Date of Issue: November 5, 1973

Report Number: K-1844

Subject Category: UC-37, Instruments

SURVEY OF AVAILABLE TECHNOLOGY FOR AUDITING ^{235}U ENRICHMENT IN CASCADE EQUIPMENT

J. C. Bailey

Isotopic Analysis Department
Laboratory Division

Oak Ridge Gaseous Diffusion Plant
Union Carbide Corporation
Oak Ridge, Tennessee

Prepared for the U. S. Atomic Energy Commission
under U. S. Government Contract W-7405 eng 26

DISCLAIMER

ABSTRACT

A search for possible nondestructive techniques which might be utilized by a safeguards inspection team for auditing ^{235}U enrichment of UF_6 in gaseous diffusion cascade equipment without access to the UF_6 itself was carried out at the ORGDP.

The work included a literature survey of safeguards techniques in use by others, and a search for other methods or equipment which might be applied to the present objective. Various possible methods are evaluated briefly.

Probable limited access to cascade equipment precludes the use of methods involving bulky equipment, including neutron and gamma generators, coincident or anticoincident counters and high energy isotopic neutron sources of sufficient strength to produce a measurable fission rate in ^{238}U which requires large shields. Irradiation with low energy neutrons followed by detection of fission events and passive gamma measurements could provide information on the ^{235}U content, but not on the ^{238}U.

Two methods upon which preliminary investigations were carried out are considered to warrant further development. The first involves a direct measurement of the ^{235}U gamma radiation from UF_6 within a pipe and a measurement of the absorption of gamma rays from an external gamma source when these rays pass through the pipe walls and UF_6. The ^{235}U gamma measurement indicates the amount of this isotope present, and the gamma absorption measurement, when corrected for pipe-wall absorption, indicates the total uranium present. Experimental tests indicated this method to be well within the scope of current technology. The tests included an evaluation of a commercially available ultrasonic gauge which could be used for pipe-wall thickness measurements.

The second method involves the irradiation of the UF_6 with a moderated neutron source and the detection of gamma rays resulting from neutron capture in ^{238}U and fissions induced in ^{235}U. This method is considered to warrant further investigation, but its actual feasibility has not been established.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

SURVEY OF AVAILABLE TECHNOLOGY FOR AUDITING ^{235}U ENRICHMENT IN CASCADE EQUIPMENT

INTRODUCTION

This is a report on work done at the Oak Ridge Gaseous Diffusion Plant (ORGDP) to evaluate possible nondestructive techniques for auditing uranium-235 (^{235}U) enrichment of uranium hexafluoride (UF_6) in gaseous diffusion cascade equipment without access to the UF_6 itself and without knowledge regarding all plant operating conditions. While a safeguards inspection team could conduct a ^{235}U audit more accurately by obtaining samples from various points in the plant streams and isotopically analyzing them, permission to do this might not be granted; therefore, a method for determining the ^{235}U enrichment of UF_6 inside process equipment from measurements made outside the equipment should be available.

The project included a nonexperimental evaluation of various nondestructive enrichment determination methods used in other safeguards applications as well as a search for additional applicable methods. The work, funded by the AEC Division of Nuclear Materials Security, was terminated after the most promising principles were reviewed and an applicable system was developed and engineering specifications were prepared but before the hardware for construction of a prototype or test unit could be assembled.

Specific objectives of the work were:

1. To survey the literature for techniques and instruments which could contribute toward the development of a method for evaluating the enrichment of a flowing UF_6 stream from a point outside the equipment.

2. To determine the applicability of selected techniques and instruments on pipes of different sizes containing UF_6 at different pressures and different enrichment levels.

On the basis of these studies, two techniques appear to warrant further investigation directed toward possible field application. The first involves a measurement of the ^{235}U gamma radiation from the UF_6 to provide an estimate of the ^{235}U present. A measurement of the attenuation of gamma rays from an external source passing through the pipe walls and UF_6 gas, when corrected for pipe-wall absorption, would provide an estimate of the total uranium present. The ratio of ^{235}U to total uranium is the enrichment value desired. This method was investigated in preliminary experiments, and it was concluded that development for plant application is feasible and is well within the scope of current technology.

The second method involves the irradiation of the UF_6 gas with an external neutron source. Detection of gamma rays resulting from neutron capture in uranium-238 (^{238}U) which would exhibit a characteristic energy and the continuous spectrum of gamma rays resulting from ^{235}U fissions might then permit evaluation of the enrichment. Work on this method has been limited to exploratory calculations to evaluate the effects of moderating material around the source on the anticipated fission and capture events.

The remaining sections of this report consist of (1) a summary, (2) a brief discussion of system requirements peculiar to application in a gaseous diffusion plant, (3) comments concerning specific nondestructive techniques for determining uranium enrichment, (4) descriptions of experiments concerning the passive measurement of the ^{235}U gamma radiation and a gamma attenuation measurement to determine total uranium, (5) calculations to evaluate the effects on the relative ^{235}U fission rate and ^{238}U capture rate of various factors affecting the spectrum of neutrons from an isotopic neutron source, and (6) conclusions. Specifications developed for the purchase of the components for a germanium-lithium (Ge-Li) gamma spectrometry system, and a computer code developed for gamma attenuation calculations are treated in two appendixes.

SUMMARY

A literature search for nondestructive techniques which might be utilized by a safeguards inspection team for auditing ^{235}U enrichment of UF_6 in gaseous diffusion cascade equipment without access to the UF_6 itself was conducted. While an inspection team could conduct a ^{235}U audit more accurately by obtaining samples of UF_6 from various points in the plant streams and isotopically analyzing them, permission to do this might not be granted; therefore, methods for determining UF_6 enrichment inside process equipment from measurements made outside the equipment were sought.

Principal special requirements for equipment to be used in this application were that it be usable in locations with only limited access to vessels to be monitored and in environmental temperatures up to 150°F,* and that the equipment be easily moved from one location to another. It was assumed that data regarding cascade operating conditions, such as pressure, would not be available.

The work included a literature survey of safeguards techniques in use by others, and a search for other methods or equipment which might be applied to the objectives.

The limited access to cascade equipment anticipated in field application precluded the consideration of methods involving neutron and gamma generators, and coincident or anticoincident counting of nuclear events in interrogated materials. The use of high-energy isotopic neutron sources of sufficient strength to produce a measurable fission rate in ^{238}U was also considered to be limited by the bulk of the source shielding required. Irradiation with low-energy neutrons followed by detection of fission events would yield information about the ^{235}U present but would not indicate the quantity of ^{238}U involved. Passive gamma measurements could also provide information on the ^{235}U content, but since ^{238}U does not emit gamma radiation and is separated from its gamma emitting daughter products in the cascade, such measurements alone do not give sufficient data for an enrichment determination.

*This is the highest temperature, in the opinion of the ORGDP medical staff, to which personnel should be exposed without heat protective equipment.

Two methods upon which preliminary investigations were carried out are considered to warrant further development if interest in the project is renewed. The first involves a direct measurement of the ^{235}U gamma radiation from UF_6 within a pipe and a measurement of the absorption of gamma rays from an external gamma source when these rays pass through the pipe walls and UF_6. The ^{235}U gamma measurement indicates the amount of this isotope present, and the gamma absorption measurement, when corrected for pipe-wall absorption, indicates the total uranium present. Experiments indicated this method is well within the scope of current technology. The tests included an evaluation of a commerically available ultrasonic gauge which could be used for pipe-wall thickness measurements.

The second method involves the irradiation of the UF_6 with a moderated neutron source and the detection of gamma rays resulting from neutron capture in ^{238}U and fissions induced in ^{235}U. This method warrants further investigation, but its actual feasibility has not been established.

SYSTEM REQUIREMENTS

In addition to the obvious requirement that the system yield the necessary information regarding the quantities of ^{235}U and ^{238}U present, that part of the system which must be adjacent to the equipment being monitored must be usable in locations with rather limited space availability. The equipment must be operable in locations with ambient temperatures up to 150°F, the highest temperature, in the opinion of the ORGDP medical staff, to which personnel should be exposed without heat protective equipment. It should be sufficiently portable that its application would not be limited to a single location.

COMMENTS ON SPECIFIC TECHNIQUES[1-4]

PASSIVE GAMMA MEASUREMENTS

The detection of gamma rays emitted by ^{235}U in a gas stream provides a means for determining the ^{235}U content of the stream. Uranium-238 does not emit a gamma which would provide a measurement of the quantity of this isotope present. The daughter products of ^{238}U, which do emit gamma rays, are removed from the gas stream of a diffusion cascade by deposition on cascade surfaces, since these daughter products do not form volatile fluorides.

Deposition occurs on surfaces providing high contact with the gas stream. The gas stream and pipe surfaces are essentially free of such daughter products. Thus, passive gamma measurements are not applicable to the determination of ^{238}U.

The use of passive gamma measurements to determine ^{235}U content of a pipe used in conjunction with a gamma attenuation measurement to determine total uranium was noted in the introduction, and experiments directed toward this purpose are described later in this report.

ACTIVE INTERROGATION USING NEUTRON OR GAMMA GENERATORS

Active interrogation using neutron or gamma generators was not considered to be applicable to this particular problem, because of the bulk of such generators and the additional mass of the required shielding, along with the attendant lack of portability.

ACTIVE INTERROGATION USING ISOTOPIC NEUTRON SOURCE

Active interrogation of uranium material for ^{235}U measurement may be carried out by irradiation with low-energy neutrons, as from an americium-lithium source or a source of thermal neutrons, and measurement of the resulting fission events by coincidence counting of neutrons or gamma rays. The use of multiple counters and the recording of events with simultaneous activation of two or more counters provides high discrimination against counts caused by the interrogating neutrons or other random events.

Another technique involving low-energy or thermal neutrons is the detection of fast neutrons with a plastic scintillation counter biased to exclude pulses from the low-energy interrogating neutrons. Interrogation with low-energy neutrons, with detection of induced fission events, yields information on ^{235}U content only, and will not in itself indicate the quantity of ^{238}U present or the desired enrichment.

With high energy neutrons, fissions are produced in ^{238}U as well as in ^{235}U. The use of neutrons with two different spectra will provide measurements of both the ^{235}U and ^{238}U in the interrogated material. In the application of fast-neutron interrogation, coincidence counting, rather than pulse height discrimination, would be required to separate counts due to fission neutrons from those produced by the interrogating neutrons.

With respect to application to the present problem, it is noted that coincidence counting of fission events requires high counting efficiency to assure a sufficient probability that two or more counters will be activated simultaneously with the occurrence of a fission in the interrogated material. Thus, the interrogated substance must be essentially surrounded by an array of counters to obtain high geometric efficiency. This would limit application to locations with good accessibility. An additional problem in the use of a fast neutron source would be the requirement for a relatively bulky shield for the source.

DETECTION OF ^{238}U BY SPONTANEOUS FISSION DETERMINATION

The spontaneous fissions of ^{238}U may be measured by coincidence counting of fission neutrons in a manner similar to that described above for active interrogation with external neutrons. In this application coincidence counting is required to discriminate against background neutrons, largely from the α,n reaction associated with uranium alpha irradiation of the fluorine of UF_6. The low sensitivity and the size limitations of the coincidence counters make this method impractical. For example, a 3-ft length of 12-in.-dia pipe will contain only 150 g of ^{238}U at 1% ^{235}U enrichment, 4 psia pressure and 150°F. With a spontaneous fission rate of 7.5 fissions per second per kg of ^{238}U and 2% coincidence counting geometry[5], the count rate would be only about 1.4 counts/min. The background, attributable partly to cosmic ray activity, would make accurate measurements at this level impossible, even if very long counting time were acceptable. Cosmic-ray induced counts[5] on a 4π barrel counter, which should be comparable in size to equipment needed for a determination of spontaneous fissions in a process pipe, varied from about 30 counts/min at the altitude of Los Alamos (about 7,300 ft above sea level) to about 5 counts/min at the level of Cincinnati (about 500 ft).

CHARACTERISTIC CAPTURE GAMMA RAYS

The possibility of detecting the gamma rays of characteristic energies associated with the capture of neutrons in ^{235}U and/or ^{238}U was investigated briefly. One system[6] utilized gamma detectors operating in anticoincidence with neutron detectors, the anticoincidence operation being utilized to suppress the multitudinous gamma rays associated with the fission of ^{235}U so as to selectively register counts associated with neutron capture. As noted previously, the physical arrangements required for coincidence detection of fission events drastically limit application of this method.

A second possibility in the detection of capture gamma radiation is the use of a Ge-Li detector with a sodium iodine (NaI) crystal around the detector, the two operating in coincidence as a pair spectrometer. The energy of interest would be that of the specific gamma reduced by the energy required for producing an electron-positron pair (1.02 Mev). Coincidence at this energy (double escape peak) occurs when the kinetic energy of both the electron and positron formed by the gamma is totally deposited in the Ge-Li detector, and the two gamma rays (0.51 Mev/photon) resulting from the annihilation of the positron both escape from the Ge-Li detector. The surrounding NaI coincidence detector provides a suppression of counts not involving pair production, and thus a favorable peak-to-background ratio.

Detection of the double-escape peak of the 4059.4 kev neutron-capture gamma of ^{238}U (yield--11 photons/100 captures) without the coincidence feature appeared promising enough to warrant additional investigation, and preliminary factors affecting the neutron spectrum from an isotopic source are calculated later.

^{235}U GAMMA MEASUREMENT EMPLOYING GAMMA TRANSMISSION

A series of experiments was carried out to determine whether a direct measurement of the ^{235}U gamma emission from UF_6 in a pipe, combined with a gamma transmission measurement to determine the total uranium in the pipe, would yield useful estimates of the enrichment. Specific steps in the method involve (1) a measurement of the 0.185-Mev ^{235}U gamma radiation to determine the ^{235}U in a section of pipe, (2) a gamma transmission measurement to determine attenuation by the pipe and UF_6 combined, (3) a correction to this attenuation factor for pipe wall effects to provide an estimate of absorption due to the UF_6 alone, and (4) a calculation of the total uranium in the pipe based on this attenuation effect. The ratio of ^{235}U to total uranium would then be the necessary enrichment value.

EXPERIMENTAL

The experiments involved radiation measurements on pipes of three diameters--36, 24, and 12-in.--which were installed in a heated enclosure and were filled with UF_6 at approximately 1.5% enrichment to pressures from 0 to approximately 9 psia. For each pressure condition, readings of the ^{235}U peak were obtained at the side of the pipe, both with and without an external radiation source of enriched uranium metal being placed on the side of the pipe opposite the detector. The difference between these two readings represented the transmitted radiation, or source contribution.

Each of the three pipe sections (36 in. dia x 24 ft, 25 in. x 20 ft, and 12 in. x 20 ft) was equipped with a pressure transmitter connection, sample line, and multiple thermocouples mounted in wells which extended a minimum of 8 in. from the surface of the pipe into the gas. Six thermocouples were used on the 36-in. pipe; these were mounted on top and bottom of the horizontal pipe approximately 3 ft from each end and at the center. The 24- and 12-in. pipes were fitted with four thermocouples each, these being at the top and bottom of the end caps. Temperatures were read from a multipoint recorder which was automatically connected sequentially to the various thermocouples.

Two pressure transmitters were connected in parallel to the pressure tap; one covered the range from 0 to 20 psia and the other the range from 0 to 2 psia. The low-range transmitter was isolated from the system when pressures in excess of its range were used. The pressure indicated by each of the transmitters was displayed on a separate pressure gauge and recorded by a 2-pen pressure recorder.

Radiation measurements were made with the mobile gamma spectrometer system developed at ORGDP for use in extreme temperature locations. The detector, a 3 in. x 3 in. NaI crystal, was mounted with the photomultiplier and preamplifier in an insulated probe. The probe provided an annulus filled with refrigerant-11 which maintains the probe temperature at about 74°F by evaporation.

Readings were also taken using a portable Ludlum single-channel analyzer.* Although the instrument performed very well under elevated temperatures, the single-channel analyzer seemed inadequate for precise assay determination since shifts in the peak due to instrument drift could not be readily detected.

The gamma transmission source was 93.2% uranium-235 metal in the form of plates 2-7/8 in. x 5-11/16 in. x 0.004 in. thick. These were stacked in units of three plates each to give a total thickness of 0.012 in., or a little more than one half-value layer for the ^{235}U gamma radiation. The stacks were inserted in fitted paper envelopes attached to a 1/8-in.-thick aluminum plate to form the radiation source. Six of these stacks, providing a source area with overall dimensions of about 12 in. long x 9 in. high were used with the 36-in. pipe; two stacks giving a source about 12 in. long x 2-7/8 in. high were used with the 24-in. pipe, and one stack 5-11/16 in. long x 2-7/8 in. high was used with the 12-in. pipe.

During the first experiments, which were made on the 36-in. pipe, a calibration measurement was taken at the beginning and end of each series of measurements. The series consisted of three 4-min readings and one 10-min reading, both with and without the source in place, at a single pressure. Preliminary analyses indicated the desirability of a more precise basis for calibration corrections, and in subsequent runs a calibration reading was obtained both before and after each of three 10-min measurements without the source and similar readings with the source in place. The calibration source was a 110-mg enriched-uranium metal disc which was mounted in the base of the probe holder on the spectrometer cart. Including the calibration measurements, 747 readings were obtained during this experiment.

DATA ANALYSIS

Two computer codes were used in examining the data. The first was a spectrum-analysis curve-fitting code which provides the best fit which can be made to the data with a Gaussian curve and a straight-line combination and then the area under the Gaussian peak. Gamma rays from the source plate which are degraded slightly by scattering still have sufficient energy to fall within the area of the peak, although tending to fall at the low-energy side of the peak. It was observed that the introduction of UF_6 between the source and the detector produced a greater proportional reduction in the low-energy side of the peak than at the top of the peak, thus effecting both a reduction in the peak intensity observed for the source and a change in the peak shape. This change in peak shape makes it questionable whether the curve-fitting approach would be the most precise method available for analyzing the data, particularly where the low-energy side of the peak is included in the fit. An additional computer run was made with this code, but with the area of

*Brand names mentioned in this report are intended to be descriptive, not limiting. Another brand of comparable characteristics could perform equally well.

interest restricted to a region extending from just below the top of the peak to a point well out on the upper side of the peak. Although this did improve the consistency of the results, variability of values obtained under a given condition was slightly greater when this code was used than was the case with the second computer code; accordingly, the second code was used in the analyses described below.

The second computer code, described in Appendix B, was written for this project and is a relatively simple analytical tool. It provides a printout of the spectral data converted to counts per minute. In a separate tabulation it also gives the sum of three channels centering on the ^{235}U peak (in this case, channels 49, 50, and 51), averages five channels of higher energy which are essentially clear of the peak (channels 73 through 77) and provides a correction to the peak sum on the basis of this average. The correction was based on extrapolation of a spectrum obtained without any UF_6 present, which represents essentially the contribution of residual daughter products of ^{238}U. Although this analysis provides, in effect, a very narrow window, scattered gamma rays will still be detected in this region, since even a degraded photon which is detected with a relatively high-energy-conversion efficiency may produce a pulse in this peak region. This point is considered further in the discussion below concerning the advantages of a germanium detector for this application. Samples of the output of this code are shown in table 1, the conversion of the raw data to a count per minute form, and table 2, the tabulated results of the calculations. The code provides three options, designated by the form number, for the channels to be considered, and the weighting factor to be included in the calculations. For this particular set of calculations, all the options were programmed identically.

Results are listed in table 3 and are shown graphically in figures 1 through 3. Each point shown represents the weighted average of all readings taken for a specific condition, the weighting being based on the length of counting time for each reading. Uranium hexafluoride pressures were corrected to a temperature of 130°F.

The cause of the erratic results obtained with the source plate in the second run with the 36-in. pipe could not be determined. In view of the consistency of the results obtained on the first run and subsequent runs with the other pipes, however, it was not considered to reflect any fundamental limitation to the application of the method.

Figures 2 and 3, for the 24- and 12-in. pipes, represent the results of two runs by a single line. At the higher count rates, where the counting statistics should be best, the individual points are within 2% of the line representing the combined results. At these higher count rates, and on the basis of counting statistics alone, the 95% confidence limit on these measurements would also be approximately 2%. Accordingly, it seems reasonable to assume that some appreciable part of the variation noted is due to the inherent statistical nature of counting, and that the variations could be reduced by longer counting times. The measurement requiring the greatest precision, however, is the attenuation

Table 1

SAMPLE OF COMPUTER OUTPUT
SHOWING SPECTRAL DATA CONVERTED TO COUNTS PER MINUTE*

449 CAL 6.8P 12 IN
FORM 1
COUNTS/MINUTE FOR EACH CHANNEL

4.0	0.8	0.5	1.0	232.5	414.3	479.0	408.0	390.0	384.3
427.3	522.0	720.5	994.8	1223.8	1250.0	1237.8	1378.5	1565.3	1728.0
1961.8	2273.3	2658.0	2985.3	3237.0	3327.0	3309.5	3111.3	2900.0	2712.0
2626.3	2429.0	2197.5	1929.3	1649.0	1546.8	1611.3	1778.8	1937.3	2025.0
1887.8	1674.3	1503.5	1451.0	1542.8	1807.0	2374.5	3203.8	4136.0	4730.8
4942.0	4528.3	3645.8	2758.8	1940.0	1293.5	898.5	623.8	451.5	335.8
249.0	210.5	186.3	171.5	158.3	147.3	137.3	136.3	127.5	129.0
119.0	112.3	112.8	110.5	111.0	111.3	105.5	99.0	107.0	95.3
91.3	88.8	90.0	84.3	82.0	76.0	69.5	63.5	70.8	66.0
64.8	66.0	62.8	62.8	61.8	60.5	52.0	47.0	53.5	53.5

U-235 -- 13788.39 NET COUNTS PER MINUTE

450 CAL 6.8P 12 IN
FORM 1
COUNTS/MINUTE FOR EACH CHANNEL

4.0	0.8	0.3	0.5	246.0	417.3	476.8	426.5	376.0	389.3
433.5	508.8	712.5	959.8	1196.3	1236.0	1271.8	1318.0	1457.8	1628.0
1861.8	2107.5	2562.8	2929.5	3261.8	3417.5	3350.3	3211.0	2943.8	2757.0
2660.0	2390.3	2201.3	1904.3	1668.0	1518.0	1559.5	1761.0	1946.3	2017.3
1900.8	1684.3	1517.5	1391.3	1476.3	1764.0	2254.8	3050.5	3918.5	4608.0
4852.8	4627.3	3825.3	2952.8	2036.5	1413.3	952.5	690.0	472.8	345.8
277.5	215.5	178.3	166.5	155.0	153.5	149.8	127.3	127.5	122.8
108.8	108.8	108.5	115.0	112.3	109.3	103.8	110.0	110.3	104.5
94.8	91.5	80.5	82.8	85.3	66.5	69.3	77.8	67.3	68.3
63.8	70.0	63.5	57.0	60.5	59.0	56.0	49.8	51.5	48.3

U-235 -- 13665.41 NET COUNTS PER MINUTE

451 SP 6.8P 12 IN
FORM 1
COUNTS/MINUTE FOR EACH CHANNEL

10.0	1.2	0.7	0.4	159.4	193.7	204.2	232.2	258.0	300.1
355.4	383.8	398.3	413.8	444.9	515.4	643.7	848.8	1098.1	1319.4
1422.4	1351.1	1247.0	1173.1	1164.7	1229.6	1279.8	1418.5	1512.5	1631.4
1690.4	1722.6	1732.5	1702.3	1720.9	1811.9	1989.6	2181.5	2357.5	2544.8
2653.3	2751.1	2885.1	3050.2	3306.6	3698.9	4212.8	4843.8	5509.7	5841.1
5731.0	5085.1	4153.8	3095.7	2188.8	1500.9	1026.1	710.6	479.8	331.9
235.2	173.5	139.7	111.7	107.1	91.7	90.6	83.1	79.3	76.9
76.9	71.3	68.1	72.1	68.0	66.4	66.8	60.7	68.5	66.5
57.3	65.5	57.4	55.9	58.1	56.3	55.0	56.7	56.1	51.7
53.6	51.0	55.1	53.1	50.4	47.6	51.4	49.0	48.8	45.6

U-235 -- 16400.69 NET COUNTS PER MINUTE

*Zero channel value (first number in first row) is live counting time in minutes.

Table 2

SAMPLE OF COMPUTER OUTPUT SHOWING RESULTS OF CALCULATIONS

NOTATION -
NET COUNT RATE IS CALCULATED BY THE FORMULA -
   NET COUNT RATE = (SUM OF CHANNELS A-B)
                    -(AVERAGE OF CHANNELS C-D)*E

FORM 1 REFERS TO U-235
A = 49
B = 51
C = 73
D = 77
E = 3.84

FORM 2 REFERS TO U-235
A = 49
B = 51
C = 73
D = 77
E = 3.84

FORM 3 REFERS TO U-235
A = 49
B = 51
C = 73
D = 77
E = 3.84

	FORM	TIME	SUM	AVG	PROD	NET COUNTS
449 CAL 6.8P 12 IN	1	4.00	14201.0	107.4	412.6	13788.4
450 CAL 6.8P 12 IN	1	4.00	14088.0	110.0	422.6	13665.4
451 SP 6.8P 12 IN	1	10.00	16657.2	66.8	256.5	16400.7
452 CAL 6.8P 12 IN	1	4.00	14115.0	110.6	424.9	13690.1
453 CAL 6.8P 12 IN	1	4.00	14121.3	109.8	421.4	13699.8
454 CAL 6.8P 12 IN	1	4.00	14215.0	110.5	424.3	13790.7
455 SP 6.8P 12 IN	1	10.00	16835.7	67.5	259.0	16576.7
456 CAL 6.8P 12 IN	1	4.00	14259.0	110.3	423.4	13835.6
6/29/71 457 CAL 4.4P 12 IN	1	4.00	13231.8	105.6	405.7	12826.1
458 CAL 4.4P 12 IN	1	4.00	13483.0	102.9	395.3	13087.7
459 CALX 4.4P 12 IN	1	10.00	2181.0	49.7	190.7	1990.3
460 CAL 4.4P 12 IN	1	4.00	13338.0	106.5	409.0	12929.0
461 4.4P 12 IN	1	10.00	2183.0	48.0	184.2	1998.8
462 CAL 4.4P 12 IN	1	4.00	13380.8	104.9	402.8	12977.9
463 CAL 4.4P 12 IN	1	4.00	13544.3	102.4	393.4	13150.8

Table 3

RADIATION READINGS ON PIPES

Pipe Diameter, in.	Run No.	Pressure Reading, psia	UF_6 Pressure at 130°F, psia	Corrected Counts/Min in Peak Channels: No Source	With Source	Difference
36	1	9.2	7.99	8,190	13,392	5,202
		6.82	6.38	6,758	13,160	6,402
		4.62	4.41	5,102	12,923	7,821
		2.3	2.34	2,909	12,206	9,297
		1.0	1.13	1,568	11,557	9,989
		0	0	75	10,838	10,763
36	2	9.22	8.99	8,812	14,200	5,388
		7.00	6.80	7,391	14,347	6,956
		4.20	4.06	4,842	12,788	7,946
		1.9	1.86	2,338	11,159	8,821
		1.0	0.98	1,414	11,749	10,335
		0.5	0.49	771	11,445	10,675
24	1	0	0	57	8,980	8,923
		9.20	8.65	6,841	12,364	5,523
		6.82	6.40	5,369	11,563	6,194
		4.40	4.09	3,642	10,797	7,155
		1.87	1.764	1,656	9,762	8,106
		1.00	0.95	944	9,659	8,715
		0.50	0.468	509	9,296	8,787
		0	0	73	9,044	8,971
24	2	0	0	73	9,044	8,971
		9.26	8.84	7,026	12,261	5,595
		6.84	6.48	5,561	11,812	6,251
		4.44	4.17	3,828	10,808	6,980
		1.94	1.86	1,797	9,890	8,093
		1.01	0.94	994	9,556	8,562
		0.51	0.471	530	9,198	8,668
		0	0	67	8,968	8,901
12	1	0	0	62	14,635	14,573
		8.96	8.39	3,608	15,099	11,491
		6.52	6.01	2,730	14,968	12,238
		4.36	3.99	1,879	14,985	13,106

Table 3, Continued

Pipe Diameter, in.	Run No.	Pressure Reading, psia	UF_6 Pressure at 130°F, psia	Corrected Counts/Min in Peak Channels: No Source	With Source	Difference
		1.91	1.775	886	14,776	13,890
		1.00	0.930	508	14,778	14,270
		0.50	0.462	295	14,802	14,507
		0	0	79	14,723	14,644
12	2	0	0	79	14,723	14,644
		9.20	8.63	3,661	15,183	11,522
		6.80	6.36	2,806	14,952	12,146
		4.4	4.07	1,913	15,021	13,108
		1.83	1.73	862	14,887	14,025
		1.00	0.941	513	14,688	14,175
		0.50	0.468	288	14,796	14,508
		0.02	0.016	88	14,806	14,718
		0	0	87	14,802	14,715
		Air	0	--	14,720	14,633

DWG. NO. G-71-812

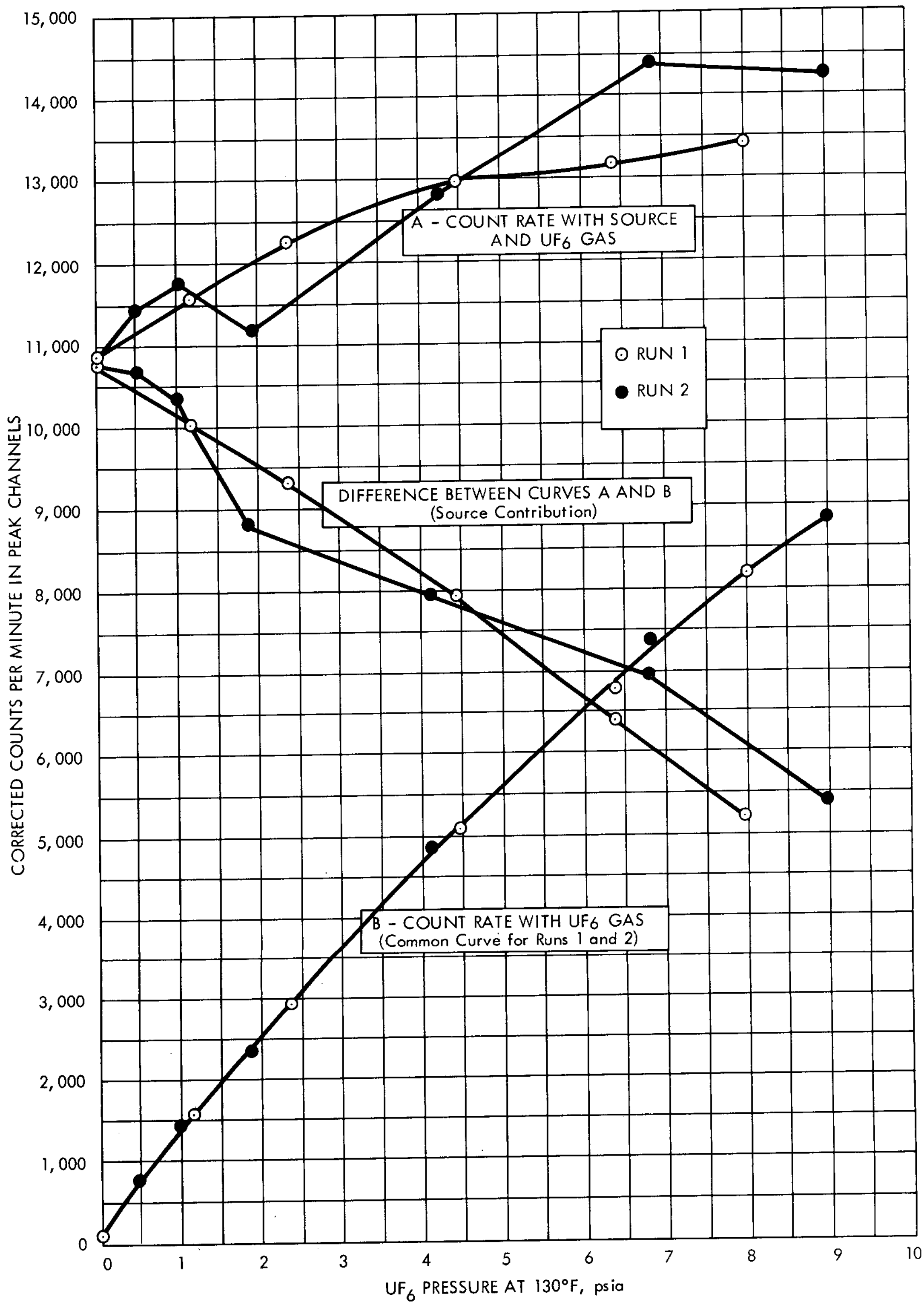


Figure 1

RADIATION READINGS ON 36-INCH-DIAMETER PIPE

DWG. NO. G-71-813

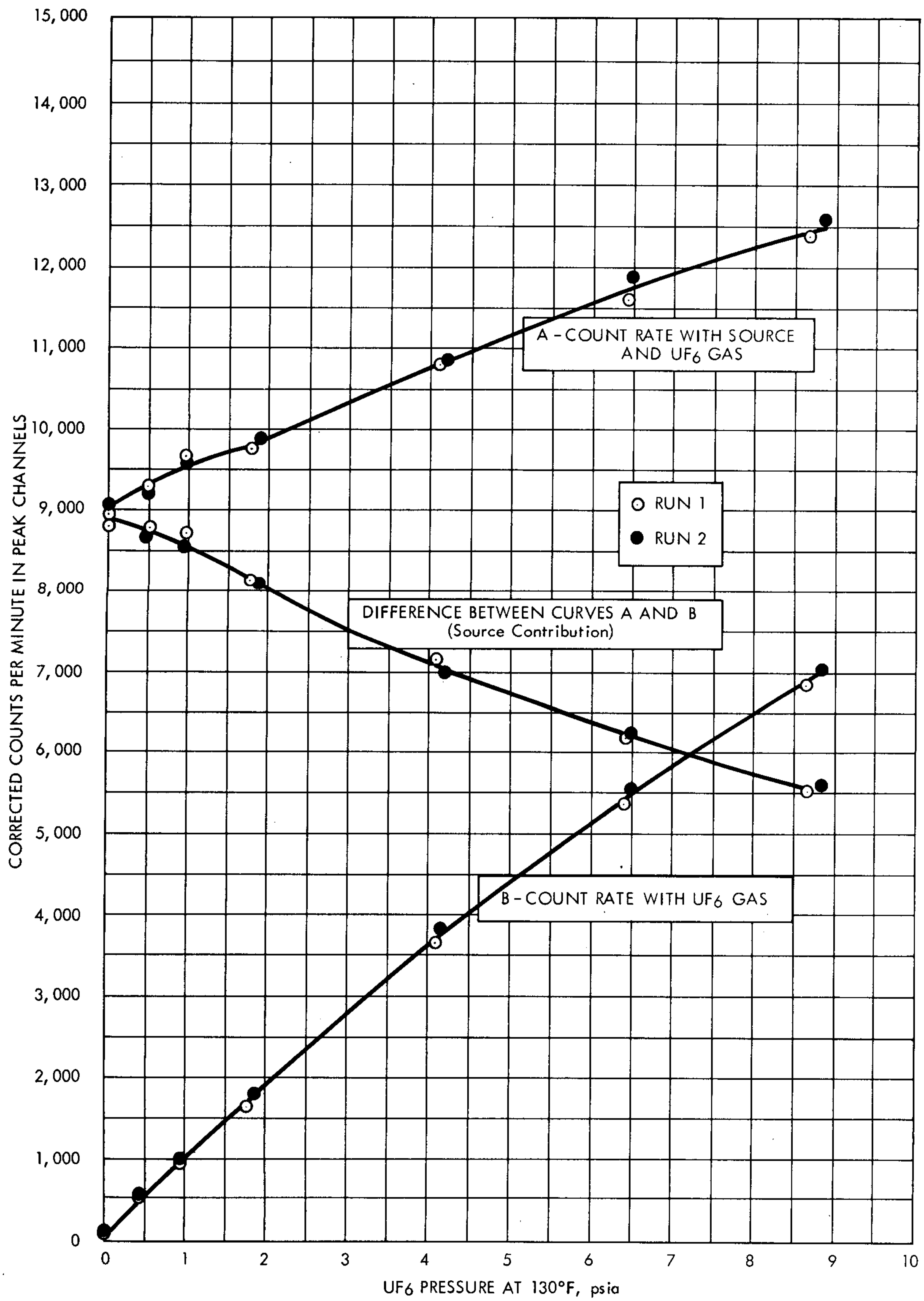


Figure 2

RADIATION READINGS ON 24-INCH-DIAMETER PIPE

DWG. NO. G-71-814

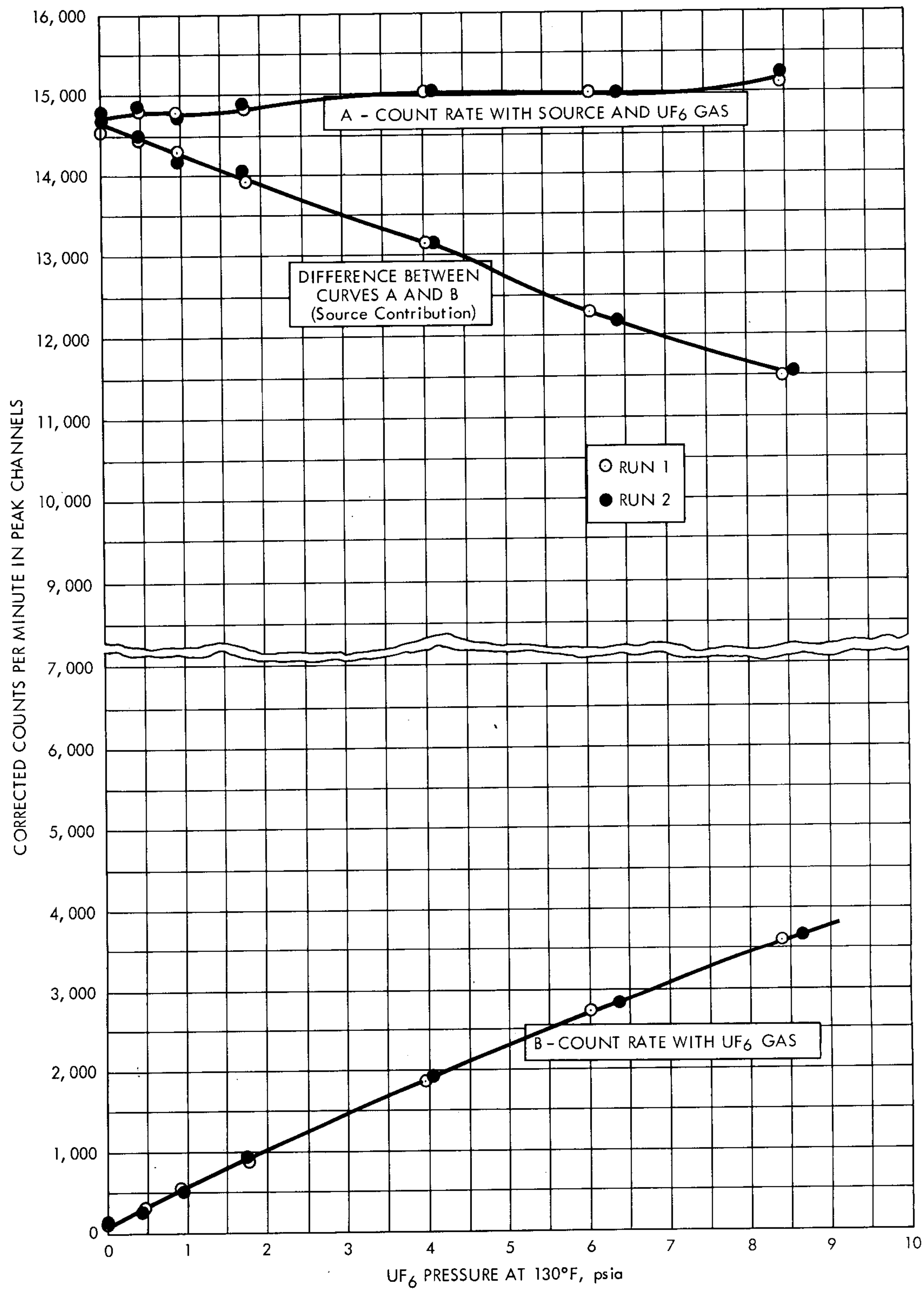


Figure 3

RADIATION READINGS ON 12-INCH-DIAMETER PIPE

measurement directed toward the determination of total uranium in the pipe. Particularly in the case of low pressure and/or small pipe size, attenuating effects of UF_6 are small, and very high precision would be required for an accurate enrichment estimate. A more attractive alternative than increasing counting times is the use of a lower energy gamma for the transmission measurement. The advantage of using a low-energy source was recognized at the beginning of the program. The choice of the ^{235}U gamma energy for the transmission measurement was based on the fact that the accurate determination of a lower energy peak; i.e., one falling slightly below the ^{235}U peak, would be complicated by incomplete resolution from the ^{235}U. This difficulty can be circumvented through the use of a germanium detector.

The following estimates of the range of pressure values over which the method would yield useful results may be made. The effects of using a germanium detector rather than NaI are also considered here.

1. The count rate for the direct ^{235}U gamma measurement was sufficiently high for accurate measurements down to one-half pound pressure in a 12-in. pipe, while using a very small fraction of the total peak for the measurement. The lower relative efficiency of a germanium detector as compared to NaI would be largely offset by the fact that the total peak would be usable.

2. Since variations on the order of 2% were noted in the differences between readings with and without the external source, it was considered that approximately a 10% reduction in the source contribution by the effects of UF_6 would permit a relative enrichment evaluation to within ±20%. Such a reduction corresponds to UF_6 pressures of 1.6 psia in a 36-in.-dia pipe, 2.2 psia in a 24-in. pipe, and 3.9 psia in a 12-in. pipe. These results are encouraging and with a germanium detector and a lower-energy source, this sensitivity could be improved.

3. The greater absorption by the pipe walls with a lower energy gamma source could be offset by the use of a more intense isotopic source. This would also permit use of a source sufficiently small in physical size to be treated as a point source for attenuation calculations. Such small size cannot be achieved with ^{235}U because of the inherent self-absorption characteristics of the uranium for its own gamma emission.

4. A germanium detector acts essentially as a *narrow-beam* detector for all geometries in that scattered radiation is reduced sufficiently in energy to fall outside the peak region. This will greatly facilitate the calculations of wall corrections and UF_6 self-absorption effects over sufficient ranges to permit application of the method to any gaseous diffusion situation.

Analysis of the data obtained in the experiments indicated that the method, even with far from optimum equipment, is sufficiently sensitive to yield useful estimates of the enrichment of a UF_6 gas stream provided gas pressures are 2 psia or above, depending on the pipe size. The experiments also demonstrated some important limitations encountered in the use of a NaI detector for this purpose; it is clear that the sensitivity of the method could be improved markedly through the use of a lithium-drifted germanium detector.

PIPE-WALL RADIATION ATTENUATION

Application of the proposed method for enrichment auditing requires an accurate evaluation of the attenuation effects of the pipe walls. A commercial ultrasonic thickness gauge with a reported accuracy to 0.0001 in. was purchased, and experience with this instrument indicates that, under field conditions, readings consistent to within approximately 0.001 in. should be readily obtained. The absolute accuracy depends on the availability of a standard with composition comparable to the object being measured. However, two radiation measurements (one through a diameter and the other through an appropriate chord of a pipe) will provide the necessary information on attenuation characteristics provided the *relative* thicknesses along the two radiation paths are known accurately. Such measurements are within the capability of the present instrument.

Instrument Tests

The Automation Industries, Inc., Model G-2B-4 Digital Thickness Gauge, an instrument designed to ultrasonically measure the thickness of metals, was used in these tests. The thickness range of the instrument is 0.0100 to 1.999 in. and the manufacturer's advertised accuracy is ±0.0001 in.

A series of tests was performed to determine the accuracy of the instrument when measuring large-diameter pipe and to determine the effect of nickel plating when measuring the thickness of nickel-plated steels. The thicknesses of pipe samples were measured with a calibrated micrometer and with the ultrasonic instrument. Twelve of the pipe samples were measured before and after nickel plating.

The first series of tests was performed on six calibrated thickness blocks with certified thicknesses of 0.250 to 2.0 in. The instrument was calibrated on other blocks of similar thicknesses and, under these ideal conditions, an instrument accuracy of ±0.0001 in. was obtained.

The next tests were conducted on sections of process piping with diameters of 24, 30, 36, and 54 in. All of these pipe samples had nickel plating on both the inside and outside surfaces. The pipe sections were measured at each quadrant, 1 in. from the end and 6 in. from the end, giving 32 measurements. Before measuring the thickness of these points, the instrument was calibrated on the opposite end of each pipe section. Under these conditions, the instrument readings ranged from -0.0060 to +0.0037 in. as compared to the micrometer measurements. The average difference for all 32 measurements was -0.0001 in.

The third series of tests was devised to determine the effect of nickel plating. Four 6 x 6 in. samples were cut from each of 14-, 24-, and 30-in. unplated steel pipe sections, making a total of 12 samples. Each of the samples was measured in two locations prior to plating; the measurement points were marked; the samples were plated on one side to a nominal thickness of 0.003 in.; and the samples were then remeasured. The inside surfaces of these samples were generally corroded and pitted as may be found under field conditions.

Prior to nickel plating, and with the instrument calibration unchanged from that used in the previous tests, the ultrasonic measurements varied from the micrometer measurements by -0.0035 to +0.0023 in., and the average difference for all 24 readings was 0.0002 in.

After nickel plating, two sets of measurements were performed, one with the instrument calibrated on unplated steel test blocks of thicknesses similar to the sample thicknesses, and the other with the instrument calibrated on the opposite ends of the measured samples. With the instrument calibrated on the unplated blocks, the ultrasonic measurements varied from the micrometer measurements by -0.0076 to +0.0104 in., and the average difference for all readings was +0.0013 in. With the instrument calibrated on the opposite ends of the samples, the variations were from -0.0068 to +0.0055 in. with an average difference of -0.0009 in. The results also showed that the plating is detected as an additional thickness of the base metal but readings may be about 0.001 to 0.002 in. too high in the thickness range measured if the instrument is not calibrated on plated samples of like conditions and thicknesses.

An ultrasonic instrument of this type does not measure the average thickness of the material under the transducer, especially when the surface opposite the transducer is pitted or uneven. The instrument operates on the pulse echo principle and the first ultrasonic pulse received back through the transducer determines the thickness reading. If an ultrasonic echo is reflected from the bottom of a pit or other depression, it will be the first pulse to be sensed by the instrument and the material thickness at the bottom of the pit will be the measured thickness. This accounts for a wide variation of thickness readings when measuring such materials, all of which may be reasonably accurate for the exact point measured. Thus, to determine the average pipe wall thickness under such conditions, it is necessary to use an average of several measurements which should provide a reasonably accurate indication of the thickness in that particular area.

A commercial ultrasonic instrument appears to be adequate for measuring the wall thicknesses of large-diameter steel pipes providing that the instrument is in good working condition; it is stabilized (or temperature compensated) for the measuring environment; and it is calibrated on samples of like material, thickness, and condition. If only one or two measurements are taken, variations of ±0.005 in. or greater may be expected; however, an accuracy of ±0.001 in. should be expected by averaging a sufficient number of measurements. For the 185-kev gamma rays of ^{235}U penetrating perpendicularly to the pipe wall, the effect of this uncertainty in wall thickness corresponds to an error of approximately 0.3% in the evaluation of the applicable attenuation factor. This degree of accuracy is considered to be acceptable in the present application.

Radiation Attenuation Along a Diameter and Chord of a Pipe

Variations in pipe wall materials will affect attenuation calculations in two ways: (1) gamma radiation absorption coefficients are dependent on the elements comprising the pipe alloy, and (2) the speed of sound in the pipe material will affect the ultrasonic thickness measurement unless the material is duplicated in the standards used in calibrating the thickness gauge. Use of a single radiation measurement with a calculation for radiation attenuation on the basis of a pipe thickness measurement would therefore require considerable information concerning the pipe alloy.

The effect of relative pipe thickness on attenuation measurements can be determined from an attenuation measurement along the pipe diameter and one along a chord. The absolute accuracy requirement is that the error in the thickness of the pipe be sufficiently small that the error in the calculated radiation path length through UF_6 be small in comparison to this path length.

The equations for the determination of UF_6 density on the basis of two such radiation measurements (with an additional source calibration measurement in air) are described below.

Three measurements are made as indicated in figure 4, with the S positions representing radiation source positions and D representing detector positions.

The following designations are made:

R_1 = Reading or count rate at position 1,

t = Thickness as indicated,

μ_1 = Linear attenuation coefficient of steel, and

μ_2 = Linear attenuation coefficient of UF_6.

The pipe wall thickness is assumed to be small in relation to the diameter, and the chord is assumed to be well within the interior cross section of the pipe.

DWG. NO. G-72-684

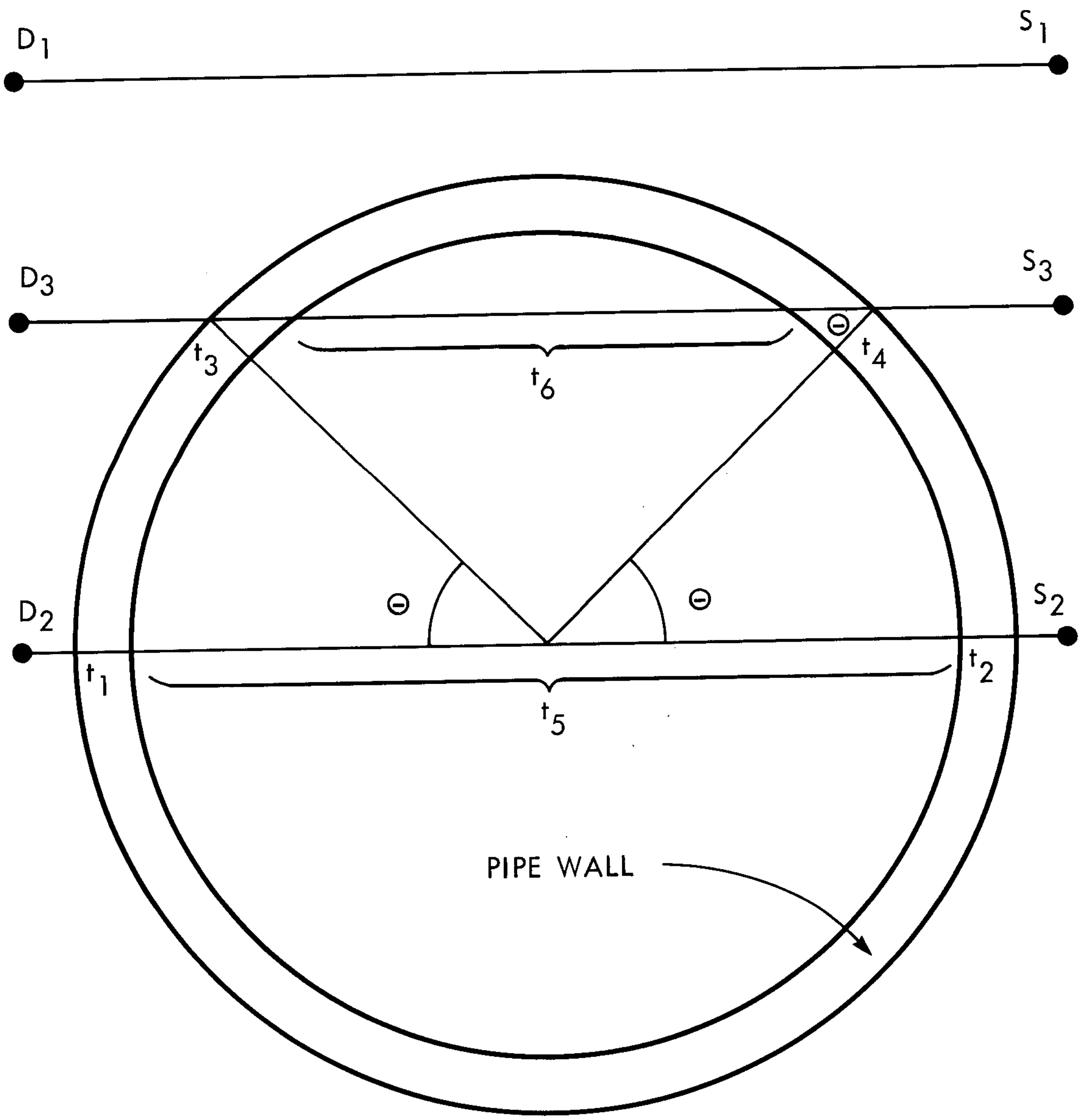


Figure 4

PLAN FOR RADIATION ATTENUATION MEASUREMENTS

$$\alpha_1 = \frac{R_2}{R_1} = e^{-[\mu_1(t_1 + t_2) + \mu_2 t_5]},$$

$$\alpha_2 = \frac{R_3}{R_1} = e^{-[\mu_1 \frac{(t_3 + t_4)}{\cos \theta} + \mu_2 t_6]},$$

$$\ln \alpha_1 = -[\mu_1(t_1 + t_2) + \mu_2 t_5],$$

$$\ln \alpha_2 = -[\mu_1(\frac{t_3 + t_4}{\cos \theta}) + \mu_2 t_6],$$

$$\ln \alpha_2 = -[\mu_1(t_1 + t_2) \frac{(t_3 + t_4)}{(t_1 + t_2)\cos \theta} + \mu_2 t_6],$$

$$\frac{t_3 + t_4}{(t_1 + t_2)\cos \theta} \ln \alpha_1 = -[\mu_1(t_1 + t_2) \frac{t_3 + t_4}{(t_1 + t_2)\cos \theta} + \mu_2 t_5 \frac{t_3 + t_4}{(t_1 + t_2)\cos \theta}],$$

$$\ln \alpha_2 - \frac{t_3 + t_4}{(t_1 + t_2)\cos \theta} \ln \alpha_1 = \mu_2 t_5 \frac{t_3 + t_4}{(t_1 + t_2)\cos \theta} - \mu_2 t_6, \text{ and}$$

$$\mu_2 = [\ln \alpha_2 - \frac{t_3 + t_4}{(t_1 + t_2)\cos \theta} \ln \alpha_1] \;/\; [t_5 \frac{t_3 + t_4}{(t_1 + t_2)\cos \theta} - t_6].$$

(Note: nominally $t_1 = t_2 = t_3 = t_4$.)

This equation indicates that the linear attenuation coefficient of the UF_6 can be determined, provided the ratio of steel thicknesses penetrated along the two paths is determined. The density of UF_6, ρ, is related to the linear absorption attenuation by the equations:

$$\frac{\mu_2}{\rho} = \text{mass absorption coefficient, and}$$

$$\rho = \mu_2/\text{mass absorption coefficient.}$$

The mass absorption coefficient of UF_6 is a constant for a given radiation energy.

Gamma Radiation Sources

Calculations indicated that the 122-kev gamma ray of ^{57}Co offers a satisfactory compromise between penetration of the walls of a pipe and acceptably high attenuation in UF_6 gas. For example, the fraction of gamma rays penetrating perpendicularly the two walls of a 1/2-in.-thick pipe would amount to about 0.5%. At 9-psia pressure and 150°F, UF_6 contained in a 3-ft-dia pipe would reduce transmission by an additional factor of 4. Three ^{57}Co sources ranging from 1 to 100 millicuries were obtained, to permit the use of a source which will produce a near-optimum count rate over a wide range of pipe thickness.

INSTRUMENT DEVELOPMENT

In order to permit future implementation of the enrichment-monitoring method described in this section, a conceptual design and specifications for the purchase of the components for a portable Ge-Li gamma spectrometer system which will function at environmental temperatures up to 150°F were developed.* This temperature corresponds to the maximum temperature, in the opinion of the ORGDP medical staff, to which personnel should be exposed without air-cooled suits or other heat protective equipment. A block diagram of the system is shown in figure 5 and the detailed specifications for the components are given in appendix A. The design includes a complete system with the Ge-Li detector connected by cable to the panel components mounted on a cart so as to be easily moved. Cooling and temperature control for the electronics components can be provided by enclosing them in a thermally-insulated cabinet, to be cooled by a liquid-nitrogen evaporative cooling system. This cooling mechanism was chosen since no mechanical refrigeration system currently available would function satisfactorily at the high ambient temperatures anticipated. Since a supply of liquid nitrogen would be required for the Ge-Li detector, the use of this supply for cooling the electronics would not entail an additional supply item.

COMPUTER-PROGRAM DEVELOPMENT

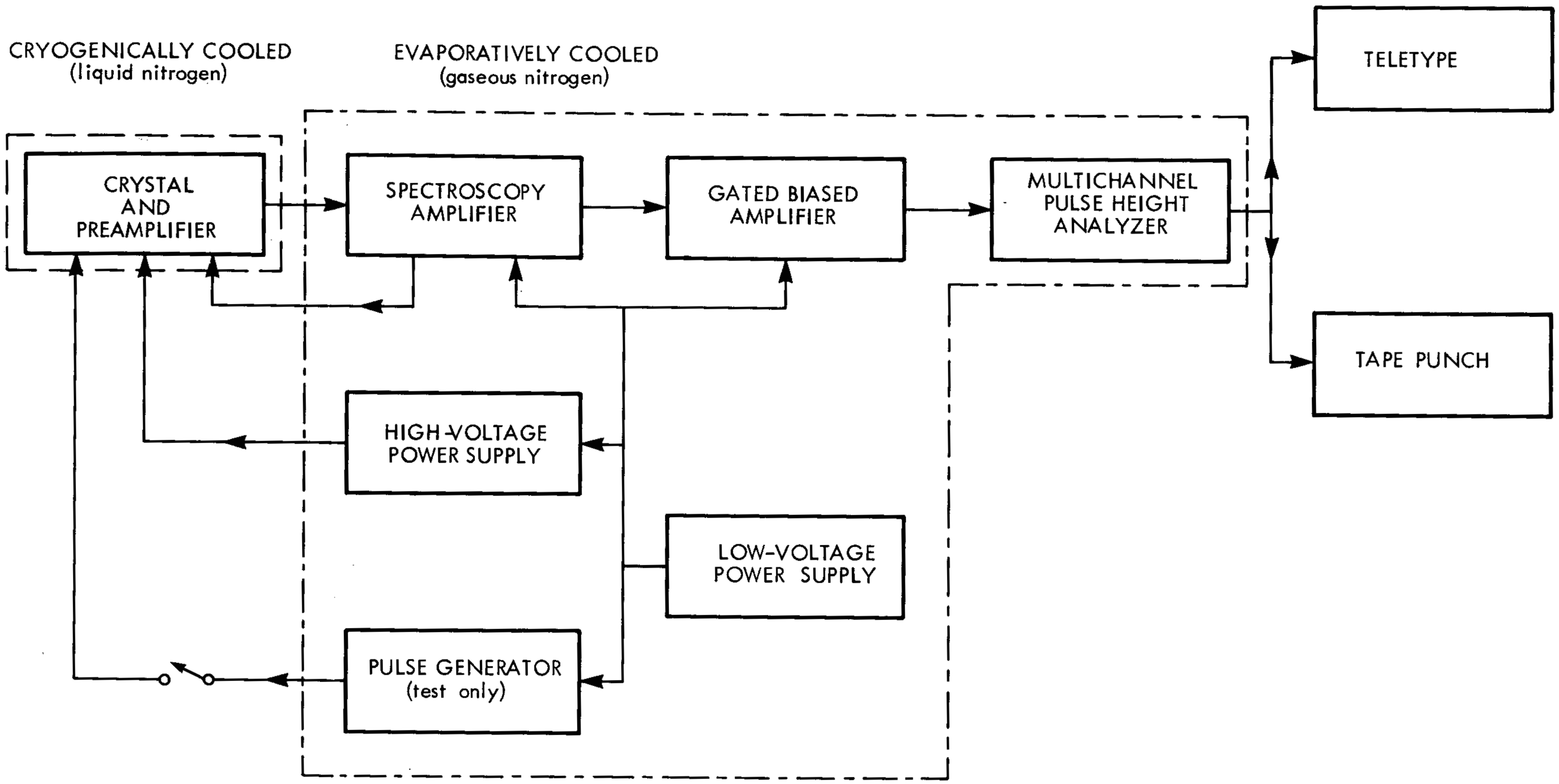
In order to relate the measurements of the ^{235}U gamma radiation and of the radiation from the external source to the quantities of ^{235}U and total uranium present, it will be necessary in both cases to take into account absorption of the radiation by the pipe walls and by the UF_6. Use of a high-resolution detector such as the Ge-Li systems greatly simplifies the necessary calculations in that it responds essentially as a *narrow-beam* detector for all geometries as far as the gamma-peak measurement is concerned. This results from the fact that a gamma photon which experiences scattering is reduced in energy and, therefore, falls outside the peak. Then the problem of calculating the effects of gamma-radiation absorption reduces to the relatively simple case of evaluating instrument response to the *uncollided* flux, and the much more complex problems involving evaluations of the scattered flux are avoided.

In the case of the external source, the problem reduces to a straightforward expoential attenuation calculation with a possible inverse-square correction for source distance from the detector.

---

*This work was done by G. B. Seaborn of the ORGDP Instrumentation and Quality Assurance Development Department.

DWG. NO. G-73-327
(U)



BLOCK DIAGRAM

Figure 5

SAFEGUARDS GAMMA SPECTROMETER SYSTEM

The evaluation of instrument response to the ^{235}U radiation, however, requires integration of an instrument response function over a cylindrical source geometry. It involves variable attenuation by both the pipe walls and the UF_6 gas penetrated and an instrument response which is a function of the angle of incidence of the gamma rays on the detector. The differential equation expressing these relationships does not yield an analytic solution and must be treated by numerical integration. In order to carry out the necessary computations, a code was written* to calculate the uncollided-gamma-ray response of a detector to a uniformly distributed source in an infinite pipe. Results obtained with the code will also be directly applicable to short sections of pipe, particularly with collimation of the detector, the effects of such collimation being reflected in an experimentally determined directional-response function for the detector. Input to the code includes detector position and angular dependence, as well as pipe thickness, diameter, and gamma ray cross sections of materials involved. Several numerical integration methods are added input options.

The code was checked out for a representative problem with the discrete ordinates code, ANISN.[7] Since ANISN does not provide options with regard to detector response as a function of the direction of incidence of the radiation on the detector, it is not directly applicable to the present problem. The newly developed code was used to calculate the uncollided gamma flux at the position of the detector and this could then be compared directly with the ANISN results.

A report of the mathematical development and methods for application of the program, including a print-out of the program, is included as appendix B.

NEUTRON-CAPTURE GAMMA RAYS

An important problem anticipated in connection with the detection of gamma rays of a discrete energy resulting from neutron capture in ^{238}U is that the gamma spectrum resulting from ^{235}U fission may be so prolific that it conceals the ^{238}U neutron-capture gamma peak. The use of anticoincidence counters, such as neutron counters with anticoincident detection of gamma rays to discriminate against gammas arising from fission, is impractical in the present application because of the bulk of the instrumentation required.

Consideration was given to the possibility of utilizing a neutron source with a low degree of moderation to provide a spectrum in which the neutrons were predominantly in the resonance energy region. This would enhance ^{238}U neutron capture over ^{235}U fission by making use of the large resonance capture characteristic of ^{238}U.

The characteristic 4059.4-kev gamma rays resulting from neutron capture in ^{238}U (yield--11 photons per 100 captures) could be detected with the Ge-Li system described above.

*This work was carried out by T. J. Hoffman and L. M. Petrie of the ORNL Mathematics Division.

An exploratory series of calculations was made* to evaluate the effects of neutron moderation on the relative ^{235}U fission and ^{238}U capture rates. Since lead shielding would be used in an actual application, two thicknesses of lead (2 in. and 3 in.) were included in the calculations. The effects of adding a cadmium thermal-neutron absorber around the outer surface of the moderator, the effects of steel surrounding the UF_6, and the effects on the neutron reaction rates of varying thicknesses of UF_6 penetrated were also included.

The calculations were made with the ANISN[7] computer transport code, a one-dimensional code requiring symmetrical geometry. The model used, therefore, consisted of a series of concentric spherical shells of the various materials surrounding a 1-in. diameter ^{252}Cf source as shown in figure 6. Moving outward from the source, the other regions were (1) lead, (2) methylmethacrylate moderator, (3) cadmium, (4) air space, (5) steel, (6) UF_6, and (7) steel. Enrichment of the UF_6 was considered to be 5.0 wt % ^{235}U in all cases.

Results of the calculations are given in table 4, and representative curves developed from these results are shown in figures 7 through 11. All of the curves indicate that the ^{238}U capture rate is a maximum with a moderator thickness of approximately 2 in. This was, therefore, considered to be the optimum thickness of methylmethacrylate plastic to be used for this purpose.

As illustrated in figure 7, and anticipated, variations in the thickness of the lead gamma-ray shield surrounding the source have only a slight effect on either the ^{238}U-capture or ^{235}U fission reaction rates, although the added moderating effect can be seen from a comparison of the curves.

From figure 8 it is seen that the addition of 0.040 in. of cadmium as a thermal neutron absorber around the source has a relatively small effect on the ^{238}U-capture reaction rate while reducing the ^{235}U fission rate by a factor of approximately 10 at the optimum 2-in. moderator thickness. However, the effect of cadmium in reducing the ^{235}U fission reaction is also a function of the amount of steel around the UF_6. The reduction amounts to a factor of only about 5 when the UF_6 is enclosed in steel 1/2-in. thick. The relatively small effect of the cadmium on the ^{238}U capture rate indicated that such capture is indeed occurring primarily in the resonance-energy region.

The addition of a 1/2-in. thickness of steel on both the inner and outer surface of the UF_6 shell resulted in appreciable increases in neutron reaction rates with both ^{235}U and ^{238}U. This is illustrated in figures 9 and 10, which treat separately the two cases of no cadmium and 0.040 in. of cadmium around the outside of the source moderator. The effect

*These calculations were made by J. R. Knight of the ORNL Mathematics Division.

DWG. NO. G-73-2
(U)

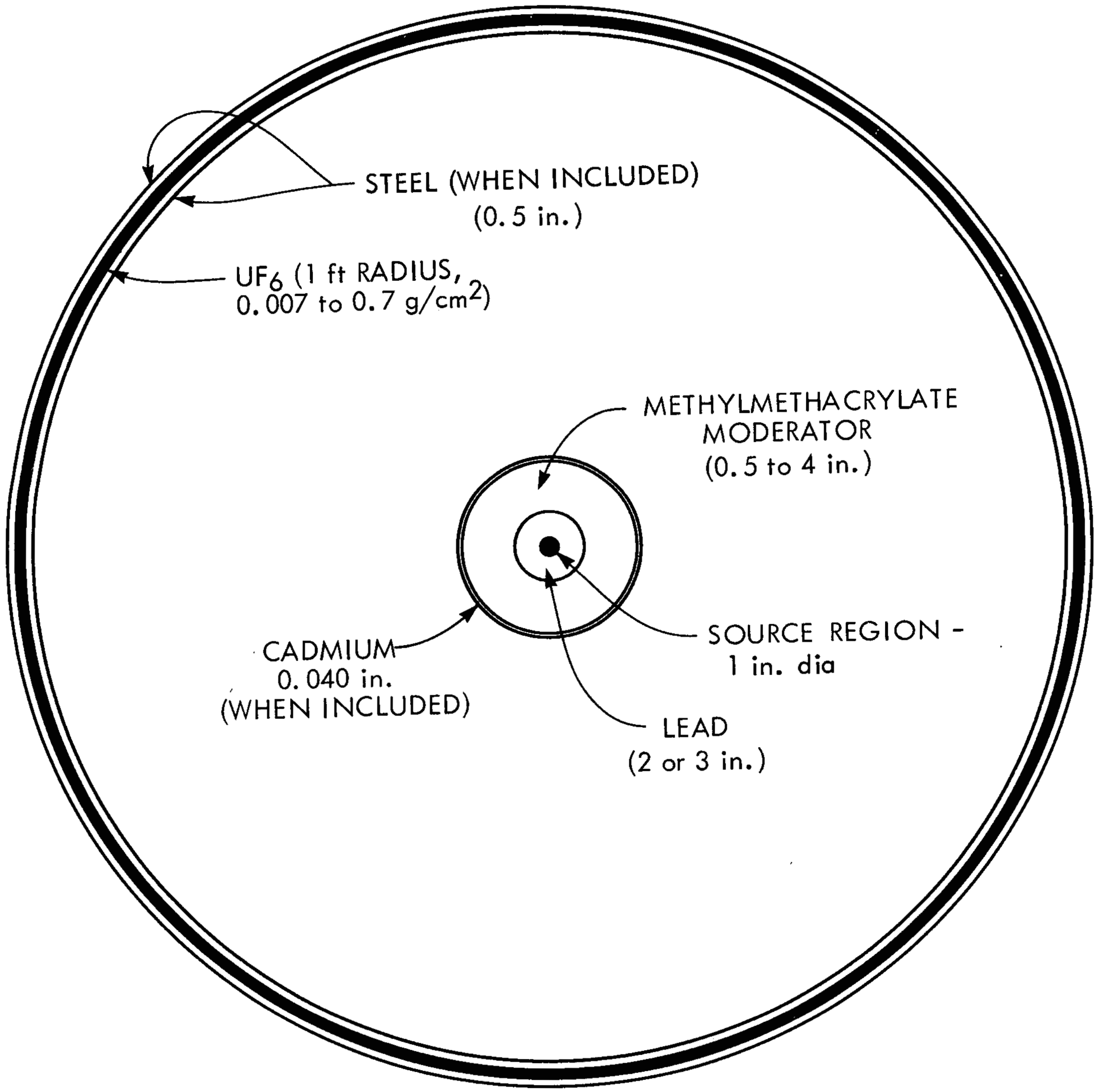


Figure 6

MODEL FOR NEUTRON MODERATION CALCULATIONS

DWG. NO. G-72-1091
(U)

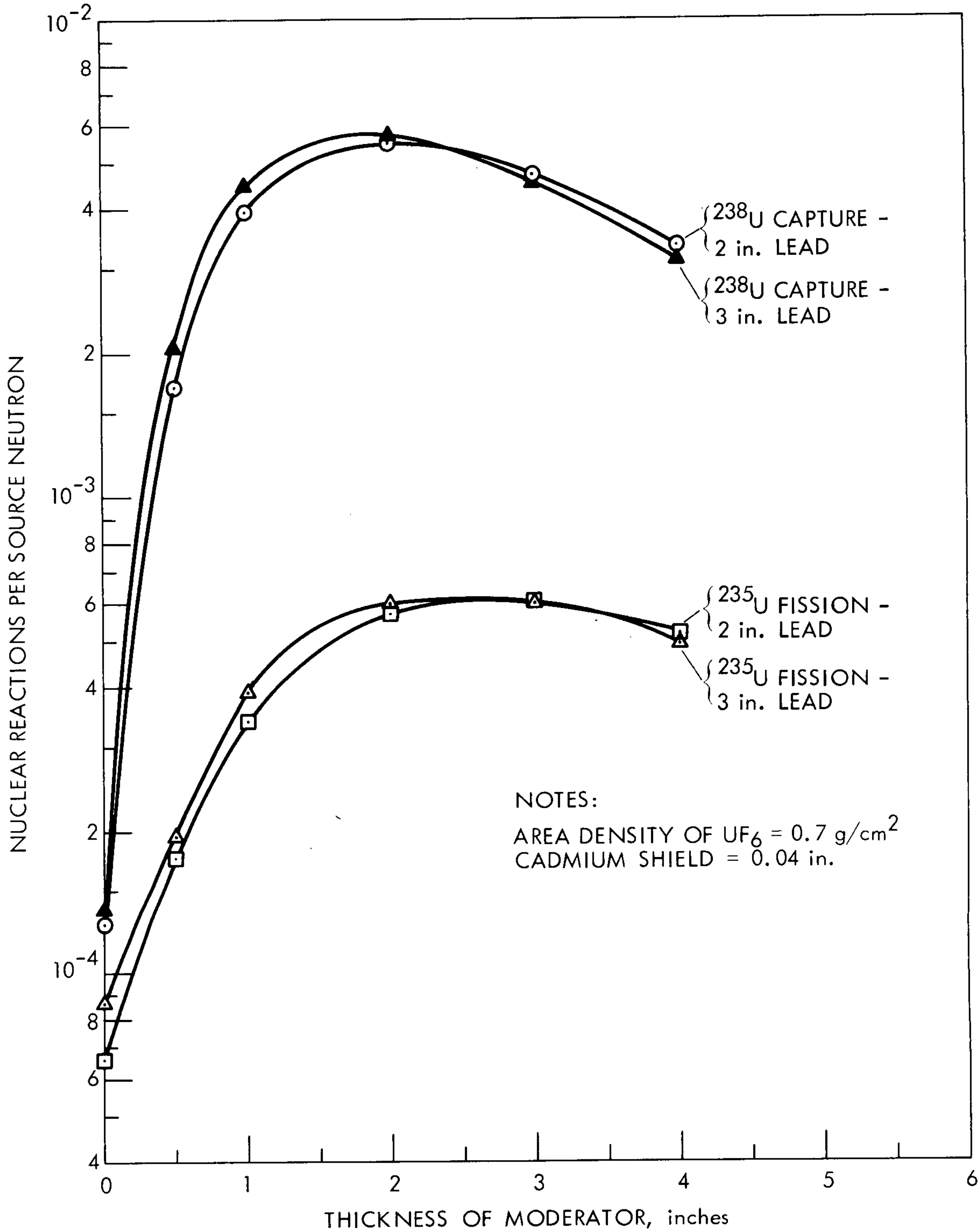


Figure 7
EFFECTS OF LEAD SHIELD THICKNESS

DWG. NO. G-72-1092
(U)

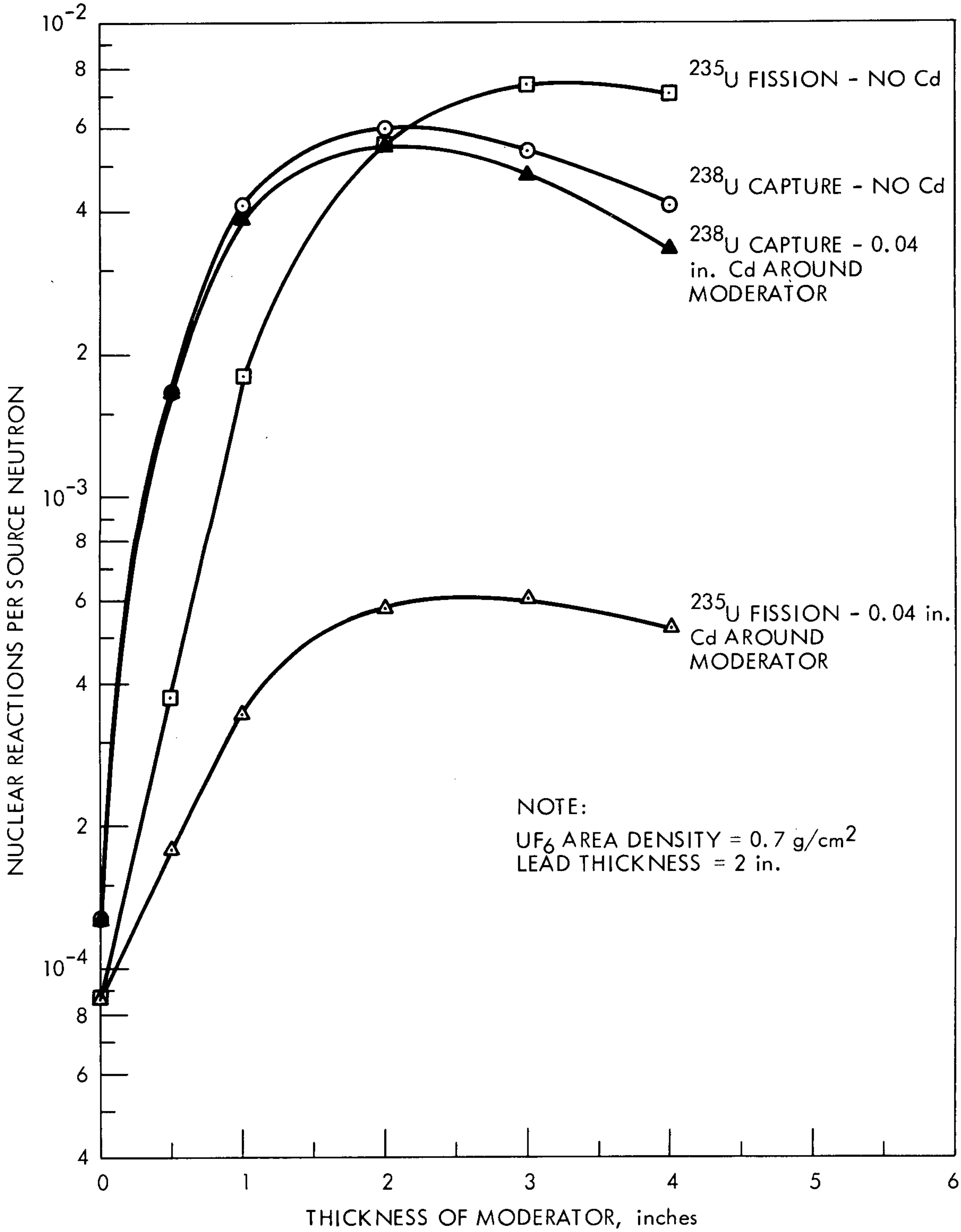


Figure 8

EFFECTS OF CADMIUM AROUND SOURCE

DWG. NO. G-72-1093
(U)

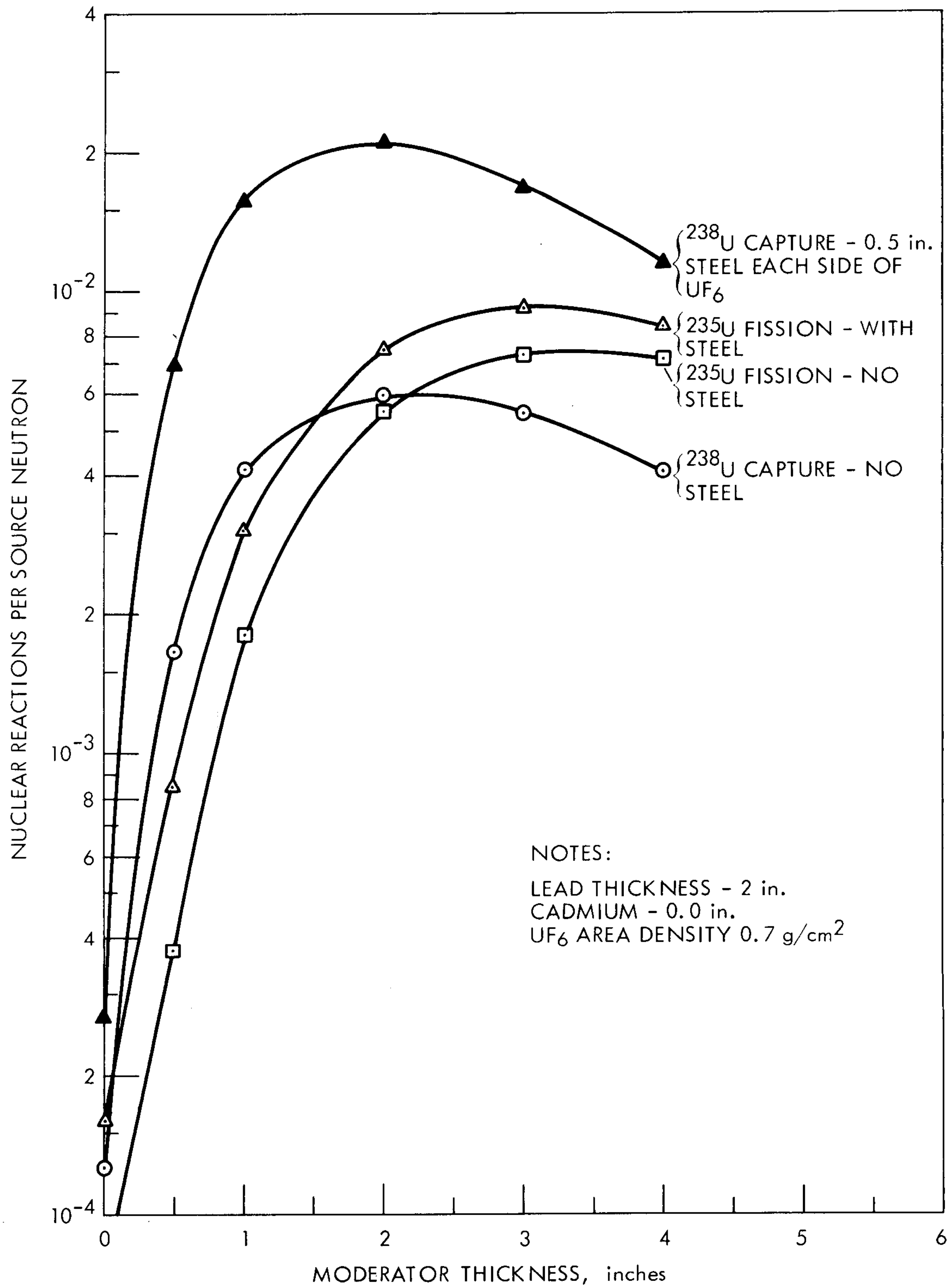


Figure 9

EFFECTS OF STEEL SURROUNDING UF_6
WITH NO CADMIUM AROUND SOURCE

DWG. NO. G-72-1094
(U)

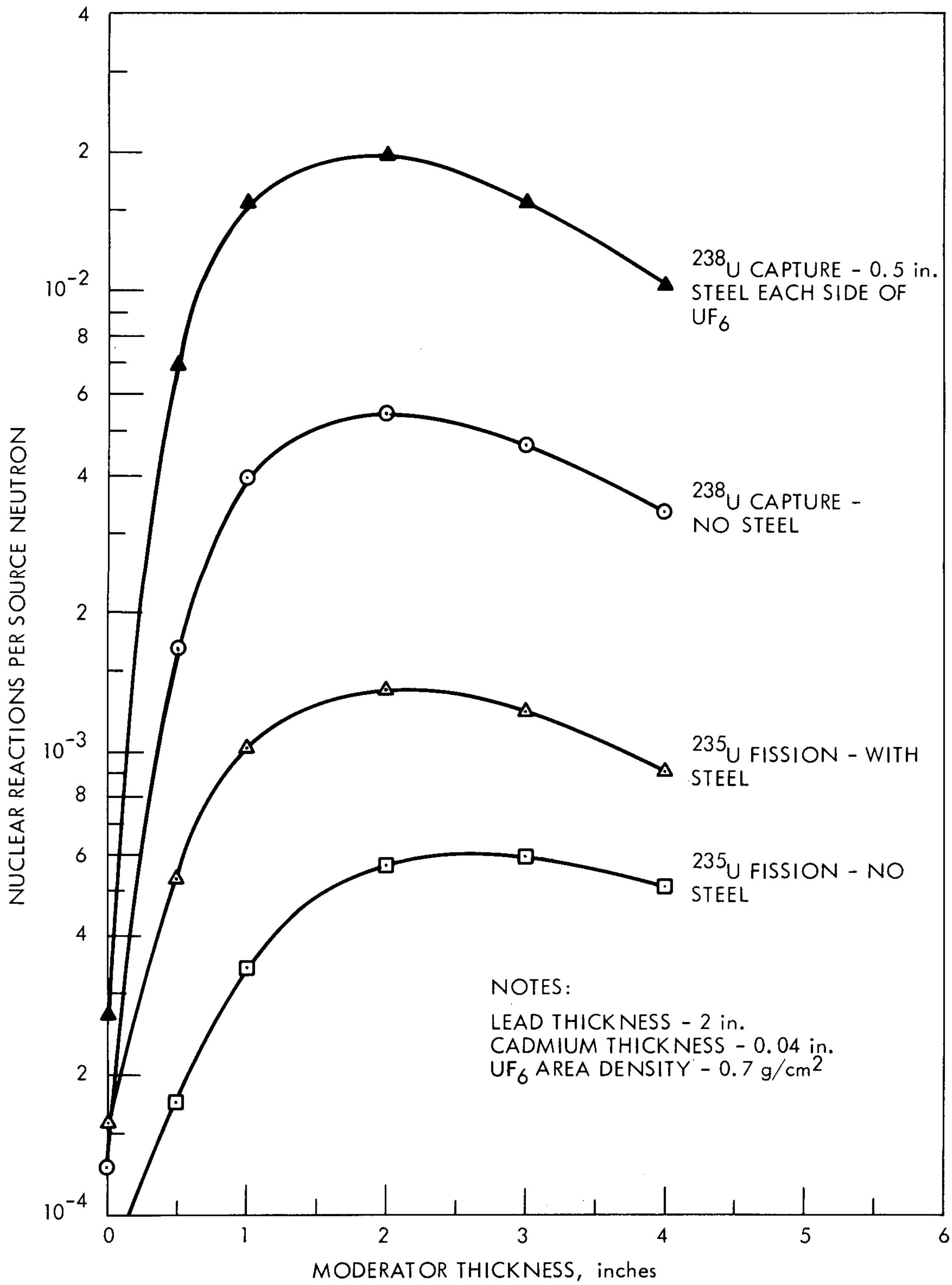


Figure 10

EFFECTS OF STEEL SURROUNDING UF_6 WHEN SOURCE IS SHIELDED WITH CADMIUM

DWG. NO. G-72-1095
(U)

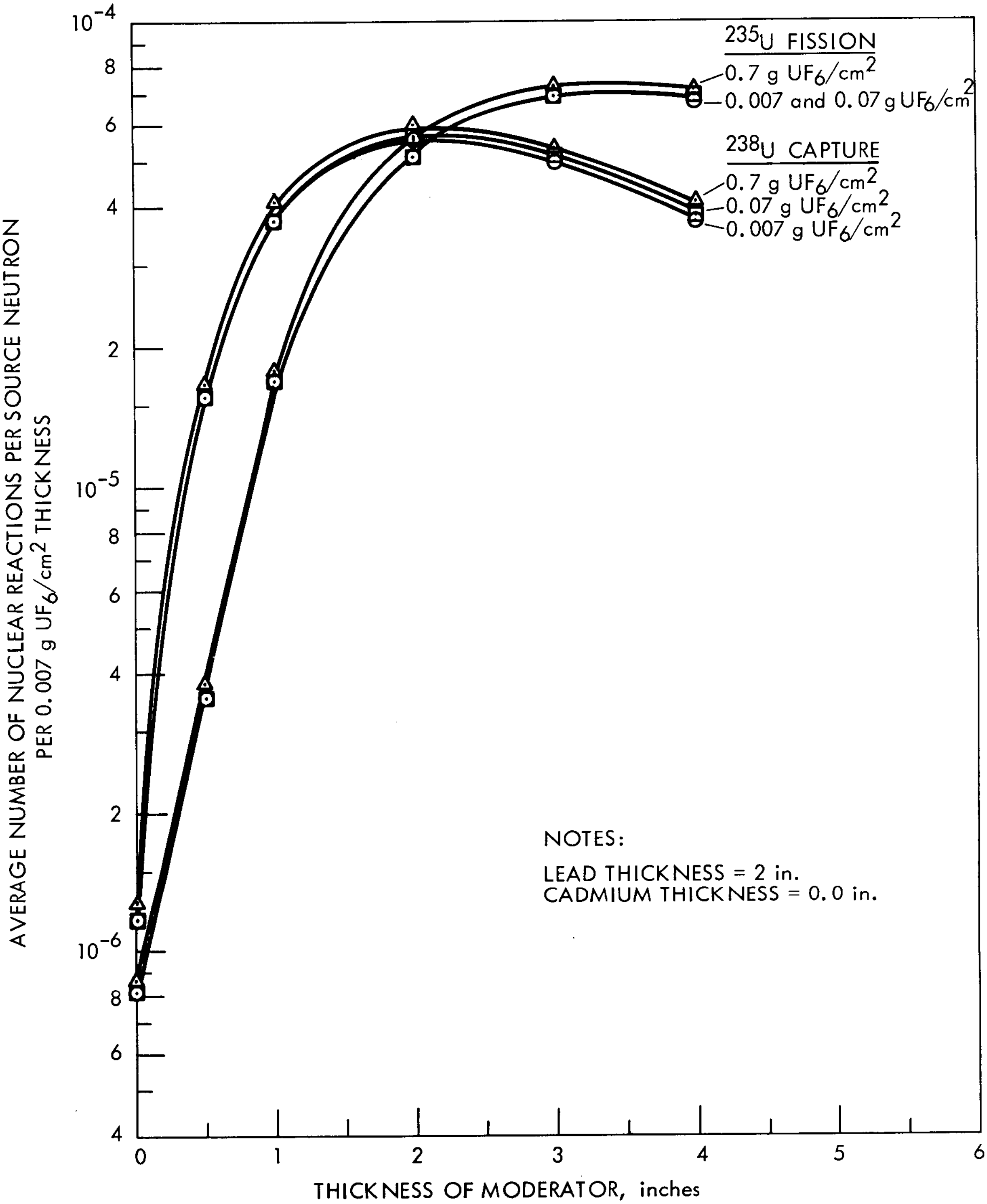


Figure 11

EFFECTS OF UF_6 THICKNESS

of the addition of steel is least for the ^{235}U reaction rate with no cadmium and the maximum effect (an increase by a factor of 3.5 with 2 in. of moderator) is noted in the ^{238}U reaction rate with or without cadmium.

On comparing the two sets of curves, it is noted that cadmium reduces the ^{235}U reaction rate only by a factor of about 5 when steel is present as compared to a factor of 10 when the steel is not present.

The large increase in the ^{238}U reaction rate is attributed to the fact that the scattering cross section for steel in the energy groups covering the major ^{238}U resonances is quite large (about 11 barns), 1/2 in. of steel representing approximately one mean-free-path thickness for neutrons in these groups. At the same time, the steel capture cross sections for these groups is very low (approximately 0.1 to 0.01 barns). Thus, internal reflection from the outer steel shell results in both single and multiple traverses of the UF_6 layer by neutrons, this being particularly significant for neutrons in the energy groups mentioned. The result is a large increase in the flux represented by these energy groups in the UF_6 region, with the resulting increase in reaction rates. Such an increase would not be anticipated for neutron irradiation by a source outside the UF_6 system, since reflection would reduce, rather than increase, the flux. The relatively small increase in the ^{235}U fission rate is attributable to a relatively large steel capture cross section for thermal neutrons (2.24 barns), which would tend to reduce the effects of reflection on the thermal flux which produces most of the ^{235}U fissions.

The primary purpose in including the cases involving steel, however, was to determine whether modifications of the spectrum might affect the ^{238}U-capture to the ^{235}U-fission ratio appreciably. Such effects were noted. With no steel present and with 2 in. of moderator, the ^{238}U-capture to ^{235}U-fission ratios (table 4) were approximately 1.1 and 9.6 for the cases of no cadmium and 0.04-in. of cadmium around the moderator, respectively. With steel, the corresponding ratios were approximately 2.7 and 14.2 respectively.

In a development of the neutron-capture gamma method of determining enrichment, should further study indicate that it is indeed feasible, consideration should be given to the possible use of a steel shell around the moderator and cadmium of a source assembly. The purpose would be to modify the neutron spectrum at the source so that further modifications effected by steel piping would occasion smaller variations in the factor by which the ^{235}U fission rate is reduced by the insertion of the cadmium. If such a constant factor in the reduction of the fission rate could be obtained when the cadmium is placed around the moderator independent of pipe thicknesses involved, the magnitude of this effect would be useful in determining the absolute level of the fission-gamma spectrum.

Area densities of the UF_6 shell were varied from 0.7 to 0.007 g/sq cm. The higher value represents the area density penetrated by neutrons traversing the diameter of a 3-ft diameter pipe filled with UF_6 at about 9

Table 4

^{238}U CAPTURE AND ^{235}U FISSION RATES IN TOTAL UF_6 SHELL ENCLOSING ^{252}Cf SOURCE OF 1 NEUTRON PER SECOND*

Moderator Thickness, In.	Cd, In.	0.7 g/cm² UF_6 U-238 Capture	0.7 g/cm² UF_6 U-235 Fission	0.07 g/cm² UF_6 U-238 Capture	0.07 g/cm² UF_6 U-235 Fission	0.007 g/cm² UF_6 U-238 Capture	0.007 g/cm² UF_6 U-235 Fission	^{238}U Capture/^{235}U Fission, g UF_6/cm² 0.7	0.07	0.007
2 In. Pb Around Source										
0	0	1.2537-4	8.5859-5	1.1597-5	8.1089-6	1.1503-6	8.0608-7	1.46	1.43	1.43
1/2	0	1.6698-3	3.7413-4	1.5545-4	3.5193-5	1.5427-5	3.4949-6	4.46	4.42	4.41
1	0	4.0593-3	1.7817-3	3.7905-4	1.6871-4	3.7625-5	1.6761-5	2.28	2.25	2.24
2	0	5.9868-3	5.4602-3	5.6023-4	5.1910-4	5.5630-5	5.1597-5	1.10	1.08	1.08
3	0	5.3585-3	7.2417-3	5.0259-4	6.9041-4	4.9919-5	6.8648-5	0.740	0.728	0.727
4	0	4.0226-3	7.1058-3	3.7761-4	6.7861-4	3.7513-5	6.7496-5	0.566	0.556	0.556
0	0.04	1.2610-4	8.5921-5	1.1664-5	8.1134-6	1.1569-6	8.0651-7	1.47	1.44	1.43
1/2	0.04	1.6878-3	1.7738-4	1.5716-4	1.6567-5	1.5596-5	1.6447-6	9.52	9.49	9.48
1	0.04	3.9143-3	3.4056-4	3.6549-4	3.1857-5	3.6280-5	3.1625-6	11.49	11.47	11.47
2	0.04	5.4477-3	5.6488-4	5.0970-4	5.3148-5	5.0613-5	5.2787-6	9.64	9.59	9.59
3	0.04	4.6596-3	5.9445-4	4.3693-4	5.6181-5	4.3399-5	5.5826-6	7.84	7.78	7.77
4	0.04	3.3506-3	5.1290-4	3.1455-4	4.8689-5	3.1243-5	4.8399-6	6.53	6.46	6.46
2 In. Pb Around Source and 0.5 In. Steel on Each Side of UF_6										
0	0	2.6788-4	1.5883-4	2.5580-5	1.5399-5	2.5461-6	1.5351-6	1.69	1.66	1.66
1/2	0	6.9931-3	8.5156-4	7.0933-4	8.7069-5	7.1042-5	8.7290-6	8.21	8.15	8.14
1	0	1.5733-2	3.0493-3	1.6036-3	3.1996-4	1.6068-4	3.2165-5	5.16	5.01	5.00
2	0	2.0674-2	7.5276-3	2.1112-3	8.0025-4	2.1158-4	8.0559-5	2.75	2.64	2.63
3	0	1.6741-2	9.1243-3	1.7087-3	9.7406-4	1.7124-4	9.8098-5	1.83	1.75	1.75
4	0	1.1363-2	8.4130-3	1.1579-3	8.9984-4	1.1602-4	9.0642-5	1.35	1.29	1.28
0	0.04	2.6912-4	1.5897-4	2.5696-5	1.5411-5	2.5575-6	1.5362-6	1.69	1.67	1.66
1/2	0.04	7.0460-3	5.2588-4	7.1495-4	5.2467-5	7.1605-5	5.2457-6	13.40	13.63	13.65
1	0.04	1.5368-2	1.0124-3	1.5664-3	1.0234-4	1.5696-4	1.0247-5	15.18	15.31	15.32
2	0.04	1.9605-2	1.3834-3	2.0021-3	1.4142-4	2.0066-4	1.4176-5	14.17	14.16	14.15
3	0.04	1.5540-2	1.2219-3	1.5870-3	1.2570-4	1.5904-4	1.2609-5	12.72	12.63	12.61
4	0.04	1.0318-2	9.0284-4	1.0530-3	9.3294-5	1.0552-4	9.3630-6	11.43	11.29	11.27
3 In. Pb Around Source										
0	0	1.3640-4	8.7360-5	1.2602-5	8.2290-6	1.2499-6	8.1781-7	1.56	1.53	1.53
1/2	0	2.0284-3	4.5741-4	1.8868-4	4.2968-5	1.8726-5	4.2670-6	4.43	4.39	4.39
1	0	4.6723-3	2.1632-3	4.3621-4	2.0474-4	4.3307-5	2.0344-5	2.16	2.13	2.13
2	0	6.2830-3	6.0369-3	5.8885-4	5.7465-4	5.8483-5	5.7130-5	1.04	1.02	1.02
3	0	5.3150-3	7.5092-3	4.9878-4	7.1653-4	4.9550-5	7.1262-5	0.708	0.696	0.695
4	0	3.8299-3	7.0361-3	3.5984-4	6.7267-4	3.5739-5	6.6888-5	0.544	0.535	0.534
0	0.04	1.3714-4	8.7428-5	1.2669-5	8.2340-6	1.2565-6	8.1829-7	1.57	1.54	1.54
1/2	0.04	2.0439-3	1.9872-4	1.9018-4	1.8527-5	1.8874-5	1.8391-6	10.29	10.27	10.26
1	0.04	4.4842-3	3.8334-4	4.1869-4	3.5850-5	4.1568-5	3.5593-6	11.70	11.68	11.68
2	0.04	5.6818-3	5.9826-4	5.3245-4	5.6351-5	5.2883-5	5.5985-6	9.50	9.45	9.45
3	0.04	4.5865-3	5.9710-4	4.3050-4	5.6565-5	4.2759-5	5.6220-6	7.68	7.61	7.61
4	0.04	3.1574-3	4.9510-4	2.9737-4	4.7157-5	2.9540-5	4.6880-6	6.38	6.31	6.30

*Negative numbers in table are powers of 10, indicating the factor by which the numbers are to be multiplied.

psia at a temperature of 150°F or to about 13 psia at 400°F. These conditions are given only to indicate to the reader the amount of gaseous UF_6 corresponding to these area densities, and are not given as typical values or as conditions necessarily anticipated in any given diffusion plant.

A comparison of the ^{238}U capture to ^{235}U fission ratios listed in table 4 shows that, within the range covered, this ratio is nearly independent of the thickness of UF_6 considered. Figure 11 also shows that the absolute values of these two reactions are nearly independent of the UF_6 thickness. The curves for the 0.07 and 0.007 g/sq cm UF_6 area densities are essentially indistinguishable on the graph. Slight elevations in both the average ^{238}U capture and ^{235}U fission rates occur with the higher UF_6 area density. This indicates that, with the neutron spectra involved in these calculations, self shielding effects in the UF_6 are compensated for by backscattering effects and possibly by slight moderation effects of the UF_6.

If self-shielding effects were extremely pronounced, the geometry and densities of the UF_6 gas involved would be important factors in instrument response. The very minor nature of the overall changes with variations in UF_6 area density is considered to enhance the possibility of application of the neutron capture method.

CONCLUSIONS

Studies of possibilities for monitoring the enrichment of UF_6 inside the equipment of a gaseous diffusion plant without access to the UF_6 indicated two highly promising possibilities. The first of these has been investigated sufficiently to establish that it is feasible and is well within the scope of current technology. This method involves (1) passive measurement of the ^{235}U gamma rays originating from the UF_6 gas in a section of pipe to determine the ^{235}U present, (2) a measurement of the absorption of gamma rays from a low-energy gamma source as these rays penetrate the pipe and UF_6, (3) correction of this last measurement for absorption of gamma rays by the pipe walls to determine attenuation by the UF_6 alone, (4) calculation of total uranium present as based on this gamma attenuation value, and (5) calculation of the ratio of ^{235}U to total uranium present, which is the enrichment value desired.

It was shown that with two gamma attenuation measurements, one with the radiation path along a diameter and the other along an appropriate chord of the pipe, it would be necessary to determine only relative pipe thicknesses on the two radiation paths to evaluate radiation absorption by the UF_6. This eliminates the need for absolute thickness measurements and also the need for information regarding the particular alloy of which the pipe is made. Tests showed that a commercially available ultrasonic thickness gauge will provide the relative thicknesses with sufficient accuracy for this purpose.

The second method involves the possible irradiation of the UF_6 with neutrons from an isotopic source and the detection of gamma rays resulting from neutron capture in ^{238}U, which would exhibit a characteristic energy, and gamma rays resulting from ^{235}U fission. Calculations indicated that approximately 2 in. of methylmethacrylate would provide optimum moderation for a californium-252 spontaneous-fission neutron source. The resulting spectrum exhibits a relatively high flux in the resonance-energy region where neutron capture by ^{238}U is most pronounced. This tends to prevent the ^{238}U capture peak from being obscured by the multitudinous fission gamma rays which might result with thermal neutron irradiation.

Both the methods mentioned warrant further evaluation. The availability of both methods, which utilize the same spectrometry equipment, would offer the possibility of obtaining two independent evaluations of enrichment and would greatly reduce the possibility of errors which might be brought about by pipe construction or materials and which might not be detectable by external inspection.

REFERENCES

1. Auguston, R. H., et al., *Development of Techniques for Active and Passive Assay of Fissionable Materials,* Proceedings of a Symposium in Safeguards Techniques Organized by the International Atomic Energy Agency, IAEA-SM-133/51, II, Karlsruhe, pp. 53-78 (1970).

2. Keepin, G. R., et al., *Application Areas and Results of Nondestructive Assay Measurements,* Proceedings of a Symposium in Safeguards Techniques Organized by the International Atomic Energy Agency, IAEA-SM-133/49, II, Karlsruhe, pp. 79-112 (1970).

3. Gozani, T., et al., *New Developments in Nuclear Material Assay Using Photonuclear Reactions,* Proceedings of a Symposium in Safeguards Techniques Organized by the International Atomic Energy Agency, IAEA-SM-133/45, II, Karlsruhe, pp. 143-163 (1970).

4. Higginbotham, W. A. and Court, A., *Survey of Nuclear Material and Possible Measurement Techniques,* Institute of Nuclear Materials Management Tenth Annual Meeting, Las Vegas, pp. 353-374 (April 1969).

5. Keepin, G. R., *Program Status Report, Nuclear Safeguards Research and Development,* USAEC Report LA-4605-MS, Los Alamos Scientific Laboratory (January 1971).

6. Sheline, R. K., et al., *Levels in* ^{239}U*,* Physical Review, 151(3), pp. 1011-1020 (November 1966).

7. Engle, W. W., Jr., *A User's Manual for ANISN, A One-Dimensional Discrete Ordinates Transport Code with Anisotropic Scattering,* Union Carbide Corporation, Nuclear Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, March 1967 (K-1693).

APPENDIX A

Specifications

APPENDIX A

SPECIFICATIONS

Specification SP-18242

AN INSTRUMENTATION SYSTEM FOR THE DETECTION, ANALYSES AND PRESENTATION OF GAMMA RADIATION PHENOMENA*

I. SPECIFICATION DESCRIPTION

This specification covers eight major items of instrumentation. Each item is assigned a sub-number (-1 through -8). Each section of the specification indicates the other items with which the unit must interface.

II. SYSTEM DESCRIPTION

The system consists of a crystal detector with preamplifier and cryostat, a bin and power supply, several signal conditioning and power supply modules, a multi-channel pulse height analyzer, a paper tape punch, a Teletype unit, and necessary interfacing equipment.

III. GENERAL SPECIFICATIONS

All instrumentation shall perform within its specifications under any steady state conditions within the following limits:

A. Input power: 105 to 125 volts ac, 60 Hz, 1 phase.
B. Ambient temperature: 5 to 40°C (40 to 104°F).
C. Ambient humidity: 5 to 95% R. H.
D. Vibration: 1 mil p-p sinusoidal, 0 to 65 Hz.

In addition, the performance shall be unaffected by an indefinite non-operating storage temperature over the range of 0 to 50°C (32 to 122°F).

All equipment described herein shall be compatible and shall function as a system. All necessary interfacing equipment, including signal and power cables, shall be furnished.

IV. INSPECTIONS AND TESTS

A. Tests at Seller's Plant

The equipment shall be inspected and tested to show full compliance with the specifications. Certified inspection and test results shall be furnished to and approved by the Company prior to equipment shipment.

---

*Prepared by G. B. Seaborn, Instruments and Quality Assurance Development, Gaseous Diffusion Development Division.

B. Tests at Company's Plant
The Company will inspect and test the equipment after it is received. These tests will determine compliance with the specifications and will be the basis for final acceptance.

Specification SP-18242-1

GAMMA RADIATION DETECTOR ASSEMBLY

I. GENERAL DESCRIPTION
This assembly consists of a crystal detector, preamplifier, and cryostat.

II. CRYSTAL DETECTOR
A. Material: lithium drifted germanium
B. Geometry: true right-circular coaxial
C. Relative photopeak efficiency: 7%
D. Resolution (FWHM for Co^{60} 1.322 MeV): 2.5 keV
E. Peak-to-Compton ratio: 23:1

III. PREAMPLIFIER
A. Type: charge sensitive (coupled to detector).
B. Open loop gain: 20,000.
C. Non-linearity: 0.05% maximum.
D. Temperature coefficient: less than 0.005% per °C.
E. Saturation output level: ±9 volts.
F. Noise: 540 eV at 0 pf; slope of 18 eV per pf.
G. Count Rate Capabilities: 150,000 counts per second for a Co^{60} spectrum.
H. Conversion gain: 170 mv per MeV.
I. Input power: to be supplied from Spectroscopy Amplifier.

IV. CRYOSTAT
A. Capacity: 5 liters liquid nitrogen
B. Consumption: 1 liter per day @ 25°C. (77°F).

V. CONSTRUCTION
The crystal, preamplifier, and cryostat shall be assembled as a rugged, integral unit.

Provision shall be made for the high voltage supply.

VI. INTERFACING
A. Spectroscopy amplifier (SP-18242-3).
B. High voltage power supply (SP-18242-5).

Specification SP-18242-2

BIN AND POWER SUPPLY ASSEMBLY

I. GENERAL DESCRIPTION
This assembly consists of a NIM Standard bin and power supply conforming to AEC Specification TID-20893 (Rev. 3).

II. BIN
A. Capacity: 12 single width modules.
B. Connectors: 12 (one per module).
C. Wiring: Connectors wired in parallel.
D. Potentials: +12, -12, +24, -24 vdc; power ground, high quality ground; 115 vac.
E. Controls: on-off switch, power indicating lamp.
F. Test jacks: the potentials in II-D shall be brought out to front panel test jacks.

III. POWER SUPPLY
A. Outputs: 1.75A. @ +12, 1.75A. @ -12, 0.875A. @ +24, 0.875A. @ -24, vdc. Each output shall be adjustable over a ± 1 volt range.
B. Regulation: 0.05% combined load and line at constant temperature.
C. Stability: 0.3%/6 months at constant input, output, and temperature.
D. Output impedance: <0.3 ohms up to 100 kHz.
E. Temperature Coefficient: $<0.01\%/^{\circ}C$.
F. Noise and ripple: <3 mv. p-p (50 MHz bandwidth scope)
G. Recovery time: <50 µsec. to within 0.1% of rated voltage for any change in input voltage or load between 10% and 100%.
H. Circuit protection:
1. Both sides of power line fused.
2. Internal thermal overload switch.
3. Electronic output current foldback limiting with automatic recovery.

IV. INTERFACING
A. Spectroscopy amplifier (SP-18242-3)
B. Biased amplifier (SP-18242-4)
C. High voltage power supply (SP-18242-5)
D. Pulser (SP-18242-6)

Specification SP-18242-3

SPECTROSCOPY AMPLIFIER

I. GENERAL DESCRIPTION
This unit is a high quality pulse amplifier.

II. PERFORMANCE

- A. Gain range: 2.5 to 3,000, continuously adjustable.
- B. Pulse shape: Gaussian
- C. Integral non-linearity: <0.05%.
- D. Noise: <4 μv unipolar and <7 μv bipolar referred to the input using 3 μsec. shaping and coarse gain ≥ 100.
- E. Temperature stability
  1. Gain: 0.005%/°C
  2. DC level: <100 μv/°C.
- F. Crossover walk: ≥ 2 nsec for 100:1 dynamic range.
- G. Count rate stability: a pulser peak at 85% of analyzer range shifts <0.2% in the presence of 0 to 50,000 random counts/sec. from a Cs^{137} source with its peak stored at 75% of analyzer range, using 1 μsec. shaping.
- H. Overload recovery: to within 2% of rated output from 1,000 times overload in 2.5 non-overloaded bipolar pulse widths using maximum gain; degrades to 200 times for unipolar.

III. FRONT PANEL CONTROLS

- A. Coarse gain: X5 to X2,000 in 1, 2, 5 sequence.
- B. Fine gain: X0.5 to X1.5 by 10 turn precision potentiometer
- C. Input polarity: + or - pulses.
- D. Unipolar output range: suitable for use by the biased amplifier (see SP-18242-4).
- E. Shaping time: adjustable to 0.25, 0.5, 1, 2, 3, and 6 μsec.
- F. Pole-zero cancellation: continuously adjustable from 25 μsec. to ∞.
- G. Unipolar output dc level: continuously adjustable over a ± 1.5 v range.
- H. Delay: provision for inserting a 2 μsec. delay in the unipolar output pulse.
- I. Baseline restorer: 3 choices - high for duty cycles of >15%, low for <15%, and out.

IV. INPUT CHARACTERISTICS

- A. Pulse polarity: + or -.
- B. Risetimes: 10 to 650 nsec.
- C. Decay times: 25 to 2,000 μsec.
- D. Impedance: ~1,000 ohms.
- E. Coupling: dc
- F. Maximum amplitude
  1. Linear: 5.5 v.
  2. Non-linear: 20 v.
- G. Power: Compatible with power supply (see SP-18242-1).

V. OUTPUT CHARACTERISTICS

- A. Unipolar and bipolar
  1. Impedance: .93 ohms
  2. Protection: short circuit proof.
- B. Power: suitable for preamplifier (SP-18242-1).
- C. Compatible with biased amplifier (SP-18242-4).

VI. DIMENSIONS
Standard double width module.

VII. INTERFACING
A. Preamplifier (SP-18242-1).
B. Gated biased amplifier (SP-18242-4).
C. Power supply (SP-18242-2)
D. Cabinet (SP-18242-2).

Specification SP-18242-4

GATED BIASED AMPLIFIER

I. GENERAL DESCRIPTION
This unit is a high quality pulse conditioning amplifier.

II. PERFORMANCE
A. Integral non-linearity: <0.05% (dc coupled) for pulse risetime >300 μsec.
B. Temperature stability (in % of full scale input)
1. Bias level: ≤20 ppm/°C.
2. Post gain: ≤20 ppm/°C.
3. Output dc level: ≤10 ppm/°C.
4. Discriminator: ≤50 ppm/°C.
C. Automatic pileup rejection: total until output pulse ended and input discriminator reset.
D. Noise: ≤15 μv, referred to input.
E. Count rate: the centroid of a pulser spectrum at 85% of full scale will shift <0.1% when modulated by 50,000 counts/sec. of random signals from a Cs^{137} source with photopeak at 70% of full scale using an amplifier with a time constant of 1 μsec.
F. Gate Feedthrough: <1 mv with gate closed.
G. Gate pedestal: adjustable to 0 vdc.
H. Gain: Continuously adjustable from X0.33 to X30.
I. Stretcher droop: <1 mv/μsec.

III. CONTROLS
A. Front panel
1. Gain
a. Coarse: 0.66, 2, 5, 10, 20
b. Fine: 0.5 to 1.5 by precision 10 turn potentiometer.
2. Bias level: 0 to 10 turn potentiometer.
3. Input coupling
a. Base line restorer high: ac coupled input with active base line restorer for unipolar input pulse duty cycle <20%.
b. Base line restorer low: ac coupled input with passive base line restorer for bipolar pulses and unipolar input pulse duty cycle <20%.
c. DC couple: dc coupled input for input pulses from a dc coupled source with no baseline offset.

4. Mode: selects inclusion or exclusion of gating circuit.
5. Gate period: controls effective enable/disable period for gated mode with range of 0.5 to 5 μsec.
6. Discriminator level: adjusts input sensitivity level range from 0.1 to 1 v.
7. Output delay: adjusts the delay period from the peak of an input signal to the rise of an output pulse with range of 0.5 to 5 μsec.
8. DC adjust: permits adjustment of output baseline to ±1 v.

B. Rear panel
1. Gate: selects coincidence or anticoincidence mode.
2. Strobe: selects either internal or external strobe to determine the output pulse time.

IV. INPUTS

A. Linear
1. Polarity: unipolar or bipolar
2. Amplitude: 0.1 to 10 v
3. Risetime: ≥100 ηsec.
4. Impedance: ~1,000 ohms

B. Gate
1. Amplitude: ≥3v; 25 v. maximum
2. Width: ≥100 ηsec.
3. Impedance: ~2,000 ohms

C. Inhibit
1. Amplitude: ≥3 v; 25 v. maximum
2. Impedance: ~1,000 ohms

D. Strobe
1. Amplitude: ≥3 v; 25 v maximum
2. Impedance: ~1,000 ohms

E. Power: compatible with power supply (SP-18242-2).

V. OUTPUTS

A. Positive/negative
1. Range: 0 to 10 v.
2. Risetime: ~0.5 μsec.
3. Width: 1 to 5 μsec., adjustable
4. Impedance: 93 ohms

B. Busy out
1. Amplitude: ~5 v.
2. Initiation: peak of input signal
3. Termination: completion of output pulse or reset of discriminator, whichever is longer.

C. Compatible with pulse height analyzer (SP-18242-7)

VI. DIMENSIONS

Standard double width module

VII. INTERFACING

A. Spectroscopy amplifier SP-18242-3
B. Pulse height analyzer SP-18242-7
C. Bin SP-18242-2
D. Power supply SP-18242-2

Specification SP-18242-5

HIGH-VOLTAGE POWER SUPPLY

I. GENERAL DESCRIPTION
This unit is a high quality high voltage power supply.

II. PERFORMANCE
- A. Outputs
  - 1. No. 1: 100 μA maximum @ 0-500 vdc.
  - 2. No. 2: 100 μA maximum @ 0-5,000 vdc.
- B. Polarity: + or -.
- C. Noise and ripple: <10 mv p-p (5 Hz to 50 MHz).
- D. Temperature stability: <0.02%/°C.
- E. Stability: <0.1%/hr at constant temperature and load.
- F. Risetime: 5 sec., 0 to maximum.
- G. Resetability: within 0.2%

III. CONTROLS
- A. Output: 5 turn direct reading potentiometer.
- B. On-off: for high voltage.
- C. Polarity: switch, with polarity indication

IV. INPUT
Power: compatible with power supply (SP-18242-2)

V. OUTPUTS
- A. No. 1
  - 1. Amplitude: 0-500 v.
  - 2. Impedance: ~700 ohms.
- B. No. 2
  - 1. Amplitude: 0-5,000 v.
  - 2. Impedance: ~2 M ohms
  - 3. Front panel meter; direct reading
- C. Compatible with crystal (SP-18242-1)

VI. DIMENSIONS
A standard single width module

VII. INTERFACING
- A. Crystal: SP-18242-1
- B. Bin: SP-18242-2
- C. Power Supply: SP-18242-2

Specification SP-18242-6

PRECISION PULSE GENERATOR

I. GENERAL DESCRIPTION

This unit is a precision pulse generator for use in testing the radiation detection system.

II. PERFORMANCE

A. Amplitude 0 to ±1 v., continuously adjustable.

B. Risetime: 5 to 250 ηsec., adjustable

C. Falltime: ~200 μsec.

D. Amplitude stability

1. Temperature: 0.005%/°C.

2. Line voltage: 0.001% total

3. Ripple and noise: 0.003%

E. Repetition rate

1. Power line frequency

2. 70 Hz 1%

F. Repetition rate stability

1. Temperature: 0.05%/°C

2. Time: 1%/day

III. CONTROLS

A. Pulse height: 10 turn potentiometer with 0.1% of full scale linearity.

B. Normalize: 10 turn potentiometer adjusts the total range of the pulse height control - full scale adjustable from 0.5 to 1 v. linearity 0.1% of full scale.

C. Frequency

1. Power line

2. 70 Hz

3. Off

D. Polarity: + or -.

E. Risetime: 5, 20, 50, 100, 250 ηsec.

F. Attenuator: allows amplitude attenuation over a range of 2 to 2,000 in a 1, 2, 5 sequence.

IV. INPUTS

All power inputs shall be compatible with the power supply (SP-18242-2).

V. OUTPUT

Impedance: 100 ohms

VI. INTERFACING

A. Bin: SP-18242-2

B. Power Supply: SP-18242-2

C. Preamplifier: SP-18242-1

Specification SP-18242-7

MULTICHANNEL PULSE ANALYZER

I. GENERAL DESCRIPTION

This unit is a multichannel pulse analyzer capable of operation in pulse height and multiscaler modes.

II. PERFORMANCE

A. ANALOG TO DIGITAL CONVERTER

1. Inputs

a. Signal: Positive unipolar or bipolar pulse, 0 to 10 v, risetime <250 nsec (20 μsec max), decay time 30 μsec max, input impedance: 1,000 ohms. Two selectable inputs for dc or ac coupled (dc restored). Signal BNC connectors on front and rear panels with front panel test point to monitor dc zero adjustment.

b. Gate:

(1) $\geq + 3$ v ($\pm$ 25 v max), width 100 nsec min, no max limit, input impedance >1,000 ohms, dc coupled.

(2) The gating function is selected with a front panel switch to operate in the coincidence or anticoincidence mode. BNC connector in front and rear panels. Note: Internal circuit regenerates the gate width to be 5 μsec minimum; the maximum is set by the gate input signal width.

2. Performance

a. Digitizing rate: 50 MHz

b. Integral nonlinearity: $\leq \pm$ 0.05% over the top 99% full scale.

c. Differential nonlinearity: <1% over the top 99% of full scale.

d. Overall temperature stability:

(1) $\leq$100 ppm/°C from 0 to 50°C specified in percentage of full scale.

(2) Long term: A pulser peak will stay within one channel over 24 hours for constant line voltage (115 v ac ±10%, 50-60 Hz) and room temperature.

e. Channel profile: The channel profile is flat over 75% of the channel width.

f. Dead time correction: the ADC provides in conjunction with the memory system for automatic dead time correction. Note: Dead time is measured from the leading edge firing of the discriminator. Livetime acc: ≤0.05% of preset time.

3. Controls

a. Address full scale (for 10 v): ADC conversion gain specified in channels full scale for 10 v input signal.

b. Overflow: This function is implemented automatically by the "memory storage region" switch which sets the overflow bit in the ADC. The group size can be selected to be FULL memory, halves or quarters with FULL memory of being 1024.

c. Digital offset: Digital offset in steps of 1024, 512, 256, and 128 or any combination of them implemented with a set of four toggle switches.

d. Anti/coincidence: Front panel switch which selects the enable/disable function of the gate signals either in coincidence or anticoincidence.

e. Analysis region:

(1) Lower level: 10 turn front panel control to adjust between 0% to 100% of full scale. Resetability better than 0.2%. Temperature stability $\leq$200 ppm/°C (refer to description of Adjust/Operate switch).

(2) Upper level: 10 turn front panel control to adjust between 5% and 105% of full scale. Resetability and temperature stability as LLD (refer to description of Adjust/Operate switch).

f. Adjust/operate: Front panel toggle switch which, when in ADJUST, intensifies in the CRT screen the ANALYSIS REGION or the fraction of the input spectrum limited by the upper and lower level discriminators. The purpose of this function is to permit the setting of the analysis region discriminators by making reference to the stored data.

g. Zero adjust: Screwdriver adjustable from 0 to ± 5% of full scale by front panel 10 turn potentiometer. Temperature stability included in the performance specifications.

4. ADC digital outputs

a. ADC busy: Rear panel BNC connector. Nominal + 5 v pulse width duration equal to the time from the firing of discriminator to the end of the memory cycle. (Note: If a reject condition is reached at any time during the conversion, the busy period will terminate.) The output is available in BNC connector with output impedance <10 ohms and risetime $\leq$50 nsec.

b. SCA out: Rear panel BNC connector. Nominal + 5 v pulse, 1 μsec wide. Each output pulse whose amplitude falls within the lower and upper level discriminators will generate an output. Output impedance <50 nsec.

c. ROI output: Rear panel BNC connector. Nominal 10 v, 5 μsec wide. An output pulse is provided each time an event is stored within any selected "region of interest". Output enabled only in the PHA analysis mode. Output impedance <10 ohms, risetime <50 nsec.

B. DISPLAY AND MEMORY SYSTEM

1. Memory description

a. Number of words (channels): The memory can store 1024 words of BCD data.

b. Word length: 24 bits of information can be stored at each word location. This provides a maximum capacity of 999,999 counts in a BCD code.

c. Storage cycle time: One word of data is read from the memory, modified, and then written back into the memory in less than 5 μsec (Read, Add-1, Write).

2. Memory controls
   a. Storage region: Selects the portion of the memory upon which data will be stored. The action of the Display, Readout, and Erase controls is limited to the selected memory region. Overflow for ADC is automatically determined by this control.
      (1) FULL: All 1024 memory words; 1/2, 2/2: memory halves; 1/4, 2/4, 3/4, 4/4: memory quarters.
      (2) Overlap: provides for an overlayed display of all quarters of the memory (two halves for 1/2). Vertical display separation of the overlayed subgroups is obtained with the "vertical expand" potentiometer in the front panel. The storage region for both 1/4 and 1/2 overlap positions retains the full memory.
      (3) Memory segment routine: routine of input signals to any quarter or half of the memory is accomplished by externally supplied routine signals to the rear panel external connector.
   b. Storage mode: Selects the type of modification to be performed on the contents of the addresses location during each memory cycle.
      (1) Add: contents of the addresses location is incremented by one.
      (2) Off: contents of the addresses location will not be modified. When in this position, the "Analyze" indicator pushbutton will flash while taking data.
      (3) Sub: contents of the addressed location is decremented by one.
      (4) Erase: contents of the complete memory or selected portion (by the Storage Region switch) is cleared to zero when the two erase buttons are depressed.
3. Display controls
   a. Counts full scale: selects between the optionally available logarithmic (LOG) display and nine ranges of linear display.
      (1) Log display: provides six decades of resolution.
      (2) Lineary display: provides 100 to 1,000,000 counts full scale in a 1, 5, 10 sequence. In all cases, the vertical deflection amplifier gain is automatically adjusted to maintain the scale calibration. Display circuits integral nonlinearity ≤1% of full scale.
   b. Expand
      (1) Horizontal and vertical: provide VERTICAL and HORIZONTAL expansion for the display, accomplished by continuously adjusting the deflection amplifiers gain between X1 and X5. For the full CCW position, the graticule is calibrated.

(2) Scan off: defines the current position of the marker as the center of the screen. The marker will then stay fixed and the spectrum displayed when the "marker position" pot is rotated. As before, this operation is restricted to the selected memory storage region.

c. Region of interest: composed by the marker position potentiometer, region of interest SET/OFF/CLEAR switch, and a numeric readout on the CRT screen (Character Generator optional).

(1) Marker position: sets the position of the marker which is identified in the CRT screen with a vertical trace.

(2) Set/off/clear: defines the limits of one or more regions of interest in the CRT display.

(a) Set: in this position, all channels over which the marker is swept through are defined as the region of interest. They will be distinguished from the rest by permanent intensification.

(b) Off: no regions of interest are set nor reset when the marker is displaced.

(c) Clear: in this mode, the marker will erase the "region of interest" status of all channels previously intensified as they are swept by the marker. If the memory erase pushbuttons are depressed when the switch is in Clear, the "region of interest" status of all channels is erased simultaneously. Note: When the "Full Spectrum/Integral Only/ROI" front panel toggle switch is set to "Full Spectrum", all channels are given ROI status independently of their prior condition. The previously existent ROI's can be automatically retrieved by returning the switch to its previous "Integral Only" or "ROI" position.

(3) Marker readout: consists of two sets of numbers labeled Co (counts) and Ch for (Channel) in the CRT screen (internally generated by an optionally available CHARACTER GENERATOR) which indicates at all times the channel number and contents of the memory location currently selected by the marker position.

(4) Integrator readout: the integral of any region of interest will be computed and displayed on the CRT screen. This occurs when the mark is within the boundaries of the selected region of interest. The integrator display consists of a set of eight digits which are shown immediately under the mark identification characters (channel number and count content).

(5) Live static: front panel toggle switch that allows the selection between LIVE display (intensification of current address) and STATIC display (intensification of two display modes are only effective while in ANALYZE).

(6) Full-scale calibrate: in calibrate position, the display controls can be set for full-scale deflection.

d. Oscilloscope (CRT) controls: related to the CRT display.
   (1) Power/graticule: controls the brightness of the linear/log graticule attached to the CRT screen.
   (2) Intensity: controls the intensity of the CRT display.
   (3) Vertical/horizontal: control the dc vertical and horizontal deflection voltages of the CRT display.
   (4) Focus: controls the sharpness of the CRT display.

C. Functional mode controls

1. Readout: activates the proper interface circuitry to the selected output device. A description of each of the readout modes is given below.
   a. Plot: the portion of the display framed by the CRT screen and within a region of interest is read out at a maximum rate of 50 addresses/second. The analog voltages generated by the X and Y DAC's are also routed to horizontal and vertical jacks located on the rear of the instrument. This, with the Point/Line rear panel switch, allows the selection of synchronous or asynchronous recorders.
   b. Type: the interface for a Teletype is activated. The contents of the locations of the selected memory group and within the region of interest will be typed out at a nominal rate of 10 characters/second. Every 10 channels the corresponding address is typed such as to permit identification of the data.
   c. Punch: enables the interface circuit card that outputs the selected data to a Paper Tape Punch at a nominal rate of 60 Hz.
   d. Transfer: the contents of the memory and address registers are connected through optionally available buffer drivers to the rear panel EXTERNAL connectors. Memory controls, analyze, stop, display, readout, erase, and busy lines are also available in these connectors. All signal levels are TTL compatible.
   e. Full spectrum/integral only/ROI: front panel toggle switch.
      (1) Full spectrum: promotes to ROI status all channels in memory (or subgroup). When in this position, all restrictions for the Readout and Preset functions derived from the existence of ROI's are eliminated.
      (2) Integral only: a subset of the "ROI's only" which further restricts the Readout function. When in this mode, ROI's will be identified by their first address and the corresponding integral readout in list form.
      (3) ROI: imposes the restrictions of ROI boundaries to all Readout and Preset functions.

2. Analysis
    a. PHA: pulse height analysis mode.
    b. MCS: multiscaler operation. Operates in conjunction with the time base which determines the dwell time in each channel. The sweep is manually started by the "ANALYZE" button or a signal in the ANALYZE INPUT BNC connector (rear panel) and once concluded, the system automatically switches to the STOP mode.
    c. MCSR: multiscaler operation as MCS but with recurrent sweeps. The system upon reaching the end of a sweep will start sweeping again. The process continues indefinitely until manually or electrically terminated.
    d. Test: all channels within the storage region will be sequentially incremented (or decremented) by one such as to verify proper functioning of the memory and control circuits. This mode is only enabled when in DISPLAY.

D. Preset controls: two rotary and one toggle switch to select and control counting period in one of three ways.
1. Preset time mode: analyzer counts for preset livetime and stops.
2. Preset counts mode: analyzer counts until it has accumulated the preset count in the tallest peak and stops.
3. Preset peak area mode: analyzer counts until it has accumulated the preset count in any selected peak or the integral of that peak.
4. BASE: OFF, X1, X2, X4, X8. The OFF position indicates that no level is preset and the analyzer will count until stopped manually.
5. MULTIPLIER: X10, X100, X1K, X10K, X100K.
6. Time base
    a. Oscillator stability: ≤0.005%/°C.
    b. Accuracy: better than 0.001% plus synchronizing error.
    c. Synchronizing error: ≤5 microseconds, noncumulative.
7. PHA mode: 1 Hz (1 second base)
8. MCS, MCSR modes: 100 KHz (10 microseconds base)
9. Modes: routes the base to the preset countdown circuits.
    a. TIME: routes the time base. The time base frequency will be stored in channel zero.
    b. ROI COUNTS: will monitor the contents of all channels in the selected storage region and in the ROI. Upon reaching in any single channel the selected preset count level, will generate a stop signal.
    c. ROI INTEGRAL: the preset stop will be generated when all integrated counts in the selected ROI reach the chosen preset count level. In this mode also, channel zero contains the time base (1 Hz) total elapsed livetime.
    d. Rear panel connectors and controls
        (1) Multichannel scaler connectors
            (a) Input: BNC input accepts logic signal to increment data register in the multiscaler mode. ≤ + 3 v to count; ≤ + 1.5 v to inhibit counting; ±25 v absolute maximum. Width 50 nsec min, no

2

max limit. Input impedance: 1K ohms dc coupled. Maximum MCS input frequency: 10M Hz; Channel dead time: 5 μsec.

(b) Channel advance output: provides an output pulse on BNC connector when the time base increments the memory address register or channel advances. Nominal ≤ + 3 v, 500 nsec wide. Output impedance: ≤10 ohms dc coupled.

(c) End of sweep output: provides an output pulse on BNC connector each time the memory address register overflows or advances through the last channel of the selected storage region. Nominal ≤ + 3 v, 500 nsec wide, output impedance: ≤10 ohms dc coupled.

(2) Controls

(a) Run in (analyze): accepts a positive logic pulse on BNC connector to set the analyzer to the RUN mode. The particular functional mode is determined by the front panel ANALYSIS switch. ≤ + 3 v for logic set, ≤ + 1.5 v to inhibit, ±25 v absolute maximum. Rise and decay times ≤100 μsec, output impedance ≥1,000 ohms dc coupled.

(b) CRT in (display): accepts a positive logic pulse on BNC connector to set the analyzer to the DISPLAY (or CRT) mode. ≤ + 3 v for logic set, ≤ + 1.5 v to inhibit, ±25 v absolute maximum. Width 500 nsec min, no max limit. Rise and decay times ≤100 μsec, output impedance ≥1,000 ohms dc coupled.

(c) I/O in (readout): accepts a positive logic pulse on BNC connector to set the analyzer to the Readout (or I/O) mode. The particular output device is selected by the front panel READOUT switch. ≥ + 3 v to set, ≤ + 1.5 v to inhibit, ±25 v absolute maximum. Width 500 nsec min, no max limit. Rise and decay times ≤100 μsec. Output impedance ≥1,000 ohms dc coupled.

(d) Memory erase: accepts a positive logic pulse on BNC connector to erase the contents of the memory or selected subgroup. For this function to be operational, the analyzer must be in the DISPLAY mode. (Note: A single 500 nsec wide erase pulse can be simultaneously connected to both the CRT IN and MEMORY ERASE BNC connectors. This will set the analyzer in the display mode and thence erase the memory). ≥ + 3 v to set, ≤ + 1.5 v to inhibit, ±25 v absolute max. Width 500 nsec min, no max limit. Rise and decay times ≤100 μsec. Output impedance ≥1,000 ohms dc coupled.

(3) Time base
   (a) Internal-external: two position switch to select the internal time base or an externally supplied time base.
   (b) Input: BNC connector accepts input for use as time base.
(4) Ancillary connectors
   (a) Region of interest out: output pulse on BNC connector for each event stored within any region of interest (ROI).
   (b) ADC busy out: output dc level on BNC connector to indicate duration of ADC conversion time.
   (c) End of I/O out: provides an output pulse upon completion of the readout cycle as selected by the front panel READOUT switch. Nominal $\geq$ + 3 v, 500 nsec wide. Output impedance $\leq$10 ohms dc coupled.
(5) Interface connectors
   (a) Tape: this connector is wired for the Paper Tape Punch Interfaces. It contains all data, address, and control signals which permit interfacing and readout to this output device.

e. Optional capabilities
All options are to be supplied with interconnecting cables as required. They further take internal power and require no modification to the main frame.
(1) Memory size: the analyzer shall provide 1024 words memory full scale.
(2) Character generator: plug in circuit board containing all necessary circuitry to generate on the CRT screen the alphanumeric information corresponding to the channel number and count content of the memory location specified by the marker position control.
(3) Integrator: this optional board permits the automatic computation of the integral of any region of interest The result of this calculation is displayed as an 8-digit number in the CRT screen (CG option required) or readout to the punch.
(4) Logarithmic display: this option consists of a logarithmic converter mounted in a single pc board and activated when the front panel COUNTS FULL SCALE switch is set to LOG. Decoding Accuracy: 6 decades; integral non-linearity: $\leq$1% of full scale.
(5) Paper tape punch interface: this circuitry card incorporates all necessary driver and timing circuitry to interface with a high speed paper tape punch.
   (a) Power: All power solenoid drivers included are supplied by the main frame.
   (b) Output code: 8 level ASCII with parity.
   (c) Output rate: nominal 60 Hz.
   (d) Automatic start: circuitry is built in to automatically power up the punch motor and generate an appropriated length of tape leader.

III. INPUT SIGNAL shall accept the output signal from the biased amplifier (SP-18242-4).

IV. OUTPUT SIGNAL shall operate a high speed tape punch (SP-18242-8).

V. MAXIMUM DIMENSIONS*
   A. Width: 19 inches
   B. Depth: 18 inches
   C. Height: 9 inches

VI. INTERFACING
   A. Biased amplifier SP-18242-4
   B. Punch SP-18242-8

Specification SP-18242-8

PAPER TAPE PUNCH

I. GENERAL DESCRIPTION
This unit is a high quality, high speed paper tape punch.

II. OPERATING FEATURES
   A. Speed: variable from 0 to 60 characters per second.
   B. Standard code channels: 5, 6, 7, or 8.
   C. Code hole size: 0.072-inch diameter on standard 0.1-inch centers.
   D. Feed hole size: 0.047-inch diameter
   E. Alignment: code holes and feed holes have a common centerline.
   F. Tape accommodation: must be capable of handling standard paper, foil, and Mylar.
   G. Standard tape widths: 0.687, 0.875, 1.000 inch.
   H. Tape supply reel capacity: 1,000 feet
   I. Take-Up reels: able to handle 6 or 10-inch metal, or 7-1/2-inch plastic.
   J. Input pulse
      1. Sprocket and paper drive clutches (in parallel): 48 v dc, 110 ohms, 4.5 ± 0.5 msec (or 24 v dc, 25 ohms).
      2. Punch clutches: 48 v dc, 220 ohms, 4.5 ± 0.5 msec (or 24 v dc, 50 ohms.
   K. Drive motor: 1/20 hp
   L. Termination: to mate with analyzer (SP-18242-7).

III. OPERATING ENVIRONMENT
The unit shall perform within its specifications under any steady-state conditions within the following limits.

---

*Note: These dimensions do not include a cabinet. If the analyzer is contained in a cabinet, it must be removable and fully operable without the cabinet.

A. Input power: 105 to 125 volts ac, 60 Hz, 1 phase
B. Ambient temperature: 5 to 65°C (40 to 149°F)
C. Ambient humidity: 5 to 95% RH
D. Vibration: 1 mil p-p sinusoidal, 0 to 65 Hz

IV. EQUIPMENT
The following equipment shall be supplied with the punch.
A. 3-foot, 3-wire power cord with NEMA plug.
B. Two each 8-inch paper supply reels.
C. Four each 7-1/2-inch takeup reels.

V. INTERFACING
Analyzer SP-18242-7

VI. INSPECTIONS AND TESTS
A. Tests at Seller's Plant
The unit shall be inspected and tested to show full compliance with the specifications. Certified inspection and test results shall be furnished to and approved by the Company prior to equipment shipment.
B. Tests at Company's Plant
The Company will inspect and test the equipment after it is received. These tests will determine compliance with the specification and will be the basis for final acceptance.

Specification SP-18246

PERFORMANCE FOR A REFRIGERATED CABINET

I. GENERAL DESCRIPTION
This unit is an insulated cabinet equipped with an evaporative cooling system using liquid nitrogen as a coolant. It is intended to maintain sensitive instrumentation mounted within the cabinet at a uniform temperature in the presence of elevated ambient temperatures.

II. CONSTRUCTION
A. Inside dimensions
1. Width: 20 inches
2. Depth: 20 inches
3. Height: 20 inches
Note: The volume enclosed above shall be clear, with no structural or other intrusion permitted.
B. Wall thickness: 6 inches
C. Door
1. Opening: 20 x 20 inches, clear, perpendicular to front of cabinet.
2. Window: 20 x 20 inches, clear glass
3. Hinges: on left facing cabinet
D. Port: 1 each, 2 inches in diameter, located at bottom rear, with cover.
E. Internal ac receptacles: 2 each NEMA duplex, located at bottom rear.

F. Fan: low velocity, for internal air circulation

G. Temperature indicator: the cabinet shall be equipped with an indicator for the internal temperature, readable from the front, and accurate to 1% of the reading.

III. COOLING SYSTEM

A. Type: The cabinet shall be equipped with an evaporator type heat exchanger unit, in which the expansion of a supply gas (nitrogen) serves to cool the internal cabinet air flowing past the heat exchanger coils. The expanded nitrogen shall be exhausted to the atmosphere and not into the cabinet.

B. Design: The Company shall furnish the liquid nitrogen supply reservoir. All other parts of the cooling system, including the inlet gas line, the heat exchanger, circulating air fan, the temperature indicator and the exhaust system, shall be furnished by the Seller.

IV. PERFORMANCE

A. Temperature control: the system shall be capable of maintaining any region within the cabinet at a temperature of $25 \pm 2^{\circ}C$ ($77^{\circ}F$) over an ambient temperature range of 28 to $65^{\circ}C$ (82 to $149^{\circ}F$) with the door closed and no internal heat load.

B. Recovery time: the system shall be capable of restoring controlled internal temperature conditions within five minutes after the door is opened, the internal temperature allowed to rise $5^{\circ}C$, and the door reclosed.

C. Gas consumption: the consumption of liquid nitrogen shall not exceed 10 lb/hr.

D. Input power: 115 vac, 60 Hz, 1 phase.

V. INSPECTIONS AND TESTS

A. Tests at Seller's Plant
The equipment shall be inspected and tested to show full compliance with the specifications. Certified inspection and test results shall be furnished to and approved by the Company prior to equipment shipment.

B. Tests at Company's Plant
The Company will inspect and test the equipment after it is received. These tests will determine compliance with the specifications and will be the basis for final acceptance.

APPENDIX B

Computer Program for Calculating Instrument Response to a Cylindrical Source

APPENDIX B

COMPUTER PROGRAM FOR CALCULATING INSTRUMENT RESPONSE TO A CYLINDRICAL SOURCE*

INTRODUCTION

This report describes a computer program which calculates the response of an instrument to the uncollided gamma rays originating in a radioactive source distributed within a pipe. The main features and assumptions of this program are outlined below.

The radiation source is assumed to be isotropic and uniformly distributed within the pipe. Both the pipe and source material remove uncollided particles; the surrounding medium does not.

The detector, assumed to be a point detector, can be located an arbitrary radial distance outside the pipe. However, the detector must be at least a distance equal to the inner pipe radius from the top and bottom of the pipe. The detector response function can vary with the angle between a vector normal to the pipe (pointing toward the detector) and incoming particle direction.

In order to obtain the detector responses for many pipe configurations with a given response function, a Gaussian quadrature option is available. With this option, the angular flux is only calculated for the directions required by the quadrature. For response functions with a Gaussian shape, this option will yield a very accurate integral response with few flux calculations. The Gaussian quadrature parameters can be input or calculated by the program. A trapezoidal integration option is also included.

THEORY

DEFINITIONS

Consider two concentric, infinite cylinders along the z-axis with a detector on the y-axis:

Define the following quantities:

a = distance from the center of the cylinders to the detector, cm;

R_1 = radius of the inner cylinder, cm;

---

*Prepared by T. J. Hoffman and L. M. Petrie, Mathematics Division, Oak Ridge National Laboratory.

R_2 = radius of the outer cylinder, cm;

Θ = polar angle about the detector (this is the independent variable for the response function), radians;

ϕ = aximuthal angle (in x-z plane), radians;

Σ_1 = total cross section (linear absorption coefficient) for material inside inner cylinder, cm^{-1};

Σ_2 = total cross section for material between cylinders, cm^{-1};

S = volumetric, isotropic source inside the inner cylinder, particles $-cm^{-3}-sec^{-1}$;

r = distance from detector to a point inside the inner cylinder along ray (Θ,ϕ), cm;

$d\bar{r}$ = differential volume at point (r,Θ,ϕ) in the inner cylinder, cm^3;

$= r^2 \sin \Theta dr d\Theta d\phi$

$\beta(r,\Theta,\phi,a)$ = mean free paths (optical thickness) between point (r,Θ,ϕ) and detector, dimensionless;

$d\bar{\Omega}$ = differential solid angle, steradians;

$\Phi_a(r,\Theta,\phi)d\bar{\Omega}$ = uncollided angular flux at the detector in solid angle $d\bar{\Omega}$, $\sin \Theta d\Theta d\phi$, due to source particles in $d\bar{r}$, track-length (cm) $-cm^{-3}-sec^{-1}$;

$= \frac{S d\bar{r}}{4\pi r^2} e^{-\beta(r,\Theta,\phi,a)}$

$F(\Theta)$ = detector response function, response-tracklength^{-1}; and

λ = detector response.

DERIVATION OF EQUATIONS

The problem is to calculate the detector response due to the uncollided source particles. The response function, $F(\Theta)$, is assumed to decrease rapidly enough with Θ that angles greater than $\Theta = \tan^{-1}(R_1/a)$ can be neglected.

The tracklength in the solid angle, $\sin \Theta d\Theta d\phi$, at the detector is

$$\Phi_a(\Theta,\phi)\sin\Theta d\Theta d\phi = \int_{r = d_2(\Theta,\phi)}^{d_3(\Theta,\phi)} \Phi_a(r,\Theta,\phi)d\bar{r} \qquad \text{(B-1)}$$

where

$d_2(\Theta,\phi)$ = distance from detector along ray (Θ,ϕ) to first intersection with inner cylinder, and

$d_3(\Theta,\phi)$ = distance from detector along ray (Θ,ϕ) to second intersection with inner cylinder.

Therefore,

$$\Phi_a(\Theta,\phi)\sin\Theta d\Theta d\phi = \frac{S}{4\pi}\int_{r\,=\,d_2(\Theta,\phi)}^{d_3(\Theta,\phi)} \sin\Theta d\Theta d\phi dr e^{-\beta(r,\Theta,\phi,a)} \quad \text{(B-2)}$$

$$\Phi_a(\Theta,\phi) = \frac{S}{4\pi}\int_{d_2(\Theta,\phi)}^{d_3(\Theta,\phi)} e^{-\beta(r,\Theta,\phi,a)}dr, \quad \text{(B-3)}$$

$$= \frac{S}{4\pi}\int_{d_2(\Theta,\phi)}^{d_3(\Theta,\phi)} e^{-\Sigma_1[r-d_2(\Theta,\phi)]}\; e^{-\Sigma_2[d_2(\Theta,\phi)-d_1(\Theta,\phi)]}dr, \quad \text{(B-4)}$$

where

$d_1(\Theta,\phi)$ = distance from the detector along ray (Θ,ϕ) to the first intersection with the outer cylinder.

Upon integration of equation (B-4),

$$\Phi_a(\Theta,\phi) = \frac{S}{4\pi\Sigma_1} e^{-\Sigma_2 d_{21}(\Theta,\phi)} [1 - e^{-\Sigma_1 d_{32}(\Theta,\phi)}], \quad \text{(B-5)}$$

where

$$d_{21}(\Theta,\phi) = d_2(\Theta,\phi) - d_1(\Theta,\phi), \text{ and}$$

$$d_{32}(\Theta,\phi) = d_3(\Theta,\phi) - d_2(\Theta,\phi).$$

The detector response is

$$\lambda = \int d\bar{\Omega}\; F(\Theta)\; \Phi_a(\Theta,\phi), \quad \text{(B-6)}$$

$$\simeq \int_0^{\tan^{-1}(R_1/a)} d\Theta F(\Theta) \sin\Theta \int_0^{2\pi} d\phi \; \Phi_a(\Theta,\phi), \qquad \text{(B-7)}$$

$$= \int_{\mu_{min}}^{1} \Phi_a(\mu) \; F(\mu) \; d\mu \qquad \text{(B-8)}$$

where

$\mu = \cos\Theta$,

$\mu_{min} = a/\sqrt{a^2 + R_1^2}$, and

$$\Phi_a(\mu)d\mu = -\int_0^{2\pi} d\phi\Phi_a(\Theta,\phi)\sin\Theta d\Theta = -4\int_0^{\pi/2} d\phi\Phi_a(\Theta,\phi)\sin\Theta d\Theta. \qquad \text{(B-9)}$$

The last equality in equation B-9 is due to the symmetry of the cylinder.

To obtain $\Phi_a(\mu)$, it is necessary to integrate equation B-5 over the azimuthal angle ϕ. In order to perform this integration, it is necessary to obtain expressions for $d_{21}(\Theta,\phi)$ and $d_{32}(\Theta,\phi)$. Therefore, consider a unit vector, $\hat{\Omega}$ which points from the detector along the ray (Θ,ϕ) to a point (x, y, z) of the cylinder.

$$\hat{\Omega} = \sin\Theta\cos\phi i - \cos\Theta j + \sin\Theta\sin\phi k, \qquad \text{(B-10)}$$

$$= \frac{1}{d(\Theta,\phi)} [xi + (y - a) j + zk]$$

where

i, j, k are unit vectors along the x, y, z axes respectively,

$d(\Theta,\phi)$ is the distance from the detector to point x, y, z.

From equation B-10 it is apparent that

$$x = \sin\Theta\cos\phi \; d(\Theta,\phi),$$

$$y = a - \cos\Theta \; d(\Theta,\phi), \text{ and} \qquad \text{(B-11)}$$

$$z = \sin\Theta\sin\phi \; d(\Theta,\phi).$$

Solving equations B-11 into the equation for a cylinder, $x^2 + y^2 = R^2$, and solving for $d(\Theta,\phi)$

$$d(\Theta,\phi) = \frac{a \cos\Theta \pm \sqrt{a^2\cos^2\Theta - (a^2 - R^2)(\sin^2\Theta\cos^2\phi + \cos^2\Theta)}}{\sin^2\Theta\cos^2\phi + \cos^2\Theta} \quad \text{(B-12)}$$

Therefore, the desired distances are

$$d_{21}(\Theta,\phi) = g(R_2,\Theta,\phi) - g(R_1,\Theta,\phi), \quad \text{(B-13)}$$

$$d_{32}(\Theta,\phi) = 2\, g(R_1,\Theta,\phi), \quad \text{(B-14)}$$

where

$$g(R,\Theta,\phi) = \frac{\sqrt{R^2\cos^2\Theta + (R^2 - a^2)\sin^2\Theta\cos^2\phi}}{\sin^2\Theta\cos^2\phi + \cos^2\Theta} \quad \text{(B-15)}$$

PROGRAM DESCRIPTION (FLOW CHARTS)

A general flow chart of the program is shown in figure B-1. More detailed flow charts of the various calculations are shown in figures B-2, B-3, and B-4.

The Gaussian quadrature routines used in this program, figure B-2, were taken from MORSE.*

PROGRAM CHECKOUT

ANGULAR FLUX CHECK

A problem, illustrated in figure B-5, was run to check out the program. The program was altered slightly to output $\Phi_a(\mu)$ - (see equation B-9). The results are plotted in figure B-5.

The same problem was run with the discrete ordinates code, ANISN.** The ANISN results along with an analytic value of $\Phi_a(\mu)$ for $\Theta = 0$ are also plotted in figure B-5.

---

*Straker, E. A., Stevens, P. N., Irving, D. C., and Cain, V. R. *The MORSE Code - A Multigroup Neutron and Gamma-Ray Monte Carlo Transport Code*, Union Carbide Corporation, Nuclear Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee, 1970 (ORNL-4585). UNCLASSIFIED.

**Engle, W. W., Jr., *A User's Manual for ANISN, A One-Dimensional Discrete Ordinates Transport Code with Anisotropic Scattering*, Union Carbide Corporation, Nuclear Division, Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee, 1967 (K-1693). UNCLASSIFIED.

DWG. NO. G-73-328
(U)

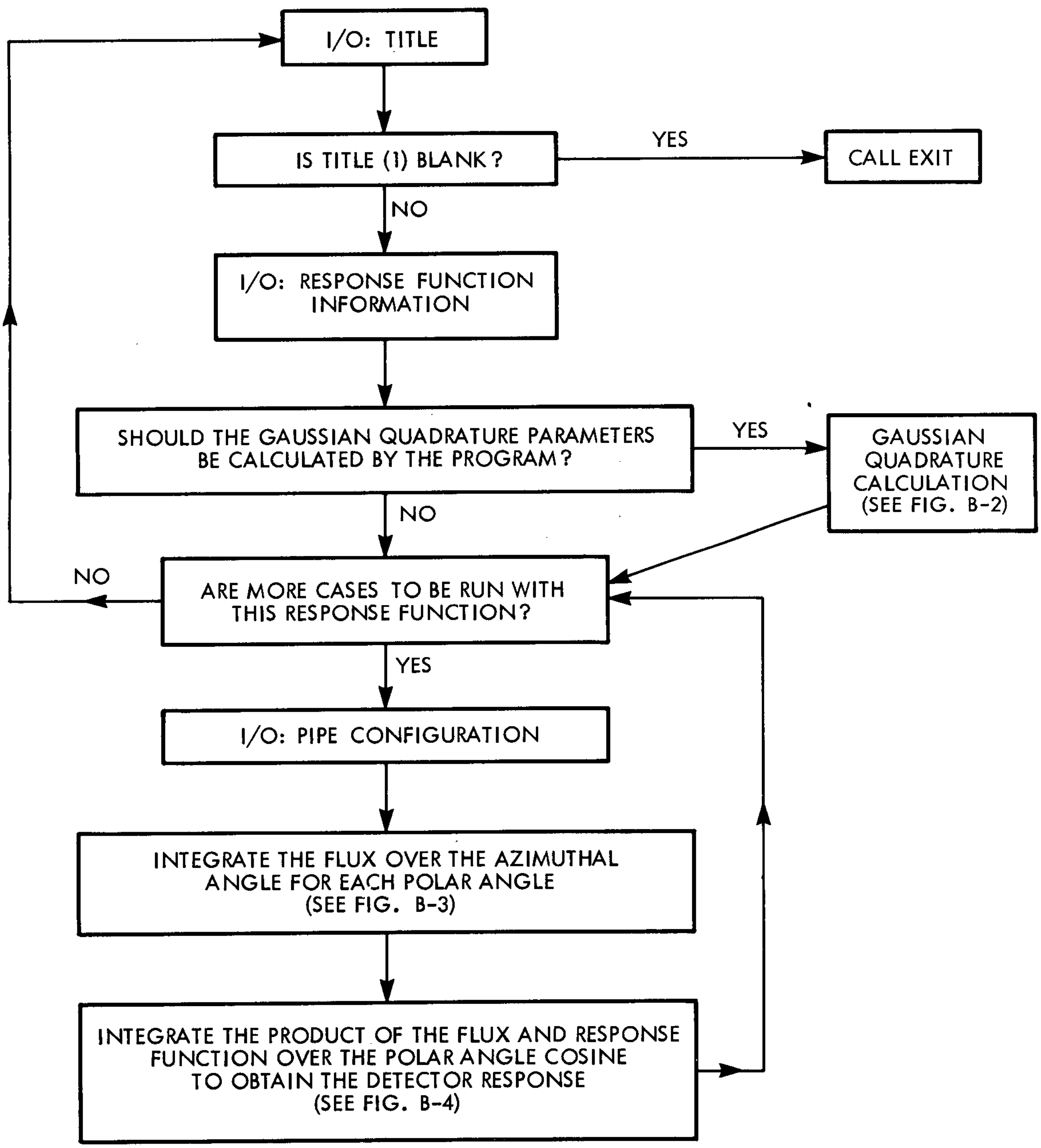


Figure B-1

OVERALL FLOW CHART

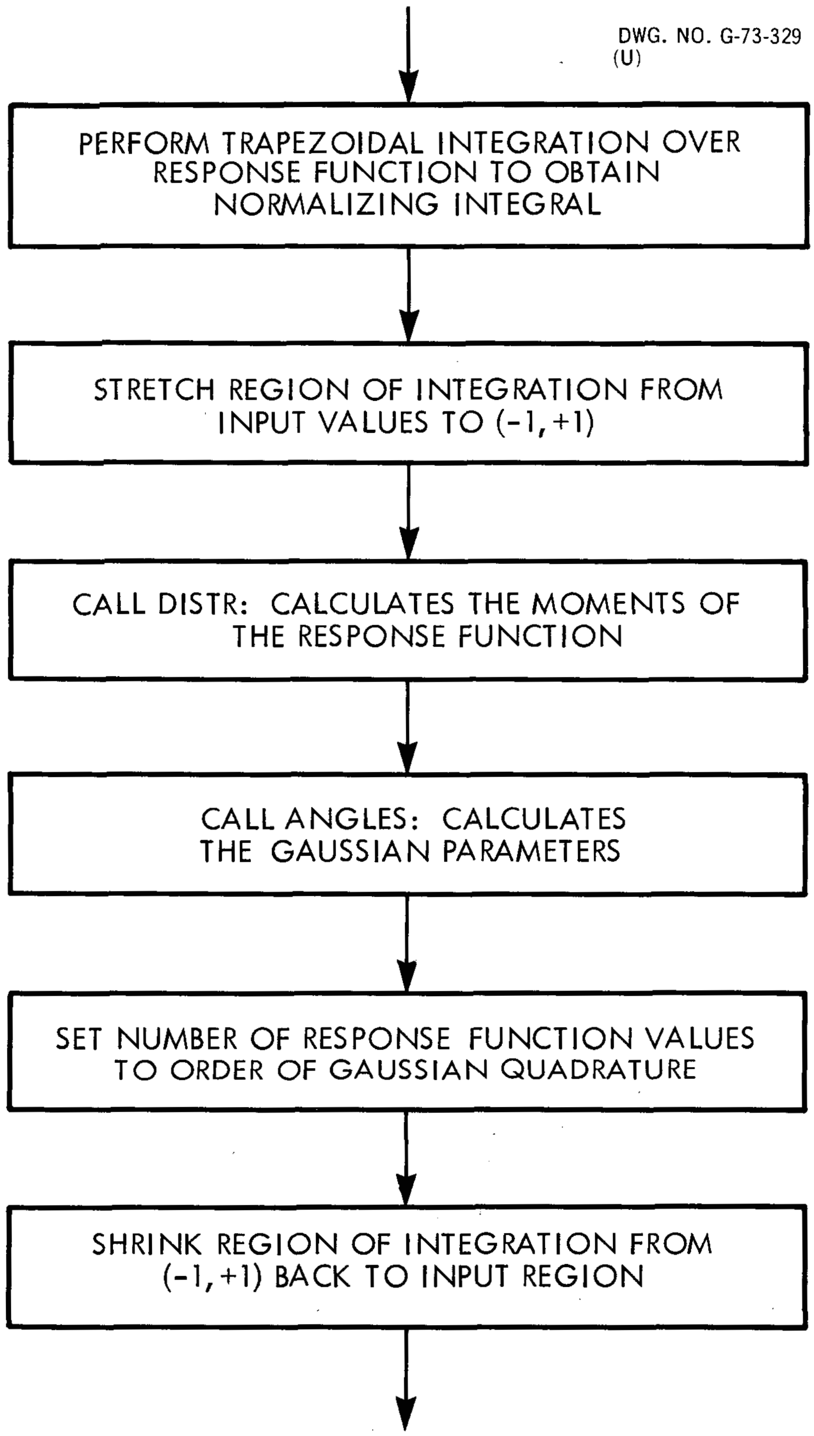


Figure B-2

GAUSSIAN QUADRATURE CALCULATION

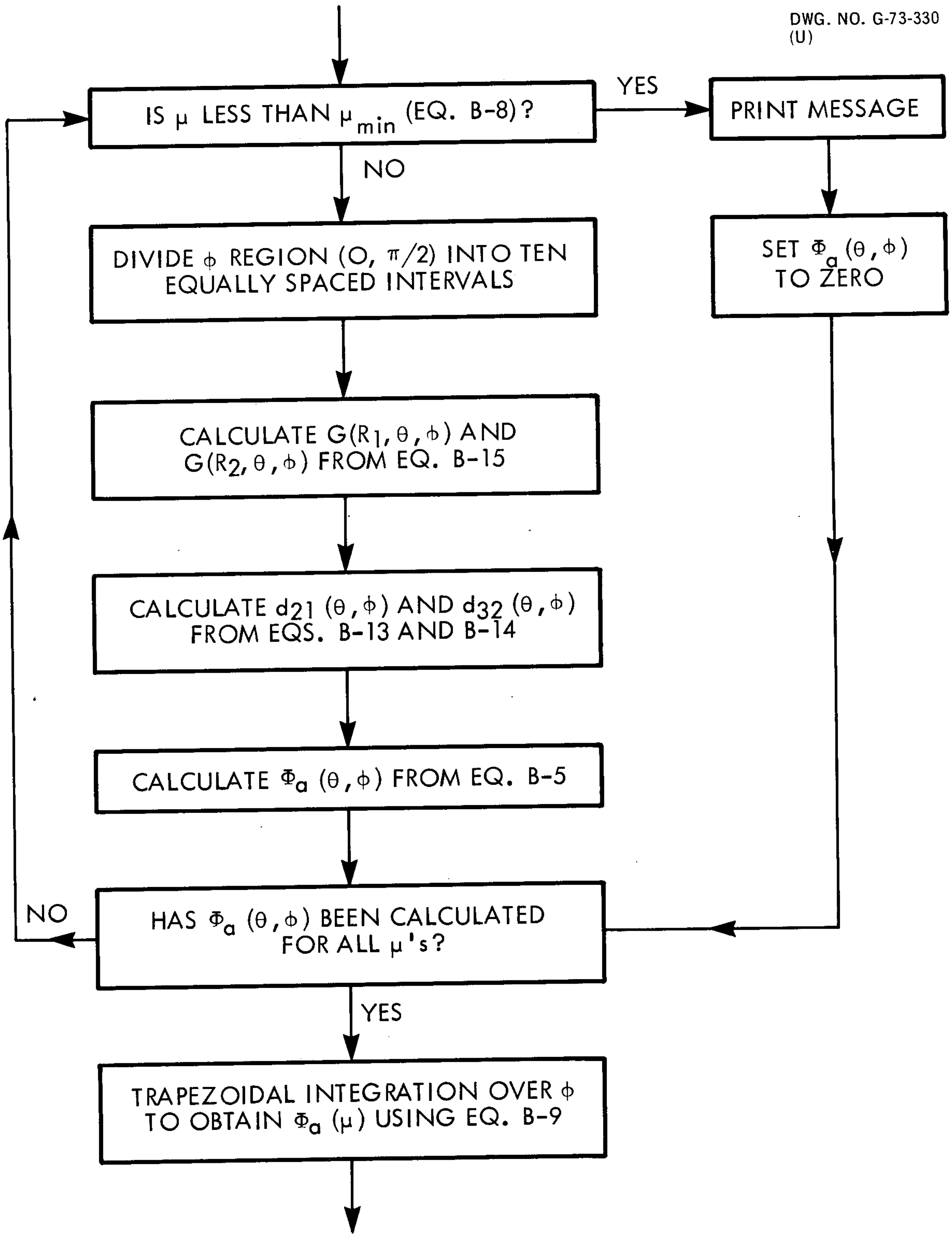


Figure B-3

AZIMUTHAL INTEGRATION OF THE FLUX

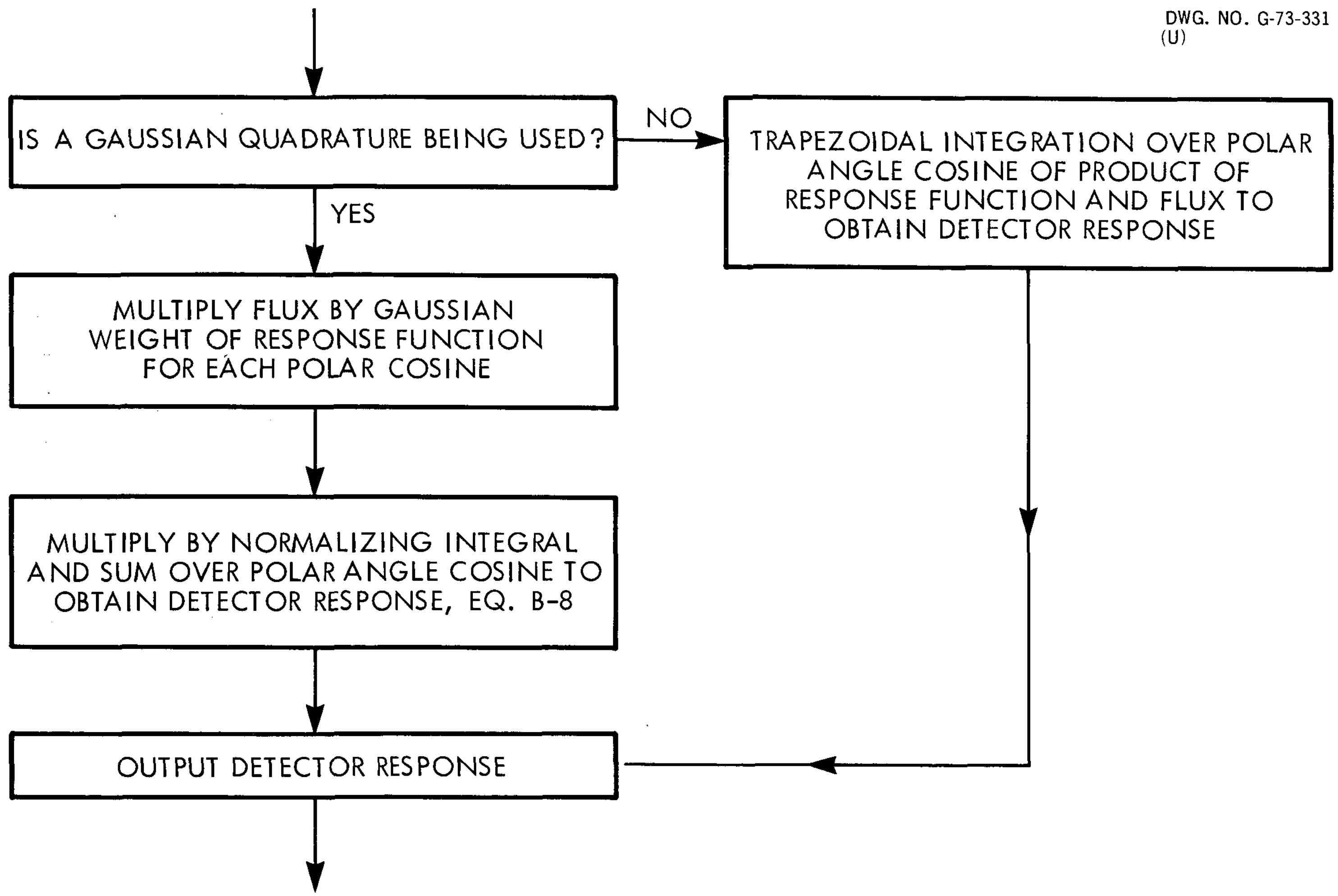


Figure B-4

INTEGRATION OF FLUX OVER RESPONSE FUNCTION

DWG. NO. G-73-326
(U)

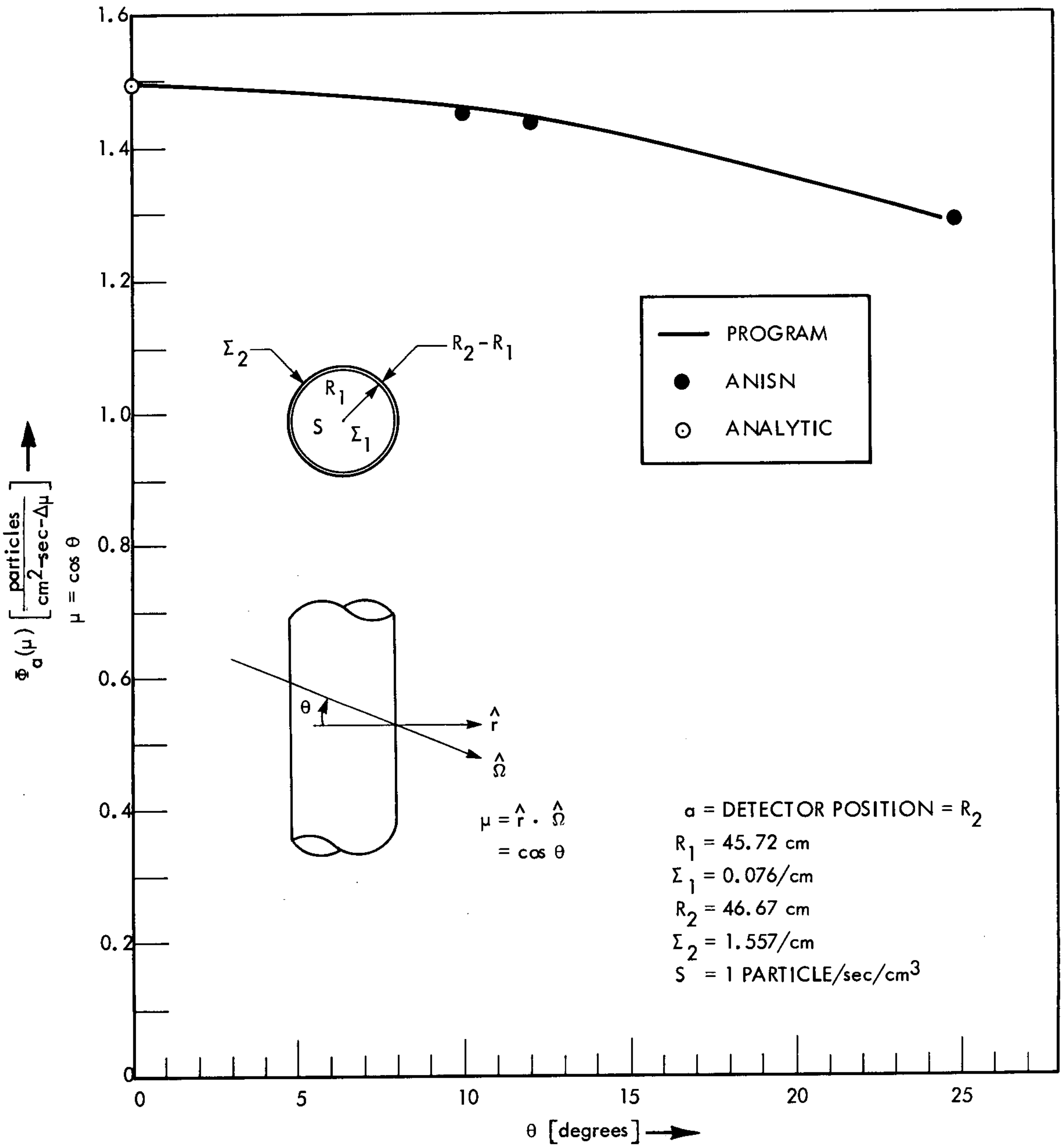


Figure B-5

CHECKOUT AND SAMPLE PROBLEM

GAUSSIAN QUADRATURE CHECK

The problem illustrated in figure B-5 was run with two detector response functions (flat and normal about $\Theta = 0$). For each response function, two methods of integration over the polar angle (Gaussian and trapezoidal) were used. The results are shown in table B-1.

The number of polar angles in the Gaussian integration is the order of the quadrature. The number of polar angles in the trapezoidal integration is the number of response function values input. For each polar angle, the flux was evaluated at ten azimuthal angles.* Therefore, the results of table B-1 not only serve as a check of the Gaussian integration, but also illustrate that accurate detector responses can be obtained with a significant reduction in flux calculations by using a Gaussian integration.

Table B-1

GAUSSIAN QUADRATURE CHECK

Flat Detector Response Function

Method	Flux Calculations	Response
Trapezoidal	230	0.27329
Gaussian	80	0.27329
Gaussian	60	0.27329
Gaussian	40	0.27329

Normal Detector Response Function

Method	Flux Calculations	Response
Trapezoidal	230	0.064421
Gaussian	80	0.064407
Gaussian	60	0.064406
Gaussian	40	0.064407

*The flux variation over the azimuthal range (0 to $\pi/2$) was well represented with ten points for this problem. For other problems, the adequacy of ten points must be investigated.

INPUT INSTRUCTIONS

Card	Format	Variables	Description
A*	20A4	TITLE(20)	problem title; if TITLE(1) is blank, program terminates
B	4I5	NCASE	number of cases to be run with given response function
		NRESP	number of response function values to be input on cards C
		INTYP	type of integration over the polar angle: = 1 - Gaussian integration parameters to be input on cards C and D (with this option, NRESP becomes the order of the Gaussian quadrature) = 2 - Gaussian integration parameters to be calculated by the program = 3 - trapezoidal integration
		NCST	order of the Gaussian quadrature (only used if INTYP = 2)
C**	8E10.4	RSP(NRESP)	detector response function values - the program reads NRESP numbers
D**	8E10.4	CθSR(NRESP)	NRESP values of the cosine of the polar angle corresponding to RSP
E†	7E10.4	A	distance in centimeters from center of pipe to detector
		R1	inner pipe radius in centimeters
		R2	outer pipe radius in centimeters
		SIG1	Total cross section of source material (cm^{-1})
		SIG2	total cross section of pipe material (cm^{-1})
		S	source strength (particle/cm^3/sec)
		DETNθR	detector normalization (only used if INTYP = 1)

*Multiple runs can be made by stacking cards A - E.

**(NRESP/8 + 1) cards needed.

†NCASE cards needed.

SAMPLE PROBLEM

The sample problem is that illustrated in figure B-5 of Program Checkout. The response function is normally distributed about $\mu = 1$.

Figure B-6 shows the input for this problem with trapezoidal and Gaussian integration over the polar angle. The output is shown in figure B-7.

80 COLUMN ENTRY

PROGRAMMER | PROBLEM | DATE | PAGE OF

1 – 5	6 – 10	11 – 15	16 – 20	21 – 25	26 – 30	31 – 35	36 – 40	41 – 45	46 – 50	51 – 55	56 – 60	61 – 65	66 – 70	71	73 – 80
TEST PROBLEM 3 - TRAPEZOIDAL															
1	23	3													
.036		.044		.054		.066		.079		.094		.111		.	130
.150		.177		.194		.218		.242		.266		.290		.	312
.333		.352		.368		.381		.391		.397		.399			
0.78		0.79		0.80		0.81		0.82		0.83		0.84		0	.85
0.86		0.87		0.88		0.89		0.90		0.91		2.90		0	.93
0.94		0.95		0.96		0.97		0.98		0.99		1.0			
4.66	70+01	4.57	20+01	4.66	70+01	0.07	60+00	1.55	70+00	1.00	00+00				
TEST PROBLEM 3 - GAUSSIAN															
1	23	2	4												
.036		.044		.054		.066		.079		.094		.111		.	130
.150		.177		.194		.218		.242		.266		.290		.	312
.333		.352		.368		.381		.391		.397		.399			
0.78		0.79		0.80		0.81		0.82		0.83		0.84		0	.85
0.86		0.87		0.88		0.89		0.90		0.91		0.92		0	.93
0.94		0.95		0.96		0.97		0.98		0.99		1.0			
4.66	0+01	4.57	20+01	4.66	70+01	0.07	60+00	1.55	70+00	1.00	00+00				
- blank card -															

UCN-6840
(236 2-65)

Figure B-6

SAMPLE PROBLEM INPUT

```
TEST PROBLEM 3 - TRAPEZOIDAL
CASES TO BE RUN                                      1
VALUES OF RESPONSE FUNCTION TO BE INPUT             23
TRAPEZOIDAL INTEGRATION
      COSINE              RESPONSE FUNCTION
     0.78000E 00            0.36000E-01
     0.79000E 00            0.44000E-01
     0.80000E 00            0.54000E-01
     0.81000E 00            0.66000E-01
     0.82000E 00            0.79000E-01
     0.83000E 00            0.94000E-01
     0.84000E 00            0.11100E 00
     0.85000E 00            0.13000E 00
     0.86000E 00            0.15000E 00
     0.87000E 00            0.17100E 00
     0.88000E 00            0.19400E 00
     0.89000E 00            0.21800E 00
     0.90000E 00            0.24200E 00
     0.91000E 00            0.26600E 00
     0.92000E 00            0.29000E 00
     0.93000E 00            0.31200E 00
     0.94000E 00            0.33300E 00
     0.95000E 00            0.35200E 00
     0.96000E 00            0.36800E 00
     0.97000E 00            0.38100E 00
     0.98000E 00            0.39100E 00
     0.99000E 00            0.39700E 00
     0.10000E 01            0.39900E 00
 A= 0.46670E 02    R1= 0.45720E 02    R2= 0.46670E 02    SIG1= 0.76000E-01    SIG2= 0.15570E 01
SOURCE= 0.10000E 01     DETECTOR NORMALIZATION= 0.48605D-01
DETECTOR RESPONSE= 0.64421E-01
```

Figure B-7

SAMPLE PROBLEM OUTPUT

TEST PROBLEM 3 - GAUSSIAN
CASES TO BE RUN 1
VALUES OF RESPONSE FUNCTION TO BE INPUT 23
GAUSSIAN INTEGRATION - - 4 WEIGHTS AND COSINES TO BE CALCULATED BY PROGRAM

COSINE	RESPONSE FUNCTION
0.78000E 00	0.36000E-01
0.79000E 00	0.44000E-01
0.80000E 00	0.54000E-01
0.81000E 00	0.66000E-01
0.82000E 00	0.79000E-01
0.83000E 00	0.94000E-01
0.84000E 00	0.11100E 00
0.85000E 00	0.13000E 00
0.86000E 00	0.15000E 00
0.87000E 00	0.17100E 00
0.88000E 00	0.19400E 00
0.89000E 00	0.21800E 00
0.90000E 00	0.24200E 00
0.91000E 00	0.26600E 00
0.92000E 00	0.29000E 00
0.93000E 00	0.31200E 00
0.94000E 00	0.33300E 00
0.95000E 00	0.35200E 00
0.96000E 00	0.36800E 00
0.97000E 00	0.38100E 00
0.98000E 00	0.39100E 00
0.99000E 00	0.39700E 00
0.10000E 01	0.39900E 00

1	0.14121D 00	0.44186D 00
2	0.14768D 00	0.44186D 00
3	0.81071D-01	0.44186D 00
4	0.88423D-01	0.44186D 00
5	0.56497D-01	0.44186D 00
6	0.63022D-01	0.44186D 00

INTERMEDIATE RESULTS OF MEANS CALCULATION

MEAN	VARIANCE	NORMALIZATION	L	Q
3.19571D-01	2.32093D-01	2.32093D-01	3.19571D-01	3.19571D-01
1.07684D-02	2.71814D-01	6.30860D-02	7.66694D-02	3.30339D-01
-1.64263D-02	2.61574D-01	1.65017D-02	1.98035D-02	3.13913D-01

COEFFICIENTS OF ORTHOGONAL POLYNOMIALS

ORDER	COEFFICIENTS			
1	-3.19571D-01	1.00000D 00		
2	-2.28652D-01	-3.30339D-01	1.00000D 00	
3	8.31078D-02	-5.05891D-01	-3.13913D-01	1.00000D 00

MOMENTS
3.19571D-01 3.34218D-01 1.83476D-01 2.00115D-01 1.27861D-01 1.42627D-01

NUMBER OF MOMENTS ACCEPTED = 7

0.80189E 00	0.59486E-01
0.86728E 00	0.24569E 00
0.93659E 00	0.42245E 00
0.98654E 00	0.27237E 00

A= 0.46670E 02 R1= 0.45720E 02 R2= 0.46670E 02 SIG1= 0.76000E-01 SIG2= 0.15570E 01
SOURCE= 0.10000E 01 DETECTOR NORMALIZATION= 0.48605D-01
DETECTOR RESPONSE= 0.64407E-01

PROGRAM LISTING

The program listing is shown in figure B-8.

```
LEVEL 20.1 (AUG 71)                    OS/360  FORTRAN H                                DATE  73.080/19.21.20

          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                                    SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
                      C * * * THIS IS THE MAIN PROGRAM
  ISN 0002                  REAL*8 SUM
  ISN 0003                  REAL*8 XL,XU
  ISN 0004                  REAL*8 MEAN(14),VAR(13),NORMAL(13),MOMENT(25),F(25),ROOT(14,14)
  ISN 0005                  REAL*8 POINT(14),WEIGHT(14)
  ISN 0006                  COMMON/TAPES/MODE,IO5,IO6,IO7,NDF8,IOT,ITP2,ITP3,ITP4
  ISN 0007                  COMMON/ANGLE/F,MOMENT,MEAN,VAR,NORMAL,ROOT,POINT,WEIGHT
  ISN 0008                  COMMON/ANGLE/NMOM,NF,N,ITEST,IPRIN
  ISN 0009                  DIMENSION TITLE(20),RSP(100),COSR(100),PHI(100),FLUX(100,10)
  ISN 0010                  DATA BLANK/4H    /
                      C * * * * INPUT CARD A
  ISN 0011            100   READ(5,1000)(TITLE(I),I=1,20)
  ISN 0012            1000  FORMAT(20A4)
  ISN 0013                  IF(TITLE(1).EQ.BLANK) CALL EXIT
  ISN 0015                  WRITE(6,1010)(TITLE(I),I=1,20)
  ISN 0016            1010  FORMAT(1H1,20A4)
                      C * * * * INPUT CARD B
  ISN 0017                  READ(5,1020)NCASE,NRESP,INTYP,NCST
  ISN 0018            1020  FORMAT(4I5)
  ISN 0019                  WRITE(6,1030) NCASE
  ISN 0020            1030  FORMAT(' CASES TO BE RUN',29X,I5)
  ISN 0021                  WRITE(6,1040)NRESP
  ISN 0022            1040  FORMAT(' VALUES OF RESPONSE FUNCTION TO BE INPUT',5X,I5)
  ISN 0023                  GO TO (1,2,3),INTYP
  ISN 0024            1     WRITE(6,1050)
  ISN 0025            1050  FORMAT(' GAUSSIAN INTEGRATION - - WEIGHTS AND COSINES INPUT')
  ISN 0026                  GO TO 4
  ISN 0027            2     WRITE(6,1060) NCST
  ISN 0028            1060  FORMAT(' GAUSSIAN INTEGRATION - -',I4,' WEIGHTS AND COSINES TO BE
                           1CALCULATED BY PROGRAM')
  ISN 0029                  GO TO 4
  ISN 0030            3     WRITE(6,1070)
  ISN 0031            1070  FORMAT(' TRAPEZOIDAL INTEGRATION')
                      C * * * * INPUT CARDS C
  ISN 0032            4     READ(5,1080)(RSP(I),I=1,NRESP)
  ISN 0033            1080  FORMAT(8E10.4)
                      C * * * * INPUT CARDS D
  ISN 0034                  READ(5,1080)(COSR(I),I=1,NRESP)
  ISN 0035                  WRITE(6,1090)
  ISN 0036            1090  FORMAT(1H ,10X,'COSINE',10X,'RESPONSE FUNCTION')
  ISN 0037                  WRITE(6,1100)((COSR(I),RSP(I)),I=1,NRESP)
  ISN 0038            1100  FORMAT(7X,E12.5,10X,E12.5)
  ISN 0039                  XL=COSR(1)
  ISN 0040                  XU=COSR(NRESP)
  ISN 0041                  SUM=0.0
  ISN 0042                  NINT=NRESP-1
  ISN 0043                  DO 17 I=1,NINT
  ISN 0044            17    SUM=SUM+0.5*(COSR(I+1)-COSR(I))*(RSP(I+1)+RSP(I))
  ISN 0045                  IF(INTYP.NE.2) GO TO 6
  ISN 0047                  DO 18 I=1,NRESP
  ISN 0048            18    COSR(I)=2.0*(COSR(I)-XU)/(XU-XL)+1.0
  ISN 0049                  NMOM=2*NCST-2
  ISN 0050                  CALL DISTR(NRESP,COSR,RSP)
  ISN 0051                  CALL ANGLES(&100)
  ISN 0052                  NRESP=NCST
  ISN 0053                  DO 5 I=1,NRESP
```

Figure B-8
PROGRAM LISTING

```
ISN 0054            RSP(I)=WEIGHT(I)
ISN 0055      5     COSR(I)=0.5*(XU-XL)*POINT(I)+0.5*(XU+XL)
ISN 0056            WRITE(6,1100)((COSR(I),RSP(I)),I=1,NRESP)
ISN 0057      6     NCASE=NCASE-1
ISN 0058            IF(NCASE.LT.0) GO TO 100
                C * * * * INPUT CARD E
ISN 0060            READ(5,1110) A,R1,R2,SIG1,SIG2,S,DETNOR
ISN 0061      1110  FORMAT(7E10.4)
ISN 0062            IF(INTYP.EQ.1) SUM=DETNOR
ISN 0064            WRITE(6,1120) A,R1,R2,SIG1,SIG2
ISN 0065      1120  FORMAT('  A=',E12.5,5X,'R1=',E12.5,5X,'R2=',E12.5,5X,'SIG1=',E12.5
                   1,5X,'SIG2=',E12.5)
ISN 0066            WRITE(6,1160) S,SUM
ISN 0067      1160  FORMAT(' SOURCE=',E12.5,5X,'DETECTOR NORMALIZATION=',E12.5)
ISN 0068            CSTHMX=A/SQRT(A*A+R1*R1)
ISN 0069            DO 15 I=1,NRESP
ISN 0070            IF(COSR(I).LT.CSTHMX) GO TO 14
ISN 0072            TH=ARCOS(COSR(I))
ISN 0073            DO 7 J=1,10
ISN 0074            PH=(J-1)*3.14159/18.0
ISN 0075            S2C2=(SIN(TH)*COS(PH))**2+COS(TH)*COS(TH)
ISN 0076            GR1=SQRT(R1*R1*S2C2-(A*SIN(TH)*COS(PH))**2)/S2C2
ISN 0077            GR2=SQRT(R2*R2*S2C2-(A*SIN(TH)*COS(PH))**2)/S2C2
ISN 0078            D21=GR2-GR1
ISN 0079            D32=2.0*GR1
ISN 0080      7     FLUX(I,J)=S*EXP(-SIG2*D21)*(1.0-EXP(-SIG1*D32))/(4.0*3.14159*SIG1)
ISN 0081            GO TO 15
ISN 0082      14    WRITE(6,1130) I,COSR(I)
ISN 0083      1130  FORMAT(' COSR(',I2,') = ',F9.4,' IS OUTSIDE THE RANGE OF VALIDITY
                   *OF THE EQUATIONS')
ISN 0084            DO 16 J=1,10
ISN 0085      16    FLUX(I,J)=0.0
ISN 0086            WRITE(6,1140) CSTHMX
ISN 0087      1140  FORMAT(' THE EQUATIONS ARE VALID FROM COS=',F7.3,' TO 1.000 - - TH
                   *E CORRESPONDING FLUX HAS BEEN SET TO ZERO')
ISN 0088      15    CONTINUE
ISN 0089            DO 9 I=1,NRESP
ISN 0090            PHI(I)=(FLUX(I,1)+FLUX(I,10))/2.0
ISN 0091            DO 8 J=2,9
ISN 0092      8     PHI(I)=PHI(I)+FLUX(I,J)
ISN 0093      9     PHI(I)=4.0*PHI(I)*(3.14159/2.0)/9.0
ISN 0094            ETA=0.0
ISN 0095            IF(INTYP.EQ.3) GO TO 11
ISN 0097            DO 10 I=1,NRESP
ISN 0098      10    ETA=ETA+SUM*PHI(I)*RSP(I)
ISN 0099            GO TO 13
ISN 0100      11    NRSRM1=NRESP-1
ISN 0101            DO 12 I=1,NRSPM1
ISN 0102      12    ETA=ETA+(PHI(I+1)*RSP(I+1)+PHI(I)*RSP(I))*(COSR(I+1)-COSR(I))/2.0
ISN 0103      13    WRITE(6,1150) ETA
ISN 0104      1150  FORMAT(' DETECTOR RESPONSE=',E12.5)
ISN 0105            GO TO 6
ISN 0106            END
```

```
           COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                               SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
  ISN 0002               SUBROUTINE DISTR ( NDATA,ANGLE,SIG )
                C        OBTAINS MOMENTS OF DISTRIBUTION BY INTEGRATION
                C        DISTR TAKES ANGLES WITH ARBITRARY SPACING AND
                C        ARBITRARY ORDER.  HOWEVER +1 AND -1 MUST BE
                C        INCLUDED AMONG THE ANGLES
  ISN 0003               COMMON /ANGLE/  F,MOMENT,MEAN,VAR,NORMAL,ROOT,POINT,WEIGHT
  ISN 0004               COMMON /ANGLE/  NMOM,NF,N,ITEST,IPRIN
  ISN 0005               REAL*8 A,B,PA,PAI,PB,PBI,FMP,FM,DELT
  ISN 0006               REAL*8 MEAN(14),VAR(13),NORMAL(13),MOMENT(25),F(25),ROOT(14,14)
  ISN 0007               REAL*8 POINT(14),WEIGHT(14)
  ISN 0008               REAL*8 SUM
  ISN 0009               DIMENSION ANGLE(NDATA),SIG(NDATA)
                C        REARRANGE ANGLES IN INCREASING ORDER
  ISN 0010               DO 20 I=1,NDATA
  ISN 0011               SMALL=ANGLE(I)
  ISN 0012               JSAVE = I
  ISN 0013               DO 10 J=I,NDATA
  ISN 0014               IF ( SMALL.LE.ANGLE(J) ) GO TO 10
  ISN 0016               JSAVE=J
  ISN 0017               SMALL = ANGLE(J)
  ISN 0018            10 CONTINUE
  ISN 0019               ANGLE(JSAVE)=ANGLE(I)
  ISN 0020               ANGLE(I)=SMALL
  ISN 0021               SIGAV = SIG(I)
  ISN 0022               SIG(I)=SIG(JSAVE)
  ISN 0023               SIG(JSAVE) = SIGAV
  ISN 0024            20 CONTINUE
  ISN 0025               DO 30 M=1,NMOM
  ISN 0026               MOMENT(M) = 0.0
  ISN 0027            30 CONTINUE
  ISN 0028               SUM = 0.0
  ISN 0029               NINT = NDATA - 1
  ISN 0030               DO 40 I=1,NINT
  ISN 0031               DELT = ANGLE(I+1) - ANGLE(I)
  ISN 0032               IF ( DELT.EQ.0.0 ) GO TO 40
  ISN 0034               A = ( SIG(I+1) - SIG(I) ) /DELT
  ISN 0035               B = ( SIG(I)*ANGLE(I+1) - SIG(I+1)*ANGLE(I) )/DELT
  ISN 0036               SUM = SUM + 0.5*DELT*( SIG(I+1) + SIG(I) )
  ISN 0037               PA = ANGLE(I)**2
  ISN 0038               PAI = ANGLE(I+1)**2
  ISN 0039               DO 40 M=1,NMOM
  ISN 0040               PB = PA
  ISN 0041               PBI = PAI
  ISN 0042               PA = PA*ANGLE(I)
  ISN 0043               PAI = PAI*ANGLE(I+1)
  ISN 0044               FMP = M + 2
  ISN 0045               FM = M + 1
  ISN 0046               MOMENT(M) = MOMENT(M) + A*( PAI - PA )/FMP + B*( PBI - PB )/FM
  ISN 0047            40 CONTINUE
  ISN 0048               DO 50 M=1,NMOM
  ISN 0049               WRITE(6,1000) M,MOMENT(M),SUM
  ISN 0050          1000 FORMAT(1H ,I5,2E12.5)
  ISN 0051               MOMENT(M) = MOMENT(M)/SUM
  ISN 0052            50 CONTINUE
  ISN 0053               RETURN
  ISN 0054               END
```

```
      COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                        SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
 ISN 0002              SUBROUTINE ANGLES (*)
 ISN 0003              REAL*8 MEAN(14),VAR(13),NORMAL(13),MOMENT(25),F(25),ROOT(14,14)
 ISN 0004              REAL*8 POINT(14),WEIGHT(14)
 ISN 0005              COMMON/TAPES/MODE,IO5,IO6,IO7,NDFR,IOT,ITP2,ITP3,ITP4
 ISN 0006              COMMON /ANGLE/  F,MOMENT,MEAN,VAR,NORMAL,ROOT,POINT,WEIGHT
 ISN 0007              COMMON /ANGLE/  NMOM,NF,N,ITEST,IPRIN
 ISN 0008              EQUIVALENCE (MUT(1),ROOT(1,1)),(MUL(1),ROOT(1,2))
 ISN 0009              EQUIVALENCE (SIG(1),ROOT(1,3))
 ISN 0010              REAL*8 TWO/2.0/,MUT(14),MUL(14),SIG(14)
 ISN 0011              REAL*8 Q,SUM,PO/1.0/,MO/-1.0/
 ISN 0012              IPRIN=1
 ISN 0013              IO6=6
 ISN 0014              CALL GETMUS
 ISN 0015              IFLAG = 0
 ISN 0016              NSCT = NMOM/2 + 1
 ISN 0017              NTST = N + 1
 ISN 0018              NN = NSCT - 1
 ISN 0019              NP1 = NSCT
 ISN 0020              DO 10 K=1,14
 ISN 0021              WEIGHT(K) = 0.0
 ISN 0022              POINT(K) = 0.0
 ISN 0023        10    CONTINUE
 ISN 0024              ROOT(1,1) = MEAN(1)
 ISN 0025              IF ( ITEST.EQ.0 )
                      *MEAN(NTST) = -VAR(N)*(Q(N-1,PO)/Q(N,PO)+Q(N-1,MO)/Q(N,MO))/TWO
 ISN 0027              IF ( NTST.GE.NSCT ) GO TO 25
 ISN 0029        15    CONTINUE
 ISN 0030              PNORM = 0.3333333
 ISN 0031              DO 20 I=NTST,NN
 ISN 0032              RP = Q(I-1,PO)/Q(I,PO)
 ISN 0033              RM = Q(I-1,MO)/Q(I,MO)
 ISN 0034              IF ( I.GT.1 ) PNORM = NORMAL(I-1)
 ISN 0036              VAR(I) = PO/(RP-RM)
 ISN 0037              IF ( VAR(I).GT.0.25 ) VAR(I) = 0.25
 ISN 0039              NORMAL(I) = VAR(I)*PNORM
 ISN 0040              MEAN(I+1) = -VAR(I)*( RP + RM )/TWO
 ISN 0041        20    CONTINUE
 ISN 0042        25    CONTINUE
 ISN 0043              N = NN
 ISN 0044              NN = NSCT
 ISN 0045              ITEST = 0
 ISN 0046              IF ( N.LE.0 ) GO TO 50
 ISN 0048              DO 30 L=2,NN
 ISN 0049              CALL FIND ( L,&110 )
 ISN 0050        30    CONTINUE
 ISN 0051        50    CONTINUE
 ISN 0052              DO 60 K=1,NP1
 ISN 0053              POINT(K) = ROOT(K,NP1)
 ISN 0054        60    CONTINUE
 ISN 0055              DO 80 K=1,NP1
 ISN 0056              SUM = 1.0
 ISN 0057              DO 70 L=1,N
 ISN 0058              SUM = SUM + (Q(L,POINT(K)))**2/NORMAL(L)
 ISN 0059        70    CONTINUE
 ISN 0060              WEIGHT(K) = 1.0/SUM
 ISN 0061        80    CONTINUE
```

```
ISN 0062          IF ( IPRIN.EQ.0 ) RETURN
ISN 0064          NM = N + NN
ISN 0065          WRITE(IO6,600)NM
ISN 0066    600   FORMAT('0NUMBER OF MOMENTS ACCEPTED = ',I3)
ISN 0067          IF ( IPRIN.LE.1 ) RETURN
ISN 0069          DO 90 I=1,NP1
ISN 0070          RP = Q(I-1,PO)/Q(I,PO)
ISN 0071          RM = Q(I-1,MO)/Q(I,MO)
ISN 0072          MUT(I) = PO - VAR(I)*RP
ISN 0073          MUL(I) = MO - VAR(I)*RM
ISN 0074          SIG(I) = TWO/(RP-RM)
ISN 0075     90   CONTINUE
ISN 0076          WRITE(IO6,700)(I,MUT(I),MUL(I),SIG(I),I=1,NP1)
ISN 0077    700   FORMAT('0INDEX-1',18X,'MU(+1)',24X,'MU(-1)',26X,'SIG'/
                 *  (I5,5X,1P3D30.15))
ISN 0078          RETURN
ISN 0079    110   CONTINUE
ISN 0080          IF ( IFLAG.EQ.1 ) RETURN 1
ISN 0082          IFLAG = 1
ISN 0083          NTST = L - 1
ISN 0084          NN = NSCT - 1
ISN 0085          NP1 = NSCT
ISN 0086          IPRIN = 2
ISN 0087          GO TO 15
ISN 0088          END
```

```
          COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                             SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
 ISN 0002             SUBROUTINE GETMUS
 ISN 0003             COMMON/TAPES/MODE,IO5,IO6,IO7,NDFB,IOT,ITP2,ITP3,ITP4
 ISN 0004             COMMON /ANGLE/  F,MOMENT,MEAN,VAR,NORMAL,ROOT,POINT,WEIGHT
 ISN 0005             COMMON /ANGLE/  NMOM,NF,N,ITEST,IPRIN
 ISN 0006             REAL*8 MEAN(14),VAR(13),NORMAL(13),MOMENT(25),F(25),ROOT(14,14)
 ISN 0007             REAL*8 POINT(14),WEIGHT(14)
 ISN 0008             REAL*8 MU(14),SIG(13),NORM(13),L(13),Q(13),A(13,14)
 ISN 0009             EQUIVALENCE (MU(1),MEAN(1)),(SIG(1),VAR(1)),(NORM(1),NORMAL(1))
 ISN 0010             EQUIVALENCE (A(1,1),ROOT(1,1)),(L(1),POINT(1)),(Q(1),WEIGHT(1))
 ISN 0011             DO 1 I=1,13
 ISN 0012             MU(I) = 0.0
 ISN 0013             SIG(I) = 0.0
 ISN 0014             NORM(I) = 0.0
 ISN 0015             L(I) = 0.0
 ISN 0016             Q(I) = 0.0
 ISN 0017             DO 1 K =1,14
 ISN 0018             A(I,K) = 0.0
 ISN 0019        1    CONTINUE
 ISN 0020             MU(14) = 0.0
 ISN 0021             N = NMOM/2
 ISN 0022             ITEST = NMOM - 2*N
 ISN 0023             MU(1) = MOMENT(1)
 ISN 0024             Q(1) = MOMENT(1)
 ISN 0025             L(1) = MOMENT(1)
 ISN 0026             A(1,1) = -MOMENT(1)
 ISN 0027             A(1,2) = 1.0
 ISN 0028             SIG(1) = MOMENT(2) - MOMENT(1)**2
 ISN 0029             NORM(1) = SIG(1)
 ISN 0030             IF ( SIG(1).LE.0.0 ) GO TO 20
 ISN 0032             IF ( N.LE.1 ) GO TO 6
 ISN 0034             L(2) = MOMENT(3) - MOMENT(1)*MOMENT(2)
 ISN 0035             Q(2) = L(2)/NORM(1)
 ISN 0036             MU(2) = Q(2) - Q(1)
 ISN 0037             A(2,3) = 1.
 ISN 0038             A(2,2) = -Q(2)
 ISN 0039             A(2,1) = (MOMENT(1)*MOMENT(3)-MOMENT(2)**2)/SIG(1)
 ISN 0040             NORM(2) = MOMENT(4) + A(2,2)*MOMENT(3) + A(2,1)*MOMENT(2)
 ISN 0041             SIG(2) = NORM(2)/NORM(1)
 ISN 0042             IF ( SIG(2).LE.0.0 ) GO TO 21
 ISN 0044             IF ( N.LE.2 ) GO TO 6
 ISN 0046             DO 5 I=3,N
 ISN 0047             IM1 = I - 1
 ISN 0048             IP1 = I + 1
 ISN 0049             DO 2 K=1,I
 ISN 0050             L(I) = L(I) + A(IM1,K)*MOMENT(IM1+K)
 ISN 0051        2    CONTINUE
 ISN 0052             Q(I) = L(I)/NORM(IM1)
 ISN 0053             MU(I) = Q(I) - Q(IM1)
 ISN 0054             A(I,IP1) = 1.0
 ISN 0055             A(I,I) = -Q(I)
 ISN 0056             DO 3 K=2,IM1
 ISN 0057             A(I,K) = A(IM1,K-1) - MU(I)*A(IM1,K) - SIG(IM1)*A(I-2,K)
 ISN 0058        3    CONTINUE
 ISN 0059             A(I,1) = -MU(I)*A(IM1,1) - SIG(IM1)*A(I-2,1)
 ISN 0060             DO 4 K=1,IP1
 ISN 0061             NORM(I) = NORM(I) + A(I,K)*MOMENT(IM1+K)
```

```
ISN 0062     4      CONTINUE
ISN 0063            SIG(I) = NORM(I)/NORM(IM1)
ISN 0064            IF ( SIG(I).LE.0.0 ) GO TO 22
ISN 0066     5      CONTINUE
ISN 0067     6      CONTINUE
ISN 0068            IF ( ITEST.EQ.0 ) GO TO 8
ISN 0070            NP1 = N + 1
ISN 0071            DO 7 K=1,NP1
ISN 0072            L(NP1) = L(NP1) + A(N,K)*MOMENT(N+K)
ISN 0073     7      CONTINUE
ISN 0074            Q(NP1) = L(NP1)/NORM(N)
ISN 0075            MU(NP1) = Q(NP1) - Q(N)
ISN 0076     8      CONTINUE
ISN 0077            IF ( IPRIN.EQ.0 ) RETURN
ISN 0079            NP = N
ISN 0080            IF ( ITEST.NE.0 ) NP = NP + 1
ISN 0082            WRITE(I06,1001)(MU(I),SIG(I),NORM(I),L(I),Q(I),I=1,NP)
ISN 0083            WRITE(I06,1004)
ISN 0084            DO 9 I=1,N
ISN 0085            IP1 = I + 1
ISN 0086            WRITE(I06,1002)I,(A(I,K),K=1,IP1)
ISN 0087     9      CONTINUE
ISN 0088            WRITE(I06,1005) (MOMENT(I),I=1,NMOM)
ISN 0089            RETURN
ISN 0090    20      I = 1
ISN 0091            GO TO 22
ISN 0092    21      I = 2
ISN 0093    22      N = I - 1
ISN 0094            ITEST = -1
ISN 0095            WRITE(I06,1003)I,N
ISN 0096            IPRIN = 1
ISN 0097            GO TO 8
ISN 0098  1001      FORMAT('0INTERMEDIATE RESULTS OF MEANS CALCULATION'/1H0,13X,'MEAN'
                   *,19X,'VARIANCE',16X,'NORMALIZATION',12X,'L',23X,'Q'/(1P5E24.5))
ISN 0099  1002      FORMAT(I5,10X,1P7E15.5/(15X,7E15.5))
ISN 0100  1003      FORMAT('0VARIANCE(',I3,') IS NEGATIVE OR ZERO. CALCULATION WILL CO
                   *NTINUE WITH N = ',I3,' AND NO CHOSEN POINT')
ISN 0101  1004      FORMAT('0COEFFICIENTS OF ORTHOGONAL POLYNOMIALS'/' ORDER
                   * COEFFICIENTS')
ISN 0102  1005      FORMAT('0        MOMENTS'/(1X,1P10E13.5))
ISN 0103            END
```

```
         COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                          SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
ISN 0002            SUBROUTINE FIND(L,*)
ISN 0003            COMMON/TAPES/MODE,I05,I06,I07,NDFB,IOT,ITP2,ITP3,ITP4
ISN 0004            COMMON /ANGLE/  F,MOMENT,MEAN,VAR,NORMAL,ROOT,POINT,WEIGHT
ISN 0005            COMMON /ANGLE/  NMOM,NF,N,ITEST,IPRIN
ISN 0006            REAL*8 MEAN(14),VAR(13),NORMAL(13),MOMENT(25),F(25),ROOT(14,14)
ISN 0007            REAL*8 POINT(14),WEIGHT(14)
ISN 0008            REAL*8 VALUE(13),Q,QTOP,QLOW,QTRY,XUP,XLOW,XTRY
ISN 0009            LM1 = L - 1
ISN 0010            DO 1 I=1,LM1
ISN 0011            VALUE(I) = Q(L,ROOT(I,LM1))
ISN 0012      1     CONTINUE
ISN 0013            ROOT(L,LM1) = 1.0
ISN 0014            QTOP = Q(L,ROOT(L,LM1))
ISN 0015            IF( QTOP.GT.0.0 ) GO TO 2
ISN 0017            WRITE(I06,1001)L
ISN 0018   1001     FORMAT('0ROOTS OF Q(',I3,') EXTEND BEYOND +1')
ISN 0019            RETURN 1
ISN 0020      2     CONTINUE
ISN 0021            XLOW = -1.
ISN 0022            QLOW = Q(L,XLOW)
ISN 0023            IF ( QLOW*VALUE(1).LE.0.0 ) GO TO 3
ISN 0025            WRITE(I06,1002)L
ISN 0026   1002     FORMAT('0ROOTS OF Q(',I3,') EXTEND BEYOND -1')
ISN 0027            RETURN 1
ISN 0028      3     CONTINUE
ISN 0029            DO 8 K=1,L
ISN 0030            XUP = ROOT(K,LM1)
ISN 0031            DO 6 NSP=1,37
ISN 0032            XTRY = ( XLOW + XUP )*0.5
ISN 0033            QTRY = Q(L,XTRY)
ISN 0034            IF ( QTRY*QLOW.LT.0.0 ) GO TO 4
ISN 0036            IF ( QTRY*QLOW.EQ.0.0 ) GO TO 7
ISN 0038            XLOW = XTRY
ISN 0039            QLOW = QTRY
ISN 0040            GO TO 5
ISN 0041      4     CONTINUE
ISN 0042            XUP = XTRY
ISN 0043      5     CONTINUE
ISN 0044            IF ( XUP.EQ.XLOW ) GO TO 7
ISN 0046      6     CONTINUE
ISN 0047      7     CONTINUE
ISN 0048            ROOT(K,L) = XTRY
ISN 0049            XLOW = ROOT(K,LM1)
ISN 0050            QLOW = VALUE(K)
ISN 0051      8     CONTINUE
ISN 0052            ROOT(L,LM1) = 0.0
ISN 0053            RETURN
ISN 0054            END
```

```
LEVEL 20.1 (AUG 71)                    OS/360  FORTRAN H                    DATE  73.080/19.21.35

       COMPILER OPTIONS - NAME=  MAIN,OPT=02,LINECNT=60,SIZE=0000K,
                          SOURCE,EBCDIC,NOLIST,NODECK,LOAD,MAP,NOEDIT,NOID,NOXREF
  ISN 0002             REAL FUNCTION Q*8 (ND,X)
  ISN 0003             COMMON /ANGLE/  F,MOMENT,MEAN,VAR,NORMAL,ROOT,POINT,WEIGHT
  ISN 0004             COMMON /ANGLE/  NMOM,NF,N,ITEST,IPRIN
  ISN 0005             REAL*8 MEAN(14),VAR(13),NORMAL(13),MOMENT(25),F(25),ROOT(14,14)
  ISN 0006             REAL*8 POINT(14),WEIGHT(14)
  ISN 0007             REAL*8 MU(14),SIG(13),NORM(13),X,A,B,C
  ISN 0008             EQUIVALENCE (MU(1),MEAN(1)),(SIG(1),VAR(1)),(NORM(1),NORMAL(1))
  ISN 0009             A = 1
  ISN 0010             B = X - MU(1)
  ISN 0011             IF ( ND.LT.1 ) GO TO 3
  ISN 0013             IF ( ND.EQ.1 ) GO TO 2
  ISN 0015             DO 1 I=2,ND
  ISN 0016             C = ( (X - MU(I))*B ) - VAR(I-1)*A
  ISN 0017             A = B
  ISN 0018             B = C
  ISN 0019      1      CONTINUE
  ISN 0020      2      CONTINUE
  ISN 0021             Q = B
  ISN 0022             RETURN
  ISN 0023      3      CONTINUE
  ISN 0024             Q = A
  ISN 0025             RETURN
  ISN 0026             END
```

DISTRIBUTION

INTERNAL

1- 2. Administrative Offices
Stief, S. S.
Winkel, R. A.

3. Computing Technology Center
Kemper, B. J.

4. Engineering Division
Patton, F. S.

5- 6. Fabrication & Maint. Div.
Elmore, E.
Krieg, E. H., Jr.

7. Gaseous Diffusion Dev. Div.
Trammell, H. E.

8-12. Laboratory Division
Bailey, J. C.
Barton, J. C.
Langdon, A.
Napolitan, D. S.
Smith, L. A.

13-21. Library
Fraser, R. J.

22-23. Operations Analysis & LRP Div.
Lang, D. M.
Pasquier, L. P.

24. Operations Division
Legeay, A. J.

25. Shift Operations & Pollution Control
Hartman, W. C.

26. Sommerfeld, K. W.

27. Technical Director
Wilcox, W. J., Jr.

28-30. ORGDP Records Department (RC

31. Goodyear Atomic Corporation
Voss, F. S.

32-33. Paducah Plant
Hopkins, C. C.
Levin, R. W.

34-54. U.S. Atomic Energy Commission
Keller, C. A. (20)
Zachry, D. S.

55-60. Y-12 Plant
Burkhart, L. E.
Case, J. M.
Griffin, J. D.
Hibbs, R. F.
Jasny, G. R.
Vanstrum, P. R.

EXTERNAL

61-241. TID-4500