ACTIV(I,J,K)/3.7E+10
   43 CONTINUE
      WRITE(6,4000) DNUM
      WRITE(6,4003) DELTIM
 4000 FORMAT(/,' THE SLUG ACTIVITY IS',1E10.3,' CURIES')
 4003 FORMAT(' THE TIME STEP IS',1F7.4,' SEC')
```

Finally, the total activity of each element, in decays per second, is computed by

$$\text{ACTIV (i,j,k)} = 0.693 \times \text{DELACT/(ABSORB} \times \text{TIMHAF)} \qquad (28)$$

The total activity of the irradiated slug is printed after summation of all ACTIV (i,j,k) values and conversion of the total activity to Curies.

3.5 Subprogram 5: Revised Activity

As the irradiated sodium slug moves through the pipe towards the detector(s), its original activity distribution changes due to two effects: (1) the overall activity decays with time; and (2) the relative distribution of the activities changes due to the mixing of the sodium.

The regision of the activities of the individual volume elements of the irradiated sodium slug is performed by Subprogram 5, which is listed in Table 8.

Initially, this subprogram changes the activity, ACTIV (i,j,k), of each element after passage of each time step DELTIM by

$$\text{ACTIV (i,j,k)} = \text{ACTIV (i,j,k)/exp (0.693 DELTIM/TIMHAF)}, \qquad (29)$$

where

TIMHAF = half life of the activated atoms.

The mixing of two radially adjacent elements is performed by averaging their specific activities whenever the TIME exceeds a new multiple of the mixing time TIMMIX. The activities of adjacent elements are averaged in two steps. First, the activities of all elements bordering the centerline of the pipe are added and then distributed evenly to all these elements as shown in Fig. 9. Second, starting from the centerline of the pipe, the specific activities of pairs of elements are averaged and new activities of each element computed from this averaged specific activity and the volume of the element. For example, for the elements 1 and 2 shown in Fig. 9, first the volume BNUM of the first element, and CNUM of the second element are computed. Then, the averaged specific activity is derived by

$$\text{DNUM} = \frac{\text{ACTIV (i,j,k) + ACTIV (i,j-1,k)}}{\text{BNUM + CNUM}}, \qquad (30)$$

and the new total activities of the mixed elements are computed as

$$\text{ACTIV (i,j,k)} = \text{BNUM} \times \text{DNUM} \qquad (31)$$

and

$$\text{ACTIV (i,j-1,k)} - \text{CNUM} \times \text{DNUM}. \qquad (32)$$

Table 8. Subprogram 5.

```
C SUBPROGRAM 5    SUBPROGRAM 5    SUBPROGRAM 5
C REVISION OF ACTIVITIES DUE TO DECAY
  500 ANUM = 1 / EXP(0.693*DELTIM/TIMHAF)
      DO 50 I = 1,NNNPHI
      DO 50 J = 1,NNNR
      DO 50 K = 1,NNNZ
   50 ACTIV(I,J,K) = ACTIV(I,J,K) * ANUM
C REVISION OF ACTIVITIES DUE TO MIXING
      IF(TIME.LT.NTMIX*TIMMIX) GO TO 501
  502 NTMIX = NTMIX + 1
      DO 51 K = 1,NNNZ
      ANUM = 0.0
      DO 52 I = 1,NNNPHI
   52 ANUM = ANUM + ACTIV(I,1,K)
      DO 51 I = 1,NNNPHI
      ACTIV(I,1,K) = ANUM / NNNPHI
      DO 51 J = 2,NNNR
      R3 = J * DELR
      R2 = R3 - DELR
      R1 = R3 - DELR*2.0
      BNUM = 3.141 * (R3**2-R2**2) * DELZ /NNNPHI
      CNUM = 3.141 * (R2**2-R1**2) * DELZ /NNNPHI
      DNUM = (ACTIV(I,J,K)+ACTIV(I,J-1,K))/(BNUM+CNUM)
      ACTIV(I,J-1,K) = CNUM * DNUM
   51 ACTIV(I,J,K) = BNUM * DNUM
      IF(TIME.GT.NTMIX*TIMMIX) GO TO 502
  501 IF((COORD(1,NNNZ)+1.5*DELZ).GT.ZDMIN) GO TO 600
      TIME = TIME + DELTIM
      NTIME = NTIME + 1
      GO TO 300
```

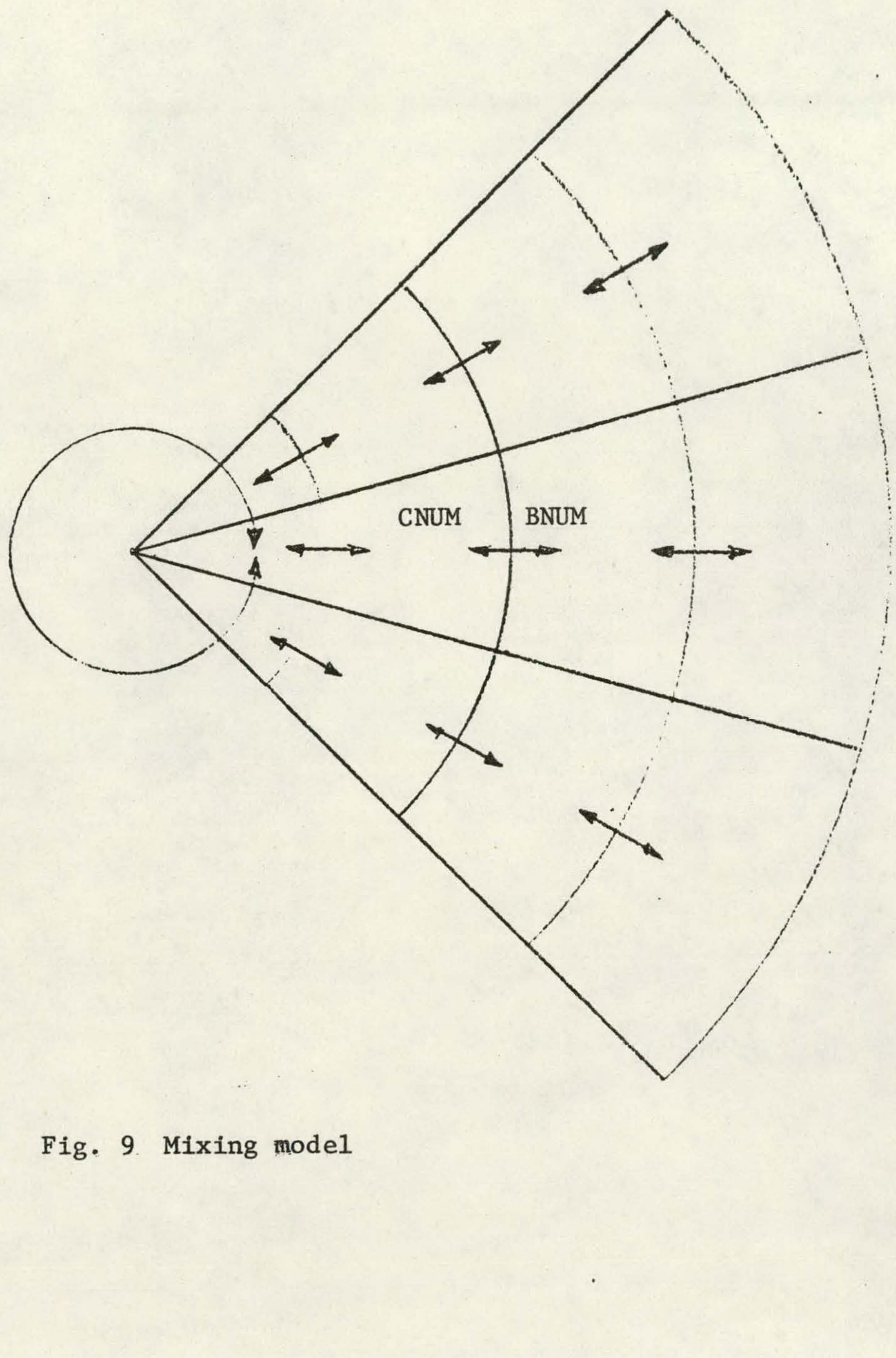

Fig. 9 Mixing model

3.6 Subprogram 6: Counting Rates

It was shown earlier that the mass averaged flow velocity can be derived by Eq. (7).

Equation (9) is evaluated numerically in Subprogram 6, which is listed in Table 9. Figure 10 shows the geometric model used to calculate the contributions of individual activated elements to the counting rate of the detector.

Initially, the cylindrical coordinates of the detector and the volume element are converted to rectangular coordinates by the subroutine POLREC. The rectangular coordinates of the volume element are X1, Y1, and COORD (j,k); and the rectangular coordinates of the detector are X2, Y2, and SORDET. From these coordinates, the length of the vector, V3, leading from the detector to the volume element is computed by the subroutine VECTOR. Next, the number of counts, ANUM, is computed that would be registered by the detector, as if there were no absorption and if the detector had an efficiency of 1.0:

$$\text{ANUM} = \frac{\text{ACTIV (i,j,k) x DELTIM x DELERA}}{4\pi \text{ (V3)}^2}, \tag{33}$$

Table 9. Subprogram 6.

```
C  SUBPROGRAM 6    SUBPROGRAM 6    SUBPROGRAM 6
C CALCULATION OF THE COUNTS FOR A GIVEN TIME INCREMENT
  600 CNTTIM = 0.0
      IF(COORD(NNNR,1)-1.5*DELZ.GT.ZDMAX) GO TO 700
      DO 60 L = 1,NNNDET
      DO 60 K = 1,NNNZ
      DO 60 J = 1,NNNR
      DO 60 I = 1,NNNPHI
      RSOD = J*DELR - DELR/2.0
      PHISOD = (I-1) * DELPHI
      PHIDET = (L-1) * DELDET
      CALL POLREC(RSOD,PHISOD,X1,Y1)
      CALL POLREC(DETSPC,PHIDET,X2,Y2)
      CALL VECTOR(X1,Y1,COORD(J,K),X2,Y2,SORDET,V3)
      R2 = J * DELR
      R1 = R2 - DELR
      DELERA = 3.141 * DETDIA**2 /4.0
      ANUM=ACTIV(I,J,K)*DELTIM*DELERA /(4.0*3.141*V3**2)
      CALL INSECT(X1,Y1,COORD(J,K),X2,Y2,SORDET,R0,X3,Y3,Z3)
      CALL VECTOR(X1,Y1,COORD(J,K),X3,Y3,Z3,V4)
      BNUM = DETEFF / EXP(V4*COEFMA+PIPWAL*COEFFE)
      DNUM=(DETSPC-RSOD*COS(PHISOD-PHIDET))*TAN(DETCOL/2.0)
      IF(COORD(J,K).LT.SORDET-DNUM) GO TO 603
      IF(COORD(J,K).GT.SORDET+DNUM) GO TO 603
      CNUM = ANUM * BNUM
      GO TO 607
  603 CNUM = 0.0
  607 CNTTIM = CNTTIM + CNUM
      IF(CNTTIM.EQ.0.0) GO TO 610
      BACKTM = BACKGR * DELTIM
      GO TO 611
  610 BACKTM = 0.0
  611 CONTINUE
   60 CONTINUE
      CPS = CNTTIM / DELTIM
      CNTTOT = CNTTOT + CNTTIM
      DENOM = DENOM + CNTTIM*EXP(0.693*(TIME+0.5*DELTIM)/TIMHAF)
      BACKTT = BACKTT + BACKTM
      TIMINV = CNTTIM / (TIME + 0.5*DELTIM)
      TIMINT = TIMINT + TIMINV
      ENUM = ENUM + TIMINV*EXP(0.693*(TIME+0.5*DELTIM)/TIMHAF)
      E1 = ERRORT**2 + (DELTIM/2.0)**2
      TNUM =(TIME + DELTIM/2.0)**2
      SIMINV = (CNTTIM / TNUM)**2 * E1
      SIMINV = (CNTTIM+BACKTM)/TNUM + SIMINV
      SIMINT = SIMINT + SIMINV
      IF(NOUTPT.EQ.1) GO TO 602
      IF(NNTIME.NE.1) GO TO 601
      WRITE(6,6002)
      WRITE(6,6000)
  601 IF(TIME/DELTIM.GT.1024.0) GO TO 700
      WRITE(6,6001) TIME,CNTTIM,CPS
      GO TO 602
  602 TIME = TIME + DELTIM
      NNTIME = NNTIME + 1
      GO TO 300
 6000 FORMAT(//,2X,'TIME,SEC    COUNTS        CPS')
 6001 FORMAT(1F10.4,2F10.2)
 6002 FORMAT(////,' COUNTS AND COUNT RATES  ARE')
 6004 FORMAT(1F7.1,1E10.3,1F7.1,4I3,2F6.1)
```

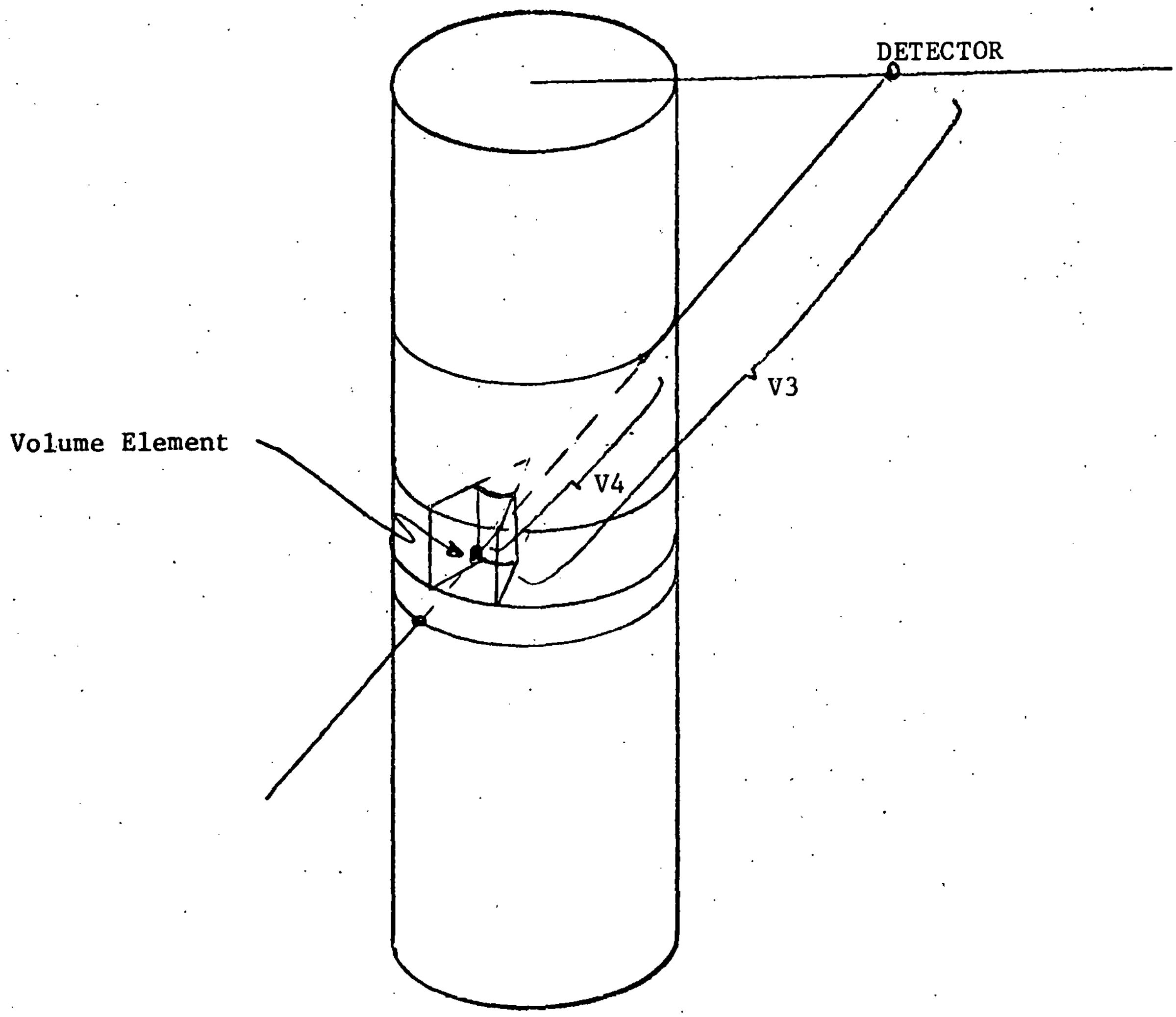

Fig. 10. Model for the calculation of counting rates.

where

ACTIV(i,j,k) = activity of the volume element,

DELTIM = measurement time,

and

DELERA = effective area of the detector.

Following this, the intersect point of vector V3 with the pipe, having the coordinates X3, Y3, and Z3 is computed by the subroutine INSECT, and the length of vector V4 from this intersect point to the volume element is computed by the subroutine VECTOR. With this length known, the correction factor BNUM is computed, which corrects ANUM for detector efficiency and for absorption by

$$\text{BNUM} = \text{DETEFF}/\exp\,(\text{V4} \times \text{COEFMA} + \text{PIPWAL} \times \text{COEFFE}), \quad (34)$$

where

DETEFF = efficiency of the detector,

COEFMA = linear gamma ray absorption coefficient in sodium,

PIPWAL = thickness of the wall of the pipe,

and

COEFFE = linear absorption coefficient of the pipe material.

The contribution CNUM of a volume element to the counts registered in one time channel is then computed as

$$\text{CNUM} = \text{ANUM} \times \text{BNUM} \ . \quad (35)$$

The total number of counts in a channel for each TIME is obtained by the summation

$$\text{CNTTIM} = \Sigma\ \text{CNUM} \ . \quad (36)$$

The number of background counts is computed by

$$\text{BACTM} = \text{BACKGR} \times \text{DELTIM} \ , \quad (37)$$

where

$$BACKGR = \text{background counting rate},$$

and

$$DELTIM = \text{length of one time step.}$$

Finally, CNTTIM is divided by the time at which the counts are being recorded to yield

$$TIMINV = \frac{CNTTIM}{TIME + 0.5 \times DELTIM} , \quad (38)$$

and summed to obtain the numerator of the Eq. (9) given for $\left(\overline{\frac{1}{t}}\right)$ in subsection 2.3 as

$$TIMINT = \Sigma\ TIMINV \quad (39)$$

and

$$CNTTOT = \Sigma\ CNTTIM \quad (40)$$

TIMINT and CNTTOT, the sum of all counts, are used for the calculation of the expected error of the velocity measurement as shown below.

The denominator of Eq. (9) is the sum of all counts after correction for decay, and the numerator is the sum of all counts after correction for decay and division by the time. These quantities are called DENOM and ENUM, and are used for the calculation of the mass averaged flow velocity FLWACT in Subprogram 7 by

$$FLWACT = SORDET \times \frac{ENUM}{DENOM} ,$$

which is equivalent to Eq. (7).

Using common notations for velocity (v), distance (x), and time (t), the mass averaged velocity was expressed earlier by Eq. (7).

Defining

$$\tau = \left(\overline{\frac{1}{t}}\right) , \quad (42)$$

Eq. (7) becomes,

$$v = x\tau , \tag{43}$$

with an error of

$$\frac{(dv)^2}{v^2} = \frac{(dx)^2}{x^2} + \frac{(d\tau)^2}{\tau^2} . \tag{44}$$

As defined above,

$$\tau = \left(\overline{\frac{1}{t}}\right) = \frac{\sum_i (n_i\Delta/t_i)}{\sum_i n_i\Delta} , \tag{45}$$

where

n_i = the counting rate at the time t_i,

and

Δ = length of individual time measurement.

Thus

$$N_i = n_i\Delta \tag{46}$$

is the total number of counts accumulated in one channel, and

$$t = \frac{\sum N_i/t_i}{\Sigma N_i} = \frac{1}{N}\sum N_i/t_i , \tag{47}$$

where

$$N = \sum N_i , \tag{48}$$

is the total number of counts registered by the detector during the passage of the activated sodium slug.

Defining

$$\nu = \sum N_i/t_i , \tag{49}$$

the value for τ becomes

$$\tau = \frac{1}{N}\nu \tag{50}$$

with an expected error of

$$\frac{(d\tau)^2}{\tau^2} = \frac{(dN)^2}{N^2} + \frac{(d\nu)^2}{\nu^2} . \tag{51}$$

Up to this point, the number of counts N was assumed to contain net as well as background counts. Separation of net and background counts leads to the substitutions

$$N \leftrightarrow N + B, \tag{52}$$

where

N = number of net counts ,

B = number of background counts,

and

$$(dN)^2 \longleftrightarrow (dN)^2 + (dB)^2 \ , \tag{53}$$

where

$(dN)^2$ = statistical error of net counts,

and

$(dB)^2$ = statistical error of background counts.

Since the statistical error of a number of counts n is generally expressed by

$$dn = \sqrt{n}, \tag{54}$$

the two error components are

$$(dN)^2 = N \tag{55}$$

and

$$(dB)^2 = B. \tag{56}$$

Thus the error equation for τ becomes

$$\frac{(d\tau)^2}{\tau^2} = \frac{1}{N} + \frac{B}{N^2} + \frac{(d\nu)^2}{\nu^2} \ . \tag{57}$$

Since ν was expressed as a sum of individual terms, its error also can be expressed as a sum of individual terms

$$(d\nu)^2 = \sum (d\nu_i)^2 = \sum \left(d\,\frac{N_i}{t_i} \right)^2 . \qquad (58)$$

For each individual time channel,

$$d\nu_i = d\,\frac{N_i}{t_i} \quad , \qquad (59)$$

with an associated error of

$$(d\nu_i)^2 = \frac{(d\,N_i)^2}{t_i^2} + \frac{N_i^2}{t_i^4}\,(dt_i)^2 \, . \qquad (60)$$

Since as mentioned before, $(dn_i)^2 = n_i$, the total counting error is the sum of the net counts and the background counts:

$$(dN_i)^2 = N_i + b \, . \qquad (61)$$

The error of the time measurement dt_i is identical for all channels, and is composed of the error in the measurement of the opening of the time channel δ and of half of the width of the time channel, $\Delta/2$. Thus

$$(dt_i)^2 = \delta^2 + (\tfrac{\Delta}{2})^2 \, . \qquad (62)$$

Insertion of these values for dt_i and dN_i in the equation for $d\nu_i$ yields

$$(d\nu_i)^2 = \frac{N_i + b}{t_i^2} + \frac{N_i^2}{t_i^4}\,[\delta^2 + (\tfrac{\Delta}{2})^2] \, . \qquad (63)$$

Insertion of this value into Eq. (58) yields

$$(d\nu)^2 = \sum \left\{ \frac{N_i + b}{t_i^2} + \left(\frac{N_i}{t_i^2} \right)^2 [\delta^2 + (\tfrac{\Delta}{2})^2] \right\} \quad , \qquad (64)$$

and

$$\frac{(d\nu)^2}{\nu^2} = \frac{\sum\left\{\frac{N_i+b}{t_i^{\,2}} + \left(\frac{N_i}{t_i^{\,2}}\right)^2 [\delta^2 + (\frac{\Delta}{2})^2]\right\}}{\left(\sum\frac{N_i}{t_i}\right)^2}, \tag{65}$$

Combination of this equation with Eqs. (57) and (44) yields the error equation for the measured velocity as,

$$(\frac{dv}{v})^2 = (\frac{dx}{x})^2 + \frac{1}{N} + \frac{B}{N^2} + \frac{\sum\left\{\frac{N_i}{t_i^{\,2}} + \left(\frac{N_i}{t_i^{\,2}}\right)^2 [\delta^2 + (\frac{\Delta}{2})^2]\right\}}{\left(\sum\frac{N_i}{t_i}\right)^2}. \tag{66}$$

The numerator and the denominator of the last term of this error equation are evaluated in Subprogram 6.

The numerator is called SIMINT and is computed according to Eq. (66) from,

N_i = CNTTIM, (67)

t_i = TIME, (68)

δ = ERRORT, and (69)

Δ = DELTIM. (70)

The denominator is called TIMINT, which is also computed in Subprogram 6 in the manner described above. The total expected error of the velocity measurement is calculated in Subprogram 7.

3.7 Subprogram 7: Output

Subprogram 7 performs the final calculations of the flow velocity and of the expected error and prints the results. Table 10 is a listing of the subprogram.

First, the flow velocity measured by the neutron activation technique is computed by

$$\text{FLWACT} = \text{SORDET} \times \frac{\text{ENUM}}{\text{DENOM}}$$

Table 10. Subprogram 7

```
C  SUBPROGRAM 7     SUBPROGRAM 7    SUBPROGRAM 7
C WRITING OF CALCULATED RESULTS
  700 WRITE(6,7012) CNTTOT
      WRITE(6,7014) BACKTT
      WRITE(6,7000) FLWAVG
      VELAVG = VELAVG /(12.0*2.54)
      WRITE(6,7013) VELAVG
      FLWACT = SORDET * ENUM / (DENOM*2.54*12.0)
      WRITE(6,7001) FLWACT
      ERRORF = (FLWACT-FLWAVG) * 100.0 / FLWAVG
      ERRORM = (ERRORX/SORDET)**2
      ERRORM = ERRORM + 1.0/CNTTOT
      ERRORM = ERRORM + BACKTT/CNTTOT**2
      ERRORM = ERRORM + SIMINT/TIMINT**2
      ERRORM = SQRT(ERRORM) * 100.0
      ERROR = SQRT(ERRORF**2+ERRORM**2)
      WRITE(6,7002)
      WRITE(6,7003)
      WRITE(6,7004)
      WRITE(6,7005)
      WRITE(6,7006) ERRORF
      WRITE(6,7011)
      WRITE(6,7007)
      WRITE(6,7008)
      WRITE(6,7009) ERRORM
      WRITE(6,7010) ERROR
 7000 FORMAT(//,' THE TRUE FLOW IS',1F7.2,' FT/SEC')
 7001 FORMAT(//,' THE MEASURED FLOW IS',1F7.2,' FT/SEC')
 7002 FORMAT(//,' THE FUNDAMENTAL ERROR,')
 7003 FORMAT(' DUE TO FLOW PROFILE, FLOW MIXING,')
 7004 FORMAT(' AND TO FINITE COLLIMATION ANGLES ')
 7005 FORMAT(' OF THE SOURCE AND THE DETECTORS,')
 7006 FORMAT(' IS',1F7.2,' PERCENT')
 7007 FORMAT(' DUE TO COUNTING STATISTICS')
 7008 FORMAT(' AND TO ERRORS IN TIME AND DISTANCE MEASUREMENTS,')
 7009 FORMAT(' IS',1F7.2,' PERCENT')
 7010 FORMAT(//,' THE TOTAL ERROR IS',1F7.2,' PERCENT')
 7011 FORMAT(//,' THE MEASUREMENT ERROR,')
 7012 FORMAT(/,' THE NUMBER OF NET COUNTS IS',1F8.1)
 7013 FORMAT(//,' THE AVERAGE VELOCITY IS',1F7.2,' FT/SEC')
 7014 FORMAT(/,' THE NUMBER OF BACKGROUND COUNTS IS',1F10.1)
```

This measurement is effected by a fundamental error due to the finite collimation angles at the source and the detector, to the flow profile, to flow mixing, and to the background counting rate. This relative fundamental error ERRORF, is computed, in percent, from the difference of the measured flow FLWACT and the true mass averaged flow FLWAVG from,

$$ERRORF = 100 \times \frac{FLWACT-FLWAVG}{FLWAVG}. \qquad (72)$$

Under realistic conditions, a measurement error will be superposed on the fundamental error. This measurement error is due to counting statistics and to errors in time and distance measurements. According to Eq. (66), the relative measurement error ERRORM, is computed as

$$ERRORM = 100 \sqrt{\left(\frac{ERRORX}{SORDET}\right)^2 + \frac{1}{CNTTOT} + \frac{SIMINT}{TIMINT^2}} \qquad (73)$$

Finally, the total expected error of the flow measurement performed by the neutron activation technique is derived as,

$$ERROR = \sqrt{ERRORF^2 + ERRORM^2}. \qquad (74)$$

3.8 Subprogram 8: Revision of Input Values

The Subprogram 8, listed in Table 11, updates the input variables if changes are required for succeeding runs.

3.9 Subroutines

Table 12 lists the three subroutines used by the main program. The first subroutine converts polar coordinates to rectangular coordinates. The second subroutine computes the length of the vector between two points in space. The third subroutine computes the point of intersection of a straight line with a cylinder.

When activating the sodium, neutrons pass through a certain thickness of sodium that acts as an absorber and scatterer, and attenuates the stream of neutrons. Gamma rays emitted by the activated atoms also have to

Table II. Subprogram 8

```
C SUBPROGRAM 8    SUBPROGRAM 8    SUBPROGRAM 8
C CONVERSION OF VARIABLES FROM METRIC TO ENGLISH UNITS
      WRITE(6,8000)
      WRITE(6,8003)
  802 READ(5,*) N
      IF(N.NE.1) GO TO 800
      PIPDIA = PIPDIA / 2.54
      PIPWAL = PIPWAL / 2.54
      SORSPC = SORSPC / 2.54
      SORSPC = SORSPC - PIPDIA/2.0
      SORDET = SORDET /2.54
      SORCOL = SORCOL * 360.0 / 6.28
      ERRORX = ERRORX /2.54
      DETEFF = DETEFF * 100.0
      DETDIA = DETDIA / 2.54
      DETLEN = DETLEN / 2.54
      DETSPC = DETSPC / 2.54
      DETSPC = DETSPC - DETLEN/2.0 -PIPDIA/2.0
      DETCOL = DETCOL * 360.0 / 6.28
C UPDATING OF INPUT VARIABLES
  801 WRITE(6,8001)
      WRITE(6,8002)
      READ(5,*) M
      IF(M.EQ.0) GO TO 105
      IF(M.EQ.1) READ(5,*) PIPDIA
      IF(M.EQ.2) READ(5,*) PIPWAL
      IF(M.EQ.3) READ(5,*) TURBIN
      IF(M.EQ.4) READ(5,*) VISKIN
      IF(M.EQ.5) READ(5,*) RUFNES
      IF(M.EQ.6) READ(5,*) SORINT
      IF(M.EQ.7) READ(5,*) SORSPC
      IF(M.EQ.8) READ(5,*) SORDET
      IF(M.EQ.9) READ(5,*) SORCOL
      IF(M.EQ.10) READ(5,*) ERRORX
      IF(M.EQ.11) READ(5,*) SIGMAR
      IF(M.EQ.12) READ(5,*) SIGMAT
      IF(M.EQ.13) READ(5,*) TIMHAF
      IF(M.EQ.14) READ(5,*) ENERGY
      IF(M.EQ.15) READ(5,*) DETEFF
      IF(M.EQ.16) READ(5,*) DETDIA
      IF(M.EQ.17) READ(5,*) DETLEN
      IF(M.EQ.18) READ(5,*) DETSPC
      IF(M.EQ.19) READ(5,*) DETCOL
      IF(M.EQ.20) READ(5,*) ERRORT
      IF(M.EQ.21) READ(5,*) COEFMA
      IF(M.EQ.22) READ(5,*) COEFFE
      IF(M.EQ.23) READ(5,*) RHOMAT
      IF(M.EQ.24) READ(5,*) WTMOLM
      IF(M.EQ.25) READ(5,*) BACKGR
      IF(M.EQ.26) READ(5,*) NNNCHA
      IF(M.EQ.27) READ(5,*) NNNDET
      IF(M.EQ.28) READ(5,*) NNNPHI
      IF(M.EQ.29) READ(5,*) NNNR
      IF(M.EQ.30) READ(5,*) NNNZ
      IF(M.EQ.31) READ(5,*) FLWAVG
      IF(M.GT.31) WRITE(6,8004)
      GO TO 801
  800 CONTINUE
 8000 FORMAT(//////////)
 8001 FORMAT(' ENTER ID NUMBER OF INPUT VARIABLE TO BE CHANGED')
 8002 FORMAT(' ENTER 0 IF STANDARD SET OF VARIABLES TO BE USED')
 8003 FORMAT(' ENTER 1 FOR REPEAT RUN')
 8004 FORMAT(' INPUT VARIABLE NOT DEFINED FOR GIVEN ID NUMBER')
      END
```

Table 12. Subroutines

```
C SUBROUTINE FOR POLAR - RECTANGULAR CONVERSION
      SUBROUTINE POLREC(R,PHI,X,Y)
      X = R * COS(PHI)
      Y = R * SIN(PHI)
      RETURN
      END
C SUBROUTINE FOR CALCULATION OF VECTOR LENGTH
      SUBROUTINE VECTOR(X1,Y1,Z1,X2,Y2,Z2,V)
      V = SQRT((X2-X1)**2 + (Y2-Y1)**2 + (Z2-Z1)**2)
      RETURN
      END
C SUBROUTINE FOR INTERSECT CALCULATION
C POINT 1 IS INSIDE OF CYLINDER, POINT 2 OUTSIDE
      SUBROUTINE INSECT(X1,Y1,Z1,X2,Y2,Z2,R,X3,Y3,Z3)
      IF(Y2.EQ.Y1) GO TO 100
      ANUM = (X2-X1) / (Y2-Y1)
      BNUM = X1 - ANUM*Y1
      CNUM = ANUM * BNUM / (1.0+ANUM**2)
      DNUM = (R**2 - BNUM**2) / (1.0+ANUM**2)
      Y31 = (-CNUM) + SQRT(CNUM**2+DNUM)
      Y32 = (-CNUM) - SQRT(CNUM**2+DNUM)
      IF(ABS(Y31-Y2).GT.ABS(Y32-Y2)) GO TO 101
      Y3 = Y31
      GO TO 102
  100 Y3 = Y1
      X3 = R
      GO TO 103
  101 Y3 = Y32
  102 X3 = BNUM + ANUM*Y3
  103 Z3 = Z1 + (Z2-Z1)*(X3-X1) / (X2-X1)
      RETURN
      END
```

pass through a certain thickness of sodium before reaching the detector. These two situations are illustrated in the Figs. 8 and 10.

The problem presented in these figures requires the calculation of the point of intersection (coordinates x_3, y_3, z_3) of a straight line with a cylinder. In both cases, the cylinder can be represented as

$$x^2 + y^2 = R^2 , \tag{75}$$

and the line connecting the two points (x_1, y_1, z_1) and (x_2, y_2, z_2) as

$$\frac{x-x_1}{x_2-x_1} = \frac{y-y_1}{y_2-y_1} = \frac{z-z_1}{z_2-z_1} . \tag{76}$$

With

$$a = \frac{x_2-y_1}{y_2-y_1} , \tag{77}$$

and

$$b = x_1 - ay_1 , \tag{78}$$

the relation between x and y can be expressed as

$$x = ay + b . \tag{79}$$

Inserting this into Eq. (75), and substituting

$$c = \frac{ab}{a^2 + 1} \tag{80}$$

and

$$d = \frac{R^2 - b^2}{a^2 + 1} , \tag{81}$$

yields an equation for the y-coordinate of the intersection point

$$y^2 + 2\,cy - d = 0 , \tag{82}$$

which has the solutions

$$y_{31} = c + \sqrt{c^2 + d} \quad (83)$$

and

$$y_{32} = -c - \sqrt{c^2 + d}. \quad (84)$$

The subroutine then picks that value for the solution y_3 which is closer to the y-coordinate of the point that is located outside of the cylinder. With y_3 known,

$$x_3 = ay_3 + b, \quad (85)$$

and

$$z_3 = \left(\frac{x_3 - x_1}{x_2 - x_1}\right) (z_2 - z_1) + z_1 \ . \quad (86)$$

4. OPTIMIZATION OF THE EBR-II EXPERIMENT

An experiment to verify the flow measurement technique by neutron activation methods is planned at the EBR-II for the last quarter of FY 1976. It will be based on the method of transit time measurements. Many parameters will affect the accuracy of this planned experiment. The most influential source of error is the strength of the neutron source. Equation (66) shows that the total number of counts N enters the error equation directly, i.e., the higher the total number of counts registered during passage of the activated sodium plug past the detector, the lower the measurement error. The background-to-net count ratio also affects the error of the measurement. Obviously, the number and size of the scintillation detectors also will affect the error directly. The collimation angles of the source and the detectors also affect the accuracy of the velocity reading. Increased collimation angles increase the counting rate and thus reduce the measurement error, but they also increase the length of the irradiated sodium slug and the detector window, and thereby increase the fundamental error. Increasing the spacing between the source and the detector decreases the relative error in measuring this distance and thereby decreases the measurement error, but it also decreases the number of counts due to the decay of the original activity and thereby increases the measurement error.

When the activated sodium slug flows past the detectors, the number of registered counts shows a time distribution with a pronounced peak. The measurement of the whole distribution is necessary for a reliable mass-averaging of the flow velocity. The number of time channels in which the total number of counts are to be divided, however, is left to the decision of the experimenter. A widening of the time channels by reducing the number of channels to be used for the storage of pulses will increase Δ and thereby increase the error of the measurement, but it will also increase N_i and thereby reduce the same error.

Thus for a minimum error of the flow measurement, the source and detector collimation angles, the source-detector spacing, and the number of information channels must be optimized. This was done utilizing the computer program described in Section 3 for various source strengths and for two source spacings (i.e., with the neutron source as close to the steel pipe as possible, and with the neutron source as close to the undisturbed insulation as possible). The expected errors for optimized experimental conditions, assuming that there are no background counts, are plotted in Fig. 11.

A neutron source yielding 10^{10} neutrons per pulse will be used. A source of such strength can be mounted close to the intact insulation and still yield experimental errors that are sufficiently low (see Fig. 11). Assuming that the background count is zero, the following are optimized experimental conditions for a flow velocity of 15.7 ft/sec, and a neutron source with an output of 10^{10} n/sec:

SORDET = 240 in.,

SORCOL = 100 deg.,

DETCOL = 120 deg., and

NNNCHA = 25.

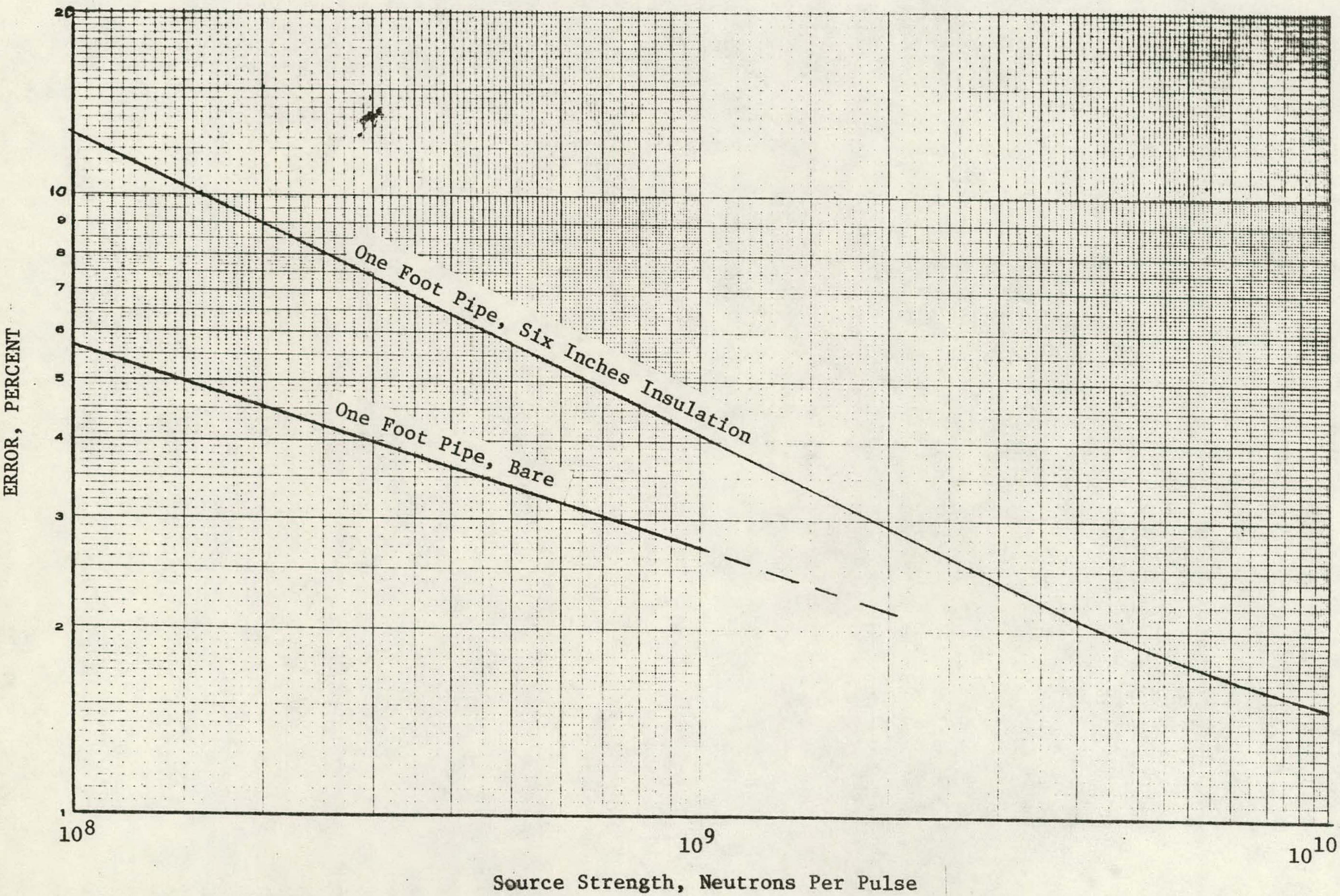

Fig. 11. Expected accuracy of sodium flow measurement.

Only poor collimation of source and detectors is necessary for an optimized experiment. This is due to the fact that self absorption of neutrons and gamma rays in the sodium effectively limits the size of the irradicated sodium slug. Changes of the expected accuracy of the flow velocity measurement due to deviation from the optimized experimental conditions are listed in Table 13.

A second series of optimization runs was performed under the assumption of a background of 200 cps, again using the computer program described in Section 3. The minimum error obtainable for this background, for a source with 10^{10} neutrons per pulse and a flow velocity of 15.7 ft/sec., is 4.0%. This minimum error was found for the following experimental conditions:

SORDET = 120 in.,

SORCOL = 140 deg.,

DETCOL = 110 deg., and

NNNCHA = 80.

Table 14 shows how this minimum error increases whenever one of these experimental conditions is varied from its optimum value.

A comparison of the optimized experimental conditions is given in Table 15 for backgrounds of 0 and 200 cps. This table shows that to compensate for the increased statistical error due to the background counts, the number of net counts must be increased by shortening the source - detector spacing and by increasing the collimation angle of the source. This increase in the total number of net counts allows a reduction of the width of the time channels used for the measurement of the activity distribution, which is expressed by the higher number of channels (NNNCHA) used for the partitioning of the activity distribution.

The true background level was not known at the time of the writing of this report. Conceivably, it could be higher than the 200 cps assumed for the preceding optimization process. A background level of this magnitude would require a further reduction of the source-detector spacing and a further increase of the source collimation angle over the values listed

Table 13. Expected Error of Flow Velocity Measurement

(Transit-Time Method, Background = 0 cps)

Variable	Dimension	Optimized Value		
SORDET	feet	15	20	25
	%	1.88	1.51	1.53
SORCOL	degrees	80	100	120
	%	1.63	1.51	1.69
DETCOL	degrees	105	120	145
	%	1.58	1.51	1.61
NNNCHA	(integer)	15	20	25
	%	1.64	1.51	1.66

Table 14. Expected Error of Flow Velocity Measurement

(Transit-Time Method, Background = 100 cps)

Variable	Dimension	Optimized Value		
SORDET	feet	90	120	150
	%	5.62	4.07	4.41
SORCOL	degrees	120	140	160
	%	4.26	4.07	10.37
DETCOL	degrees	100	120	140
	%	5.33	4.07	5.19
NNNCHA	integer	60	80	100
	%	4.09	4.07	4.08

Table 15. Effect of Background on Optimized Conditions

Background, cps	0	200
Optimized SORDET, in.	240	120
Optimized SORCOL, deg.	100	140
Optimized DETCOL, deg.	120	120
Optimized NNNCHA, integer	25	80

in Table 14, if the same strict analytical optimization procedure were applied to the situation. However, an additional reduction of the source-detector spacing and an additional increase of the source collimation angle are not pratical. Therefore, the EBR-II experiment will be performed with the experimental conditions listed in Table 14. The expected error, however, will be re-evaluated, using the computer program described in Section 3 under consideration of the true background level. The true background level will be determined prior to the flow velocity measurements in a separate experiment.

For the conditions listed in Table 14, the length of the optimized time channels for NNCHA = 80 was found to be 0.0115 sec. The activity distribution peaked at 0.641 sec. for a flow velocity of 15.7 ft/sec. Therefore, the time step that advances the storage channels of the TMC - 1024 channel analyzer used for the EBR-II test will be set to 10 milliseconds. This time step is close to the optimized value and will accomodate the while activity distribution in the 1024 channels of the multichannel analyzer.

5.0 PREDICTED ACCURACY OF THE EBR-II EXPERIMENT

The optimization for minimum error of the experimental conditions for the planned EBR-II experiment led to the conclusion that the flow velocity measurements should be performed at a source - detector spacing of ten feet, with a source collimation angle of 140 degrees, and with a detector collimation angle of 100 degrees (see Table 14). The time step should be ten milliseconds. All these conditions were derived, and can be met, for a flow velocity of 15.7 ft/sec, the maximum flow rate in the secondary loop of the EBR-II. The time step must be increased for lower flow velocities, however, to accomodate the whole activity distribution in the 1024 channels of the TMC multichannel analyzer. The computer program ACTOPT was modified, therefore, to increase the time step (originally set at 1 msec) by factors of 10, until the condition is reached that the peak of the activity distribution falls in a time channel with a number less than 512. This selection method for the time step DELTIM assures that the whole activity distribution will be recorded in the 1024 channels of the TMC multichannel analyzer. Another modification of the computer program ACTOPT was made by specifying the size and the number of detectors that are available at EBR-II. Instead of the four 3 x 3 NaI detectors used in ACTOPT, two 5 x 5 detectors are used in the modified program.

With these two modifications as listed in Table 16, the computer program was maned ACTSIM, and runs were performed for the prediction of the expected results in the planned EBR-II experiment. The activity distributions expected to be measured for various flow velocities are plotted linearly in Fig. 12 and logarithmically in Fig. 13. The total number of counts is plotted in Fig. 14. In this figure, the continuous curve is a plot of Eq. (5) for the counting rate, normalized to equal the computer output for a flow velocity of 15.7 ft/sec. Figure 14 shows excellent agreement between the analytically derived and numerically computed counting rates, at least at the higher flow velocities. At lower flow velocities, there is some discrepancy between the two sets of data, due to the effects of flow profile, the collimation of the neutron source, and the absorption of neutrons and gamma rays in the sodium.

As discussed previously, program ACTSIM computes the total error to be expected in the flow velocity measurement when the transit-time method is used. This total error is listed in column 2 of Table 17 along with errors expected for total-count method of flow velocity measurement. The counts plotted in Fig. 14 and listed in column 3 of Table 17 can be derived analytically by Eq. (5).

The relative statistical errors associated with these numbers of total counts, dN/N, are listed in column 5 of Table 17. The effects of the background counts as computed by ACTSIM and listed in column 4 of Table 17 are included in the values for the statistical error.

Table 16. Calculation of Time Step DELTIM

```
C PROGRAM EBR2SIM
C PREDICTION OF ACCURACY OF FLOW VELOCITY MEASUREMENT
C BY THE NEUTRON ACTIVATION TECHNIQUE.
C      THIS PROGRAM IS FULLY INTERACTIVE.
C      EBR2SIM USES INPUT PARAMETERS TAILORED TO THE EBR II TEST,
C      CONSIDERING AVAILABLE INSTRUMENTATION AND NEUTRON SOURCE.
C      A BACKGROUND COUNT OF 200 CPS IS ASSUMED.
C SUBPROGRAM 1    SUBPROGRAM 1    SUBPROGRAM 1
C STORAGE OF STANDDARD INPUT VARIABLES, WITH THE DIMENSIONS:
C     PIPDIA(INCHES),PIPWAL(INCHES),FLWAVG(FT/SEC),VISKIN(FT2/SEC),
C     RUFNES(INCHES),TURBIN(PERCENT),SORINT(NEUTRONS PER PULSE),
C     SORSPC(INCHES),SORDET(INCHES),SORCOL(DEGREES),ERRORX(INCHES),
C     SIGMAR(MILLIBARN),SIGMAT(MILLIBARN),TIMHAF(SEC),ENERGY(MEV),
C     DETEFF(PERCENT),DETDIA(INCHES),DETLEN(INCHES),DETSPC(INCHES),
C     DETCOL(DEGREES),ERRORT(SECONDS),DELTIM(SECONDS),COEFMA(1/CM),
C     COEFFE(1/CM),RHOMAT(G/CM3),BACKGR(1/SEC)
      DIMENSION ACTIV(24,12,24), COORD(12,24)
      PIPDIA = 12.0
      PIPWAL = .25
      TURBIN = 5.0
      VISKIN = .341E-05
      RUFNES = .001
      SORINT = .1E+11
      SORSPC = 10.0
      SORDET = 120.0
      SORCOL = 140.0
      ERRORX = 1.0
      SIGMAR = 185.0
      SIGMAT = 1400.0
      TIMHAF = 11.2
      ENERGY = 1.6
      DETEFF = 30.0
      DETDIA = 5.0
      DETLEN = 5.0
      DETSPC = 8.0
      DETCOL = 120.0
      ERRORT = .005
      COEFMA = 0.0485
      COEFFE = 0.346
      RHOMAT = 0.97
      WTMOLM = 22.99
      BACKGR = 200.0
      DELTIM = 0.001
      NNNDET = 2
      NNNPHI = 12
      NNNR = 6
      NNNZ = 24
      FLWAVG = 15.7
  100 IF(512.0*DELTIM.GE.SORDET/(FLWAVG*12.0)) GO TO 801
      DELTIM = DELTIM * 10.0
      GO TO 100
```

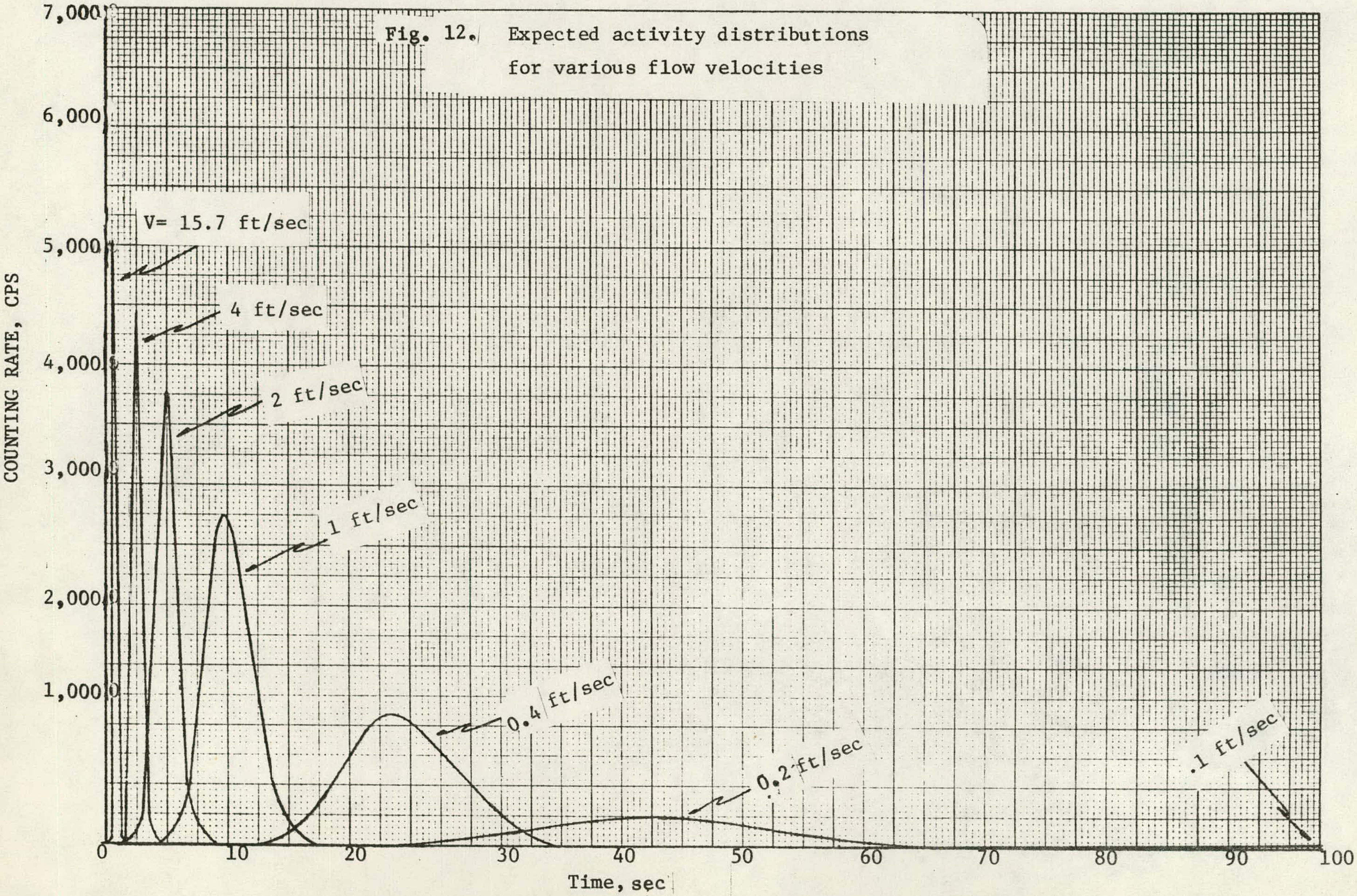

Fig. 12. Expected activity distributions for various flow velocities

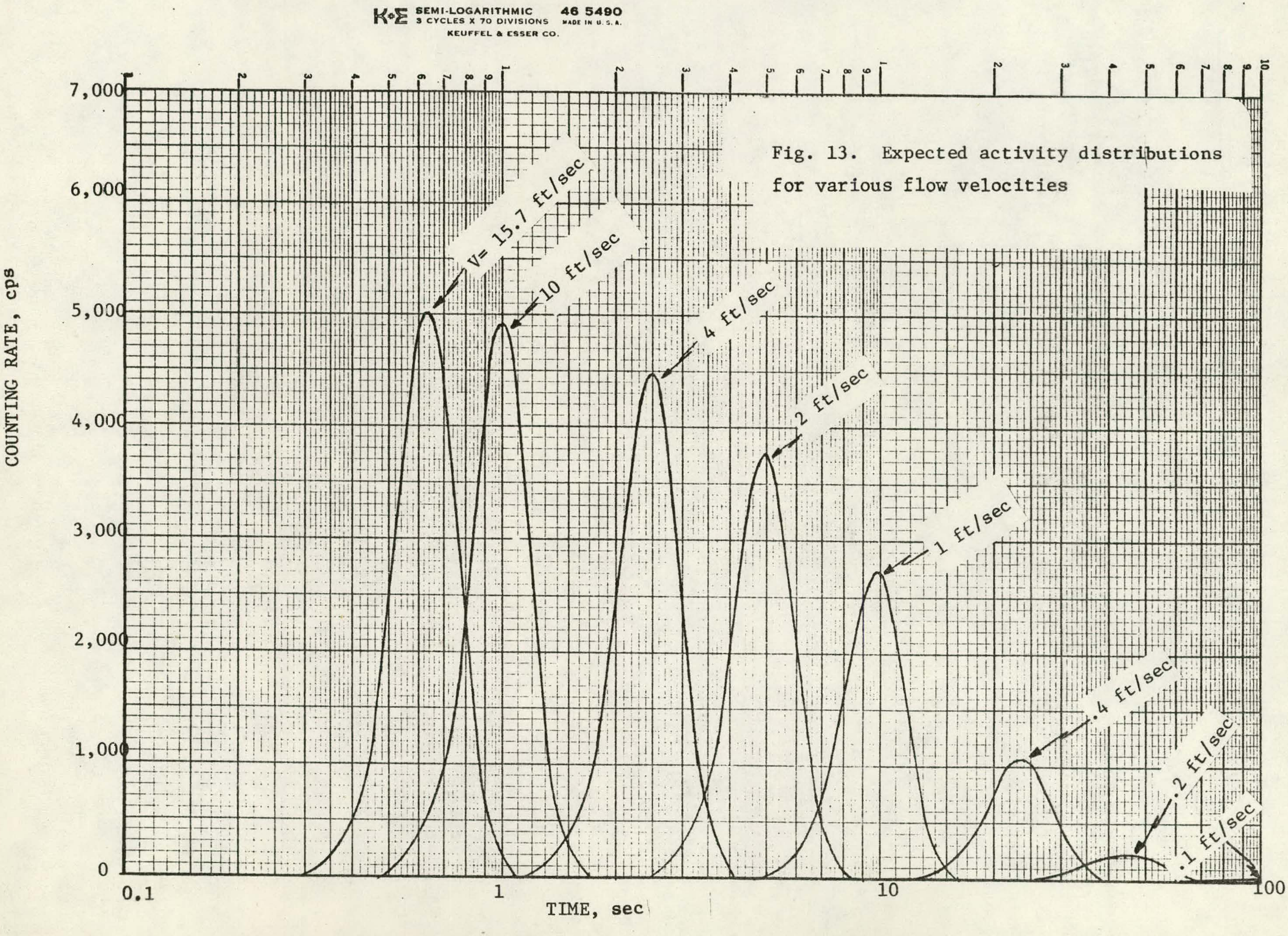

Fig. 13. Expected activity distributions for various flow velocities

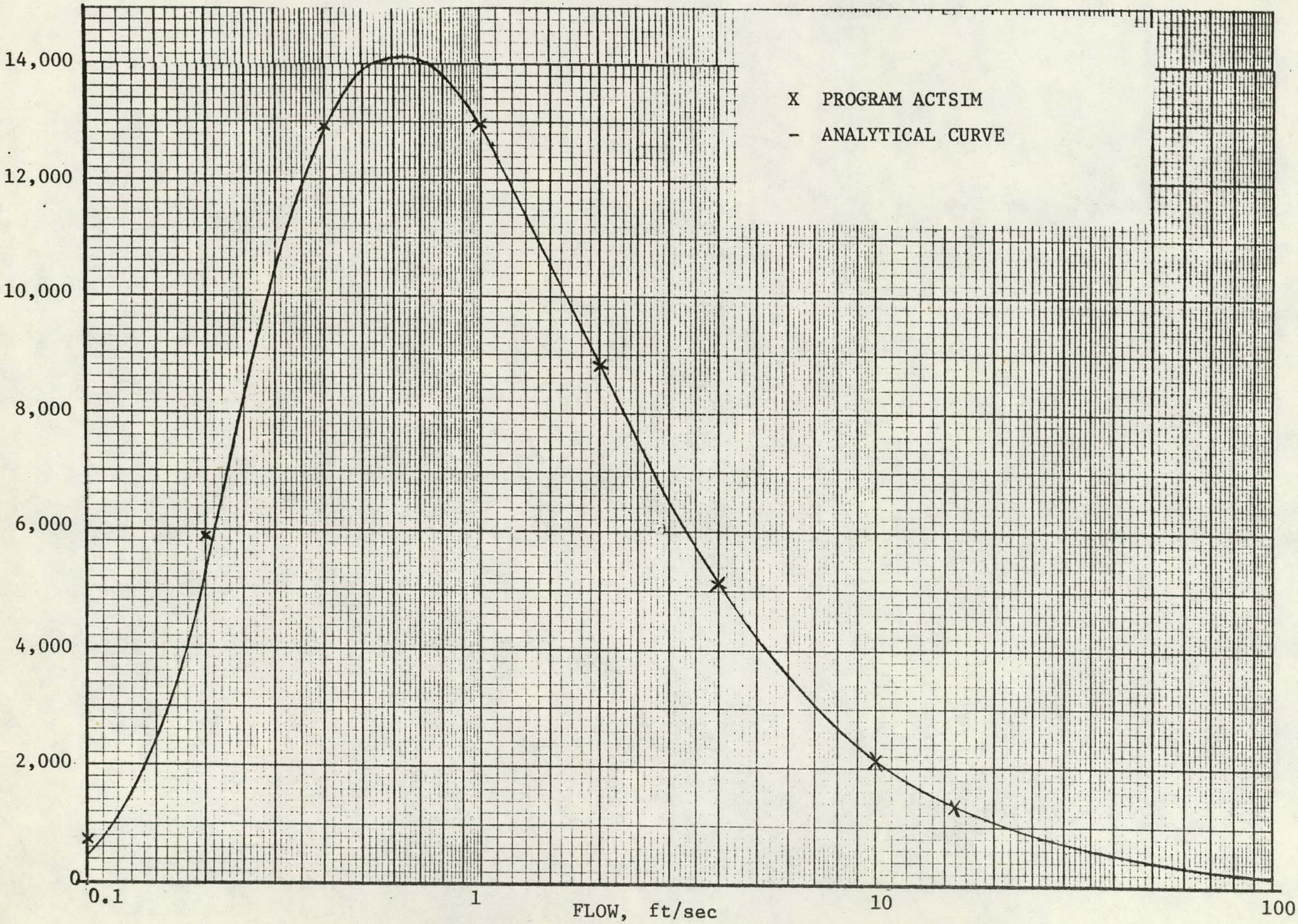

Fig. 14. Total Number of Counts

Table 17. Prediction of Accuracy of EBR-II Experiment
(Background = 200 cps)

Ft/Sec	Transit-Time Method Error %	Total-Count Method Total Counts	Background Count	Statistic Error, %	$\frac{dN/N}{dv/v}$	Error %
15.7	4.08	1,491	194	2.75	-0.96	2.86
10	3.35	2,288	302	2.24	-0.94	2.38
4	2.52	5,202	756	1.48	-0.84	1.76
2	2.47	8,885	1,520	1.15	-0.69	1.67
1	2.81	12,920	3,060	0.98	-0.38	2.58
0.4	6.46	12,812	7,759	1.12	0.55	2.04
0.2	13.52	5,876	15,757	2.50	2.10	1.19
0.1	43.0	752	31,999	24.06	5.19	4.64

Differentiation of Eq. (5) leads to

$$\frac{dN}{dv} = \frac{\text{const.}\ (\lambda d/v - 1)}{v^2\ e^{\lambda d/v}} \quad . \tag{87}$$

Thus the sensitivity S of this method is

$$S = \frac{dN/N}{dv/v} = \frac{dN}{dv} \times \frac{v}{N} \tag{88}$$

$$S = \frac{\lambda d}{v} - 1 \quad . \tag{89}$$

These sensitivities are listed in column 6 of Table 17.

Values for the statistical error of the measured flow velocity

$$\frac{dv}{v} = \frac{dN/N}{S} \tag{90}$$

are listed in the last column of Table 17 and are plotted in Fig. 15. Figure 15 also shows the total error expected from the transit time method, computed with the program ACTSIM and tabulated in column 1 of Table 17.

The total error of the total count method can be expected to be higher than the statistical error shown in Fig. 15. Therefore, for flow velocities over 1 ft/sec, the transit-time method can be expected to be more accurate than the total count method. Since in the EBR-II experiment the flow velocities will be above 1 ft/sec, and since the experimental setup for accurate and absolute activity measurement is much more elaborate than the setup for the transit time method, it was decided that the measurement of the flow velocities in the secondary loop of the EBR-II will be based primarily on the transit-time method. However, for a secondary check, the experimental data also will be evaluated in terms of the total-counts technique.

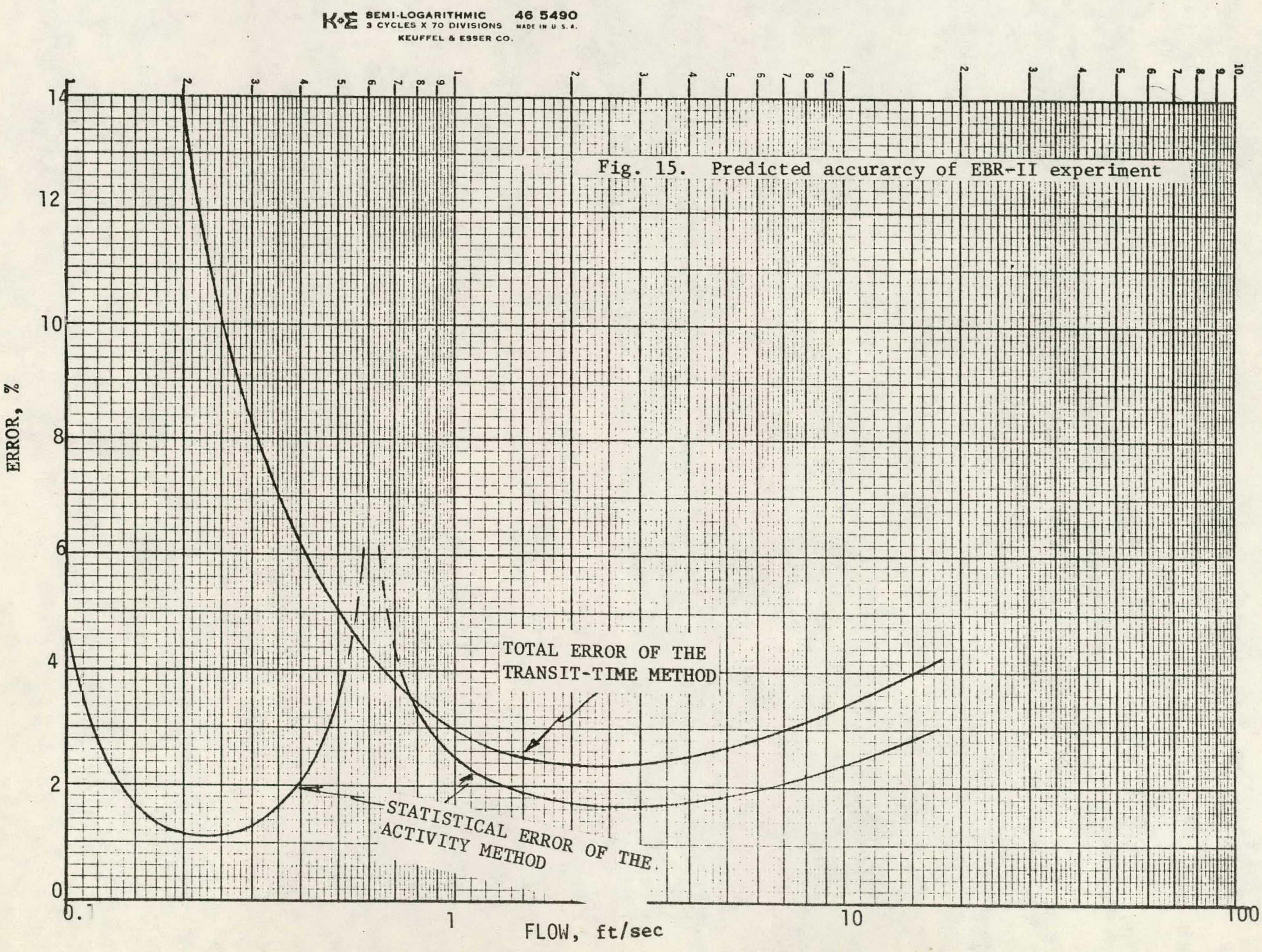

Fig. 15. Predicted accurarcy of EBR-II experiment

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