JOB SAFE PRACTICE DOCUMENT
FOR THE MIST FACILITY PHOTON DENSITOMETERS

Revision 2

April 26, 1985

I. INTRODUCTION

Photon attenuation techniques will be utilized on the Multi-Loop Integral System Test (MIST) facility to make void fraction and fluid density measurements. Photon densitometers for use on the MIST facility are being supplied to the Integral System Test (IST) Program by the United States Nuclear Regulatory Commission (NRC) as part of the IST Program cooperative arrangement. The densitometer systems are being designed and manufactured by the Idaho National Engineering Laboratory under contract with the NRC.

The measurement systems being designed for use on the MIST facility will employ thallium doped sodium iodide scintillation crystals in conjunction with photomultiplier tubes to detect the attenuation of collimated beams of photons that have passed through a medium of unknown void fraction/density. These systems will be installed at various locations on the MIST loop hot and cold leg piping in both horizontal and vertical sections. The measurement system consists of a stainless steel forging (with integral pipe stubs) that houses a low energy radioactive source on one side and a water-cooled detector cask containing the detector crystals and photomultiplier tubes on the other side. Six fully operable systems (two for the hot legs and four in the cold legs) and four systems (one in each pump suction) without detectors and electronics will be installed in MIST. Each fully operable measurement system will employ a single radioactive source for the production of photons (measurement systems without detectors and electronics will not have sources installed initially). An isotope of Americium (Am-241) will be utilized as source material for the MIST measurement systems.

Since the measurement systems addressed above utilize radioactive source material, certain procedures, safe handling guidelines, and monitoring procedures are required by the manufacturing organization (1) and the Alliance Research Center Radioisotope Committee (ARCRC) (2). It is the major purpose of this report to document the procedures and guidelines required by these organizations and to provide information required by the ARCRC to approve receipt of the measurement systems. Section II contains a brief description of the general mechanical and electronics aspects of the measurement system.

Section III describes the radioactive source and addresses the procedural requirements set forth in Reference 2. Supporting information is provided in the appendices.

II. DESCRIPTION OF THE MIST DENSITOMETER SYSTEM(S)

For completeness, a brief description of the design aspects of the MIST densitometer systems is given below. Both the mechanical and electronics features are given.

A. Mechanical Design

The mechanical design and construction of the MIST densitometer utilizes the concept of an "instrumented spool". The spool consists of a machined stainless steel (Type 304) forging with a through-bore of either 4.925 cm (1.939 in.) or 5.9 cm (2.323 in.) depending on the pipe size the particular system is designed for (see Note a), i.e., 2 in. Sch 80 or 2.5 in. Sch 80 pipe. The forging houses a radioactive source, beam collimation and window assemblies called thimbles, and a flange for mounting of a water-cooled cask containing photon detector assemblies. Integral to the forging are pipe stub lengths of the same through-bore as that in the forging. The ends of the stubs are weld-preped so that the system can be welded into the loop piping. Figure 1 presents front and side sketches of the forging showing relevant dimensions for the 2 in. and 2.5 in. Sch 80 forging.

As mentioned above, the forging houses the source used for production of photons, thimble assemblies, and a mounting flange for attaching the detector cask. Figure 2 illustrates the relative locations of the source, thimbles, and detector cask. The "thimbles" consist of a thimble-shaped piece of beryllium (Be) which is brazed to a monel cap piece. Machined stainless steel pieces are positioned inside the Be thimble/monel cap assembly to provide required collimation of the photon beam. The thimbles are held in the forging via a stainless steel/monel weld. The collimator piece on the "source side" of the forging is designed to produce two collimated beams of photons with the beam angles shown in Figures 1 and 2.

The major purpose of the thimbles in the spool design is to provide a window (Be) that is fairly transparent to low energy photons yet provides a pressure boundary with sufficient structural integrity. Beryllium is the best metal suited for this purpose in that it has a low atomic number (4) (see Note b) and possesses material tensile strength properties similar to those of zircalloy. Beryllium does not weld easily (see Note c) however, and thus must be brazed to monel which is, in turn, readily welded to stainless steel.

The detector cask shown in Figure 2 is a stainless steel water-cooling jacket housing one sodium iodide (NaI (Tl)) detector crystal, photomultiplier tube, and associated electronics (pre-amp, voltage divider, etc.) for each of the two photon beams. The cask is attached to the forging via four bolts. Insulating washers, an air space, and aluminum plates are utilized to minimize conduction and radiation heat transfer from the forging to the detector crystals (see Note d). Approximately 63 ml/s (1 gpm) of cooling water flow is required for cooling of each detector cask.

The MIST densitometer instrument spool design is such that the whole assembly can be positioned in an intended location, rotated to provide the photon beam angles desired (see Note e), and then welded in place. Figure 3 shows the beam geometry recommended for application in MIST horizontal piping sections.

B. Electronics Design

The electronics designed for use with the MIST densitometer spools is termed a "stabilized megacount" system. The electronics system is designed to operate in the so-called "pulse mode" where individual pulses from the photon detector are processed. The system is designed with stabilized, self-compensating electronics to minimize calibration and set up requirements, and to maximize stabilized measurement capability and duration without reference density checks.

Figure 4 shows a block diagram for a typical channel of electronics (see Note f). Output from the photomultiplier tube is amplified in a pre-amp so that the signal can be driven over a long distance to a baseline restorer component which does signal conditioning and ensures stability of the baseline voltage when no pulse is present. Output from the baseline restorer goes to a single channel analyzer (SCA) and to a stabilizer. The SCA provides a logic pulse to a rate meter (frequency to voltage converter) if the input pulse to the SCA falls between preset descriminator levels (the photo peak energy window). The frequency to voltage converter simply produces an output analog voltage that is proportional to the pulses per unit time output by the SCA. The block diagram in Figure 4 shows the feedback loop components that "stabilize" the system. This feedback loop automatically adjusts the bias voltage supplied to the photomultiplier tube to help account for detector sensitivity, amplifier gain, etc., dependencies on total count rate. This loop also helps the system to "lock on" to the desired photo peak or energy window when the electronics are energized.

III. RADIOACTIVE SOURCE FOR MIST DENSITOMETER SYSTEMS

The radioactive sources to be used in the MIST densitometer systems are described below. Each of the items required by the procedure given in Reference 2 is addressed.

A. Source Description

Americium-241 (Am-241) radioactive sources will be used in the MIST densitometer spool pieces to provide a source of photons. Each of the 10 measurement spools will house a single sealed source capsule. The source capsule is a welded stainless steel cylinder measuring 7mm (0.276 in.) in diameter and 10mm (0.394 in.) in length. A 5mm (0.197 in.) diameter sphere consisting of Am-241 in a ceramic matrix is contained within the sealed capsule.

As noted above, 10 such encapsulated sources will be supplied to the IST Program for use in the densitometers, normally only 6 sources will be installed in the measurement systems at any given time. Each source will be 200 (+ 50.0 - 0.0) mCi in strength. The sources will be manufactured by the Amersham Corporation (Arlington Heights, Illinois) as part number X.108. The sources were designed according to American National Standard N542 (National Bureau of Standards Handbook #126) and are Class C64444 sources. This classification number refers to the class (severity) of temperature, external pressure, impact, vibration, and puncture tests the source capsule must withstand. NBS class definitions are given in Table 1. R2

Americium decays with a half-life of about 430 years to Neptunium (Np-237) via alpha emission. Accompanying the alpha decay are emission of L X-rays and gamma-rays of Np and characteristic conversion electrons. Table 2 shows the energy levels and absolute yields of the major radiations. The 13.9-, 17.8-, and 20.8 keV lines are all "complex" and cannot be easily resolved with scintillation type detection equipment. The 26.35- and 59.5 keV energy lines are "standards" used in spectrometry. As shown in Table 2, the yield of 59.5 keV photons is much higher than that for the 26.35 keV photon. For this reason (see Note g) and also because of the greater penetration capability of the 59.5 keV photon, this energy line is used in the MIST densitometer application.

The manufacturer's rating for the 200 mCi Am-241 source capsules described is a 59.5 keV photon output of 7.E7 (70 million) photons per second per steradian. Rough calculations in Appendix A substantiate this number. Calculations shown in Appendix B indicate that the dose rate from a 250 mCi source capsule in air is 11 mr/hr at 30 cm. Using ANSI/ANS flux-to-dose rate standards (Reference 3) to compute dose rate in mrem, indicates a value of about 26 mrem/hr at 30 cm. This dose is large enough to require handling with tongs and transport of the source capsules in appropriate pigs. Once the source is installed in the spool piece, the dose rate due to electromagnetic radiation over the majority of the forging surface is expected to be small since stainless steel is an effective shield. Calculations in Appendix B indicate that with point source approximations and assuming a stainless steel thickness of 2.54 cm (1 in.), the dose rate due to electromagnetic radiation

at the spool surface is estimated to be about 2E-8 mr/hr. An exception to this value is the area directly above the source. As shown in Figure 2, the attenuation path length directly above the source consists of the back of the capsule (about 4 mm thickness) and the set screw (about 0.7 cm) holding the source in place. With this reduced path length (relative to the rest of the forging), the dose directly above the source is calculated to be as high as 0.322 mr/hr at the forging surface. A radiation survey of a hot leg spool with source installed was made during bench acceptance testing of the system (measurements were made with a Ludlum Model 14C GM counter). The maximum dose measured was at a point directly above the source (about 2.54 cm [1 inch] above the spool surface) and was 0.7 mr/hr. This dose translates to 5.1E-3 mr/hr 30 cm from the spool surface. The difference between the measured and calculated values is postulated to be partially due to secondary X-ray production in the stainless steel and Bremsstrahlung radiation.

Also shown in Appendix B are calculations comparing dose rates from the Am-241 source to more commonly used large Co-60 and Cs-137 high energy sources. In terms of dose rates, these calculations clearly illustrate the safety advantages of using the small low energy Am sources.

As indicated above, the Am-241 is in a ceramic material which contains low Z materials to limit source self-absorption as much as possible. The manufacturer indicates that an (α, n) reaction occurs between the helium nuclei produced from Am-241 decay and materials in the ceramic. According to manufacturer estimates, the resulting neutron output (stated as 1E4 n/s-Ci) produces a dose of about 1 mrem/hr at 10 cm from the capsule. Calculations in Appendix B indicate a value of 0.44 mrem/hr at 10 cm based on published Monte Carlo calculations accounting for relative biological effectiveness (RBE) of neutron radiation and multiple collision effects. These values are in reasonably good agreement.

As was mentioned in Section I, some of the densitometer systems will be installed in the MIST facility without detectors and detector casks. The current plan is to not put sources in those spools installed without detector casks. However, if sources are installed on these spools, the expected 59.5 keV photon count rates at a position where the crystal would normally be are high enough that a 0.635 cm (0.25 in.) stainless steel plate should be employed to effectively stop the photons. The plate will help avoid any inadvertant unnecessary exposure from the collimated beams. Calculations are shown in Appendix C.

In summary, the following statements can be made regarding the radiation hazards and radiotoxicity of the sources to be used in the MIST densitometer systems:

1. Ten encapsulated (sealed) 200 (+50, -0) mCi Am-241 sources will be employed in the MIST photon densitometer systems. Am-241 decays via alpha emission. Alpha emitters are hazardous if injested since particles cannot penetrate the skin and exit the body. As long as the sealed sources are not punctured, there should be no contamination problem.

2. A small neutron flux is produced by an (α, n) reaction in the ceramic matrix containing the source. Since neutrons are difficult to shield in small spaces, a neutron dose of between 0.4 and 1 mrem/hr at a distance of 10 cm from each source is to be expected.

3. As long as the sources are residing in the spool forging, the dose due to electromagnetic radiation will be small (survey measurements show 0.7 mr/hr 2.54 cm above the spool surface or 5.1E-3 mr/hr 30 cm above the spool surface.

4. Those spools not fitted with detector casks and crystals should be fitted with 0.635 cm (0.25 in.) stainless steel plates to stop the collimated photon beam (see Appendix C) if sources are installed. The current plan is to not put sources in these spools until detectors and detector casks are made available.

B. Experimental Procedures

The sources described above will be shipped to the MIST facility from the INEL in mid or late 1985. The sources will not be installed in the spool pieces until after the spools are welded into the MIST loop. The sources should not be installed until all construction work (loop piping installation, welding, guard heater installation, insulation, etc.) is completed. There are several technical and convenience reasons for this:

1. Installation of sources after the major construction work is done will minimize the possibility of damage to the sources and other densitometer equipment.

2. Installation of the sources after the major construction work is completed will minimize (or eliminate) any monitoring requirements for erection and construction personnel.

3. Once the sources and associated electronics are installed, the densitometers will be calibrated. It is desirable to eliminate (or at least minimize) perturbations to the loop after that point so as to not affect the calibration.

An outline of the procedure for accomplishing source installation is given in Table 3. INEL personnel will perform the initial installation activities and the ARC health physicist or his designate will monitor the proceedings in accordance with established ARC guidelines. R1

The sources will be shipped from the INEL to ARC in approved packaging. Generally, two source capsules will be encased in packing material and installed in a small cylindrical lead pig. The pig is then packaged in a resealable tin can. The tin cans are in turn packed in an approved appropriately marked box. Upon receipt of the box at ARC, the Radiological Safety Officer will inspect the box for damage, remove the sources from the shipping packaging, and perform initial inspection in the Radioactive Receiving Room in Building N. After inspection, the sources will be R1
repackaged and moved to a safe storage area until installation of the sources is desired.

C. Location

Initial source capsule inspection will be done in the Radioactive Receiving Room in Building N. The sources will ultimately be installed and used in the MIST facility located in Bay 20 of Building A.

D. Responsibility

The ARC Radiological Safety Officer is assigned responsibility for the control of the sources. H. R. Carter is the ARC supervisor of the project. He is responsible for personnel training. Individuals working near the densitometer systems will be made aware of the implications and potential hazards of the sources via training instruction in radiation safety. The training is provided under direction of the ARC Radioisotope Committee. The contents of the instruction are given in Section 4.0 of the ARC Radiological Safety Manual and include description of the nature, hazards and detection of radiation, discussion of radiation protection, federal require-ments, company policy, and emergency procedures. Personnel requiring this training are identified in Section E. R1 R2

Several ARC personnel will be provided additional training so that they may handle the sources. INEL personnel will perform this training during actual source installation. The ARC personnel requiring this training are also identified in Section E. R1

Per Federal Law (Reference 4), sealed radioactive sources designed to emit ionizing radiation must be checked periodically for leakage. 10CFR Part 34 Paragraph 25 of Reference 4 states that "sealed sources shall be tested for leakage at intervals not to exceed six months". Furthermore, the leak test shall be capable of detecting the presence of 0.005 microcurries of removable contamination on the sealed source. Detection of more than this amount is considered evidence that the source is leaking. The ARC Radiological Safety Officer or his designate will be responsible for conducting these tests and keeping necessary records required by the nuclear materials license. A procedure for conducting leak tests is given in Table 4.

E. Personnel

The ARC Radiological Safety Officer will perform a radiation survey following source installation. Any area where the dose rate exceeds 0.2 mr/hr will be identified as a "Restricted Area". This area will be roped off and warnings will be posted. This area will be off limits for any personnel without proper training (radiation safety training) and radiation monitoring equipment (film badge). Facility areas other than restricted areas are freely accessible. R1

The following ARC personnel will occasionally be working near the densitometer systems:

D. P. Birmingham	C. G. Koksal
D. H. Blair	A. L. Miller
J. E. Blake	T. E. Moskal
H. R. Carter	J. R. Oyster
M. T. Childerson	J. E. Paxson
R. P. Ferron	G. C. Rush
T. F. Habib	D. D. Schleappi
F. Karimi-Azad	S. D. Sproul

These individuals will receive the basic radiation safety training described in Section D. Radiation monitoring badges will be worn at all times by these individuals when in a restricted area. R2

The following ARC personnel will be trained in source handling:

M. T. Childerson
C. G. Koksal
J. E. Paxson
D. D. Schleappi

Following training by INEL personnel, they will be authorized to perform source installation and removal in accordance with ARC technical procedures approved by a Radioisotope Committee representative. A film badge, dosimeter, and ring badge is required for source handling personnel during installation or removal.

F. Disposal

The sources are the property of the USNRC. On completion of the IST project, the sources and associated densitometer systems will be shipped to the INEL for storage or disposal.

Notes:

a. The design features of the 2" Sch 80 and the 2.5" Sch 80 system are the same in principal although there are dimensional differences.

b. Atomic number has a strong influence of the photon attenuation properties of a material.

c. Although there are no health hazards handling Be, machining of the metal must be done with vacuum-equipped tools since Be vapors and dust are known to cause lung disease. Also Be is very susceptible to chloride attack and thus must be handled with gloves and used in a carefully controlled water chemistry environment.

d. The crystals must be kept at a temperature below 323 K (121F) and preferably below 316 K (109F) to avoid damage to the crystal, minimize thermionic noise, preserve signal-to-noise ratio, etc.

e. Note that the angle between the two beams is fixed.

f. Each component shown is not needed for every channel. One series controller component, for example, can drive three channels.

g. Due to the higher yield of 59.5 keV photons relative to the yield of 26.35 keV photons, a smaller source can be used to get the photon count rates desired from a measurement statistical accuracy point of view.

TABLE 1. CLASSIFICATION OF SEALED SOURCE PERFORMANCE TESTS

Test	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class X
Temperature	No Test	-40°C (20 min) +80°C (1 h)	-40°C (20 min) +400°C (1 h) and thermal shock 400°C to 20°C	-40°C (20 min) +600°C (1 h) and thermal shock 600°C to 20°C	-40°C (20 min) +600°C (1 h) and and thermal shock 800°C to 20°C	-40°C (20 min) +800°C (1 h) thermal shock	Special test
External pressure	No Test	25 kN/m² abs.	25 kN/m² abs. to 2 MN/m²	25 kN/m² abs. to 7 MN/m²	25 kN/m² abs.- to 70 MN/m²	25 kN/m² abs. to 170 MN/m²	Special test
Impact	No Test	50 g from 1 m and free drop ten times to a steel surface from 1.5 m	200 g from 1 m	2 kg from 1 m	5 kg from 1 m	20 kg from 1 m	Special test
Vibration	No Test	2 min 25 to 500 Hz at 5 g peak amp.	30 min 25 to 50 Hz at 5 g peak amp. and 50 to 90 Hz at 0.635 mm amp. peak to peak and 90 to 500 Hz at 10 g	90 min 25 to 80 Hz at 1.5 mm amp. peak to peak and 80 to 2000 Hz at 20 g	Not used	Not used	Special test
Puncture	No Test	1 g from 1 m	10 g from 1 m	50 g from 1 m	300 g from 1 m	1 kg from 1 m	Special test

Table 2
Major Radiations from Am-241 Decay

Radiation	Energy (keV)	Absolute Yield (%)
α	5486.	85.2
	5443.	12.8
X, γ	11.89	0.85
	13.9	13.3
	17.8	19.3
	20.8	4.93
	26.345	2.4
	33.195	0.103
	43.423	0.057
	59.537	35.7
e^-	22.	
	38.	
	54.	

Table 3
Source Installation Procedure

1. Workers designated to install the sources should observe the work areas to be utilized for removing the sources and the spool pieces as installed in the MIST facility piping and note any circumstances that may interfere with the source installation. Workers should ensure that the detector casks or absorption plates are installed on each spool.

2. Workers designated to install the sources should review this procedure with the ARC Radiological Safety Officer, decide where they are going to unpackage the sources (i.e., in the safe handling area or on Deck 2 of the MIST facility), and conduct a dry run of the procedure.

3. Assemble the following tools and equipment near the spool to be loaded: tongs at least two feet long, covering for floor grating (to prevent dropped equipment from falling through), magnifying glass (type with integral light preferred), portable radiation monitoring equipment, materials to rope off the radiation area during source installation and after source installation, logs for the sources, hex key drive with at least one foot extension, and step ladders as required.

4. Move the box containing the packaged sources from the storage area to the designated work area.

5. Rope off the work area and post with "Caution - Radiation Area" signs to prevent unauthorized and unnecessary personnel from entering the work area. Place the floor covering under the spool to be loaded.

6. Set up portable radiation monitoring equipment.

7. Ensure all persons involved are wearing required monitoring film badges and/or dosimeters. Persons handling sources should wear a ring badge. |R1

8. Remove all unauthorized personnel.

9. Open box containing source tin can and remove tin can.

10. Open a tin can and remove the pig containing the source capsule. Note that two capsules may be contained in each pig. Each capsule will have a unique serial number.

11. Open the pig and remove a capsule by grasping the spring affixed to the backside of the capsule using the tongs. Note that the source is located at the non-welded end of the capsule (opposite the end to which the spring is attached). Use care to keep the source end pointed away from personnel.

Caution: The radiation field from a source capsule will be significant upon opening the pig containing it. Two foot-long tongs should be used at all times to handle a capsule. The radiation field at 30 cm from an exposed capsule is not expected to exceed 26 mrem/hr. The total time required for source installation is not expected to take more than 15 minutes thus limiting exposure of hands to less than 6 mrem if a 30 cm distance is maintained.

12. Record source specifics (serial number, etc.) in the log. Note that use of the magnifying glass may be necessary to read the source serial number.

13. Leak test the source per procedure (see Table 4) and record relevant information in the log.

14. Gently grasp spring on capsule using tongs and insert source capsule in the spool per EG&G Drawing 419348. The end of the uncompressed spring should be approximately flush with the spool surface when the source capsule is fully seated in the source cavity.

15. Using at least a one-foot extension on a hex key drive, install the set screw (Part Number 35, EG&G Drawing 419348) in the source collimator cavity. Note that some compression of the spring may be required before the screw threads will engage with the threads in the collimator cavity. Tighten the set screw finger tight.

16. Record source location in the log.

17. Rope the spool off (approximately 30 cm radius) with caution ribbon.

18. Repeat Steps 3-18 for each spool piece.

Table 4
Source Leak Check Procedure

The following is intended to provide a set of guidelines for leak testing source capsules that are presently installed in spool pieces. Such leak testing is required at intervals not to exceed six months for photon emitting radioactive source capsules (10CFR34.25).

1. Schedule installed (meaning installed in a spool piece in the MIST facility) source capsule leak test activities during a time period when the facility is in a cooled down state (preferably at ambient temperature and pressure). This will facilitate manipulation of hardware and equipment. Read this procedure in total, review procedure with ARC Radiological Safety Officer, and conduct dry run before initiating actual work.

2. Workers designated to do the leak test should observe the work areas around the spool pieces and note any circumstances that may interfere with the task.

3. Assemble the following tools and equipment near the MIST spool containing the source capsule to be leak tested: at least two pair of tongs at least two feet long, covering for the floor grating (to prevent dropped equipment from falling through the floor), magnifying glass (type with integral light desired), hex drive with at least one-foot extension, portable radiation monitoring equipment, materials to rope off the work area during leak test activities, step ladders, padded tray with sides at least 2 cm high, logs for the sources, and materials required for doing smear test (i.e., ethanol [or distilled water], one-inch diameter semi-absorbant filter paper).

4. Rope off work area and post with "Caution - Radiation Area" signs to prevent unauthorized and unnecessary personnel from entering the work area.

5. Remove all unauthorized personnel.

6. Ensure persons involved are wearing required monitoring film badges and dosimeters. Persons handling sources should wear a ring badge. |R1

7. If source removal is needed, place floor covering under spool containing source capsule to be leak tested. Place padded tray in a convenient nearby location. |R1

8. Set up portable radiation monitoring equipment so that the approximate dose to the hands of the Radiological Safety Officer or his designate can be monitored (i.e., place the detector probe such that it is approximately one tong length away from the eventual location of the source on the padded tray).

9. If source relocation is planned for this particular source, proceed to Step 10. If source relocation is not being performed, merely wipe the surface of the spool piece near the set screw with a one-inch diameter piece of filter paper wetted with ethanol (or distilled water). Manipulate the filter paper with a set of tongs. Go to Step 15. R1

10. Using the hex drive and extension (a tee handle or screwdriver type handle may be useful), remove the set screw (Part Number 35, EG&G Drawing 419348) holding the source in the spool, and place the screw in the padded tray.

11. Using tongs, grasp the spring affixed to the source capsule backside. Gently remove the source from the spool and place the source capsule in the padded tray. Do not drop the source capsule.

    Caution: The radiation field from the source will be high when the source is removed from the spool. Use two foot-long tongs when handling the source and keep the "source end" (the non-welded end) pointed away from personnel. The radiation dose from the exposed capsule is not expected to exceed 26 mrem/hr at 30 cm.

12. Wipe the surface of the capsule with a one-inch diameter piece of filter pape wetted with ethanol (or distilled water). One set of tongs should be used to immobilize the capsule and a second set of tongs should be used to hold and manipulate the filter paper.

    Caution: Do not allow alcohol or water to wet the adhesive used to attach the compression spring to the capsule as this could weaken the bond.

13. Visually check the source capsule (using the magnifying glass held in tongs) for any abnormalities. Note and record the capsule serial number.

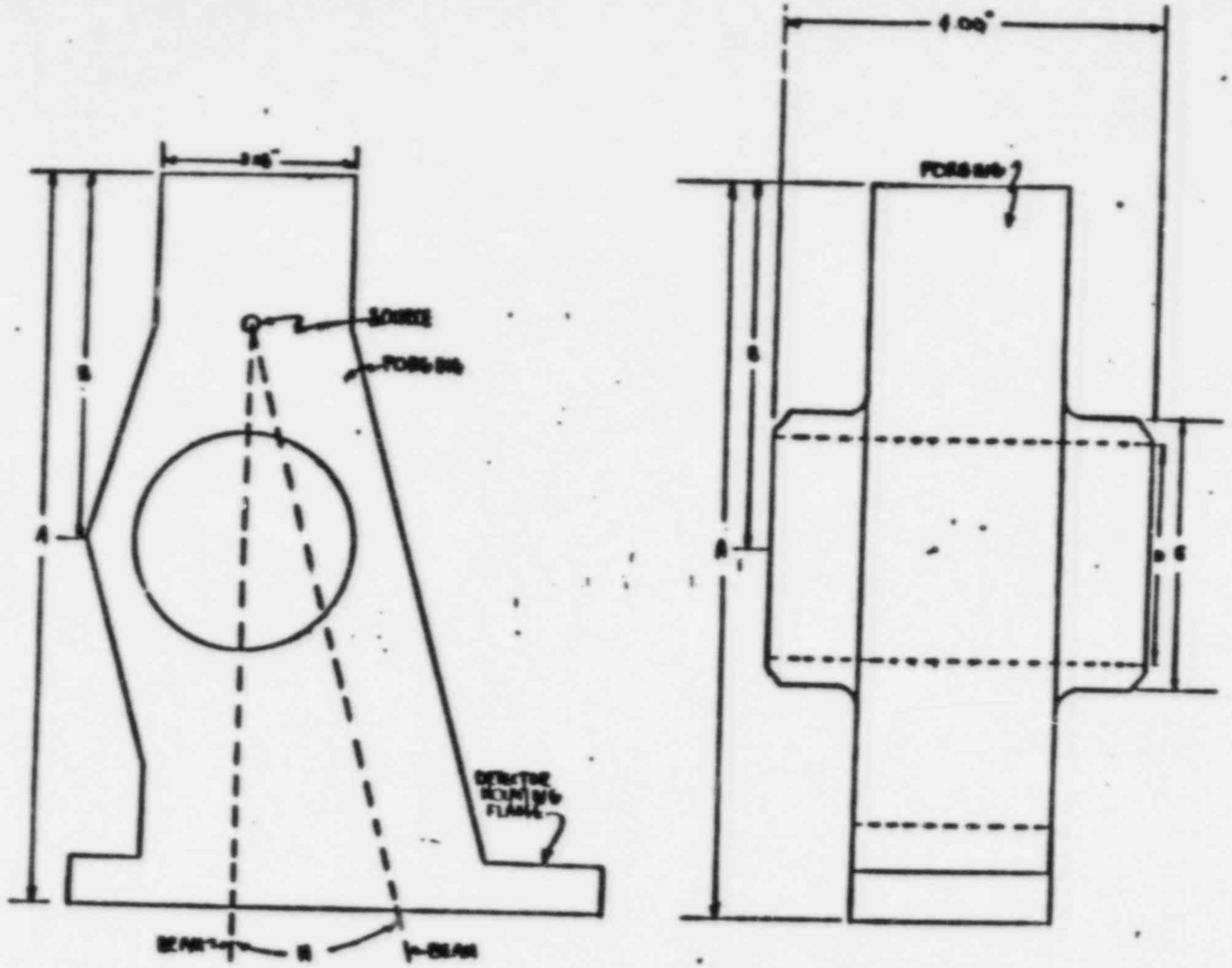
14. Reinstall the source capsule in the new spool per Steps 15 - 18 in the source installation procedure (Table 3).

15. Record relevant information in the source log. Include for future reference a sketch of the area where the leak test was performed.

16. Remove temporary barriers.

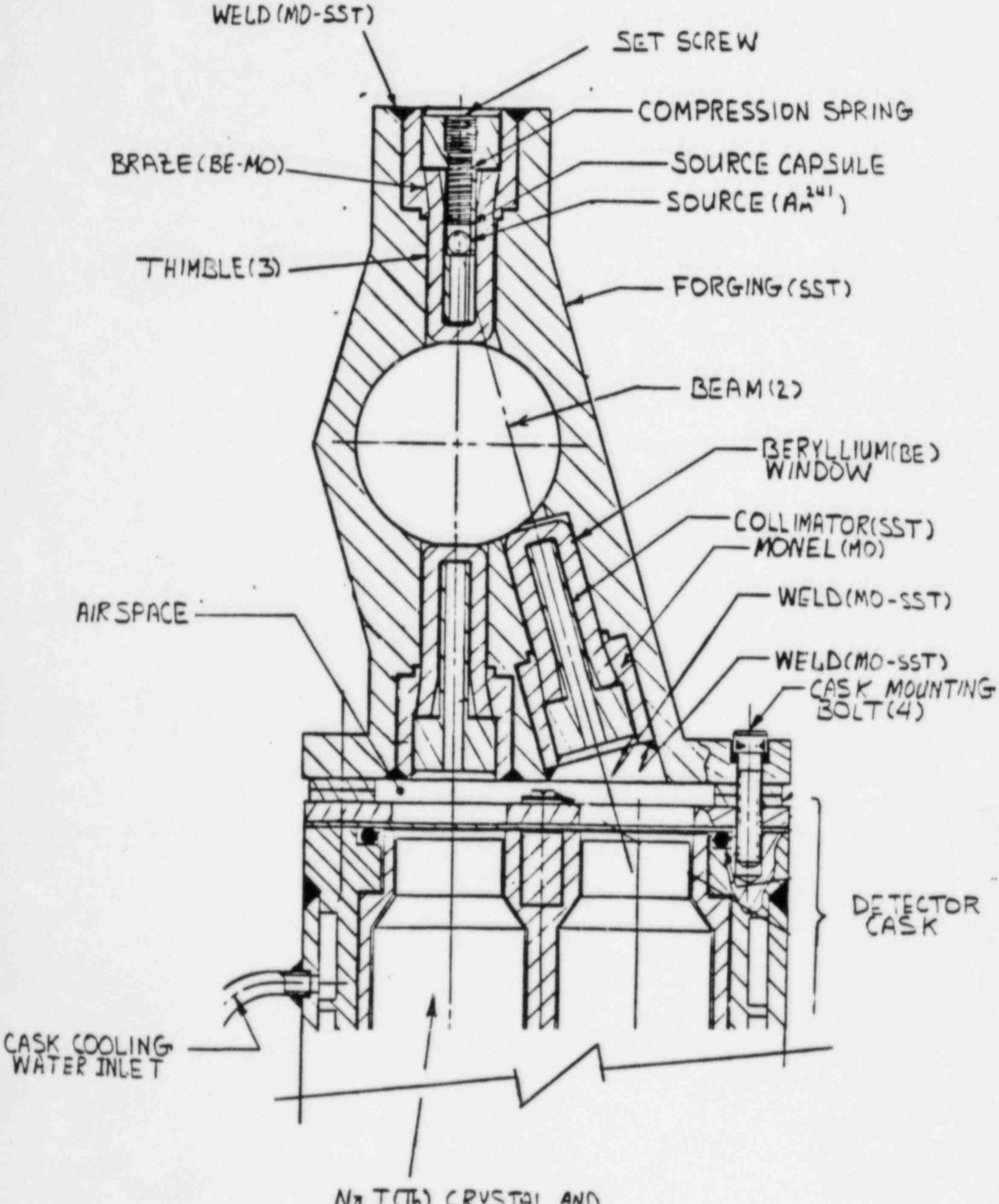
17. Record the results in the log after the count test on swipe samples has been completed.

18. Repeat Steps 3 - 17 for each installed source to be leak tested.



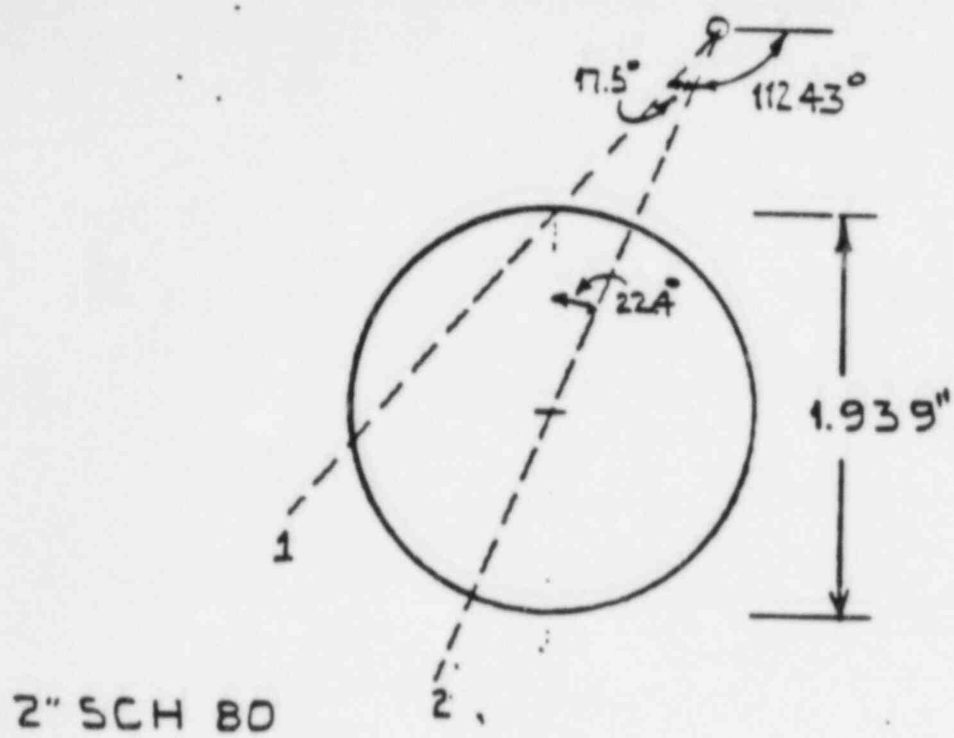
SPOOL	A(IN)	B(IN)	D(IN)	H(DEG)
2½" SCH 80	7.724	3.862	2.323	16
2" SCH 80	7.34	3.67	1.939	17.5

FIGURE 1 MIST DENSITOMETER FORGING



CONTROL NO. 8840

FIGURE 2. MIST DENSITOMETER ASSEMBLY



CASE 4

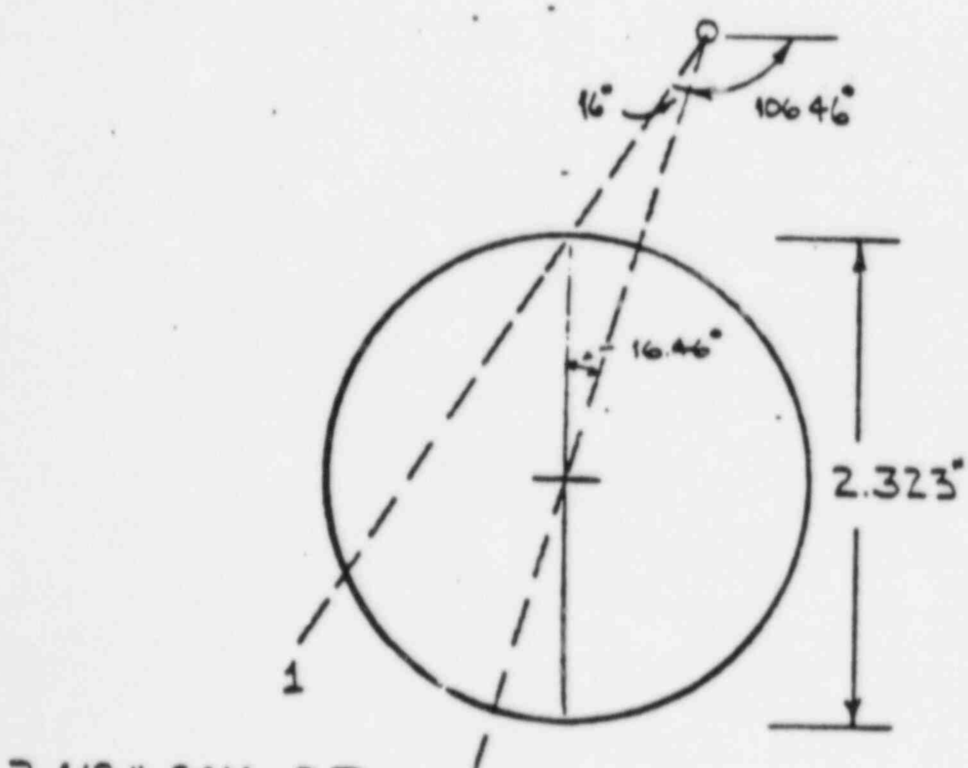


FIGURE 3. RECOMMENDED BEAM ORIENTATIONS

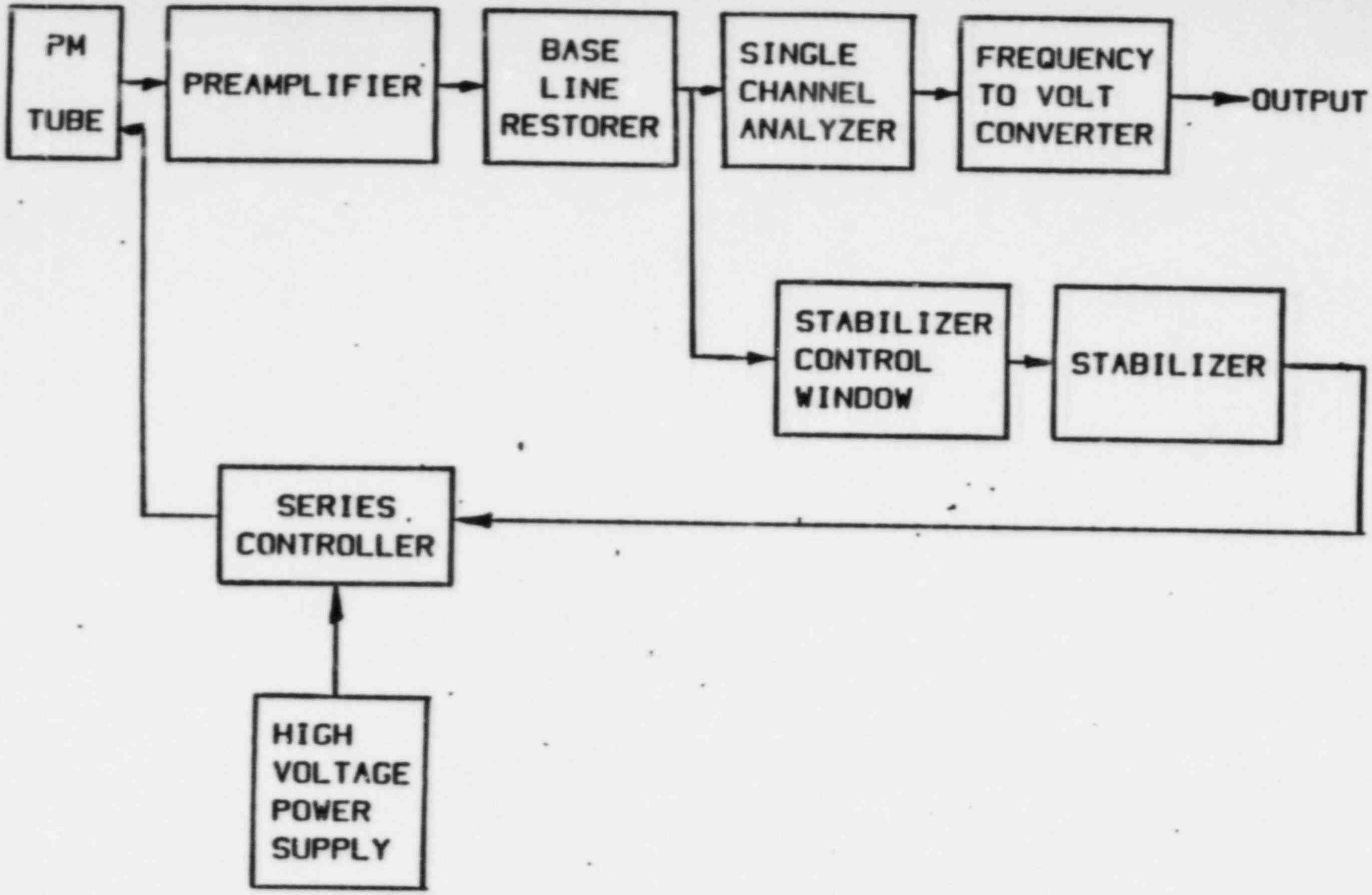
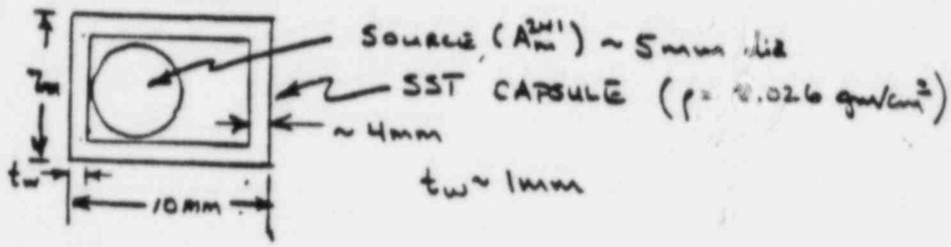


FIGURE 4. MEGACOUNT STABILIZED DENSITOMETER BLOCK DIAGRAM

APPENDIX A 59.5 keV PHOTON YIELD FOR NIST Am^{241} SOURCES

SOURCE STRENGTH ~ 200 mCi
YIELD OF 59.5 keV PHOTON / DISINTEGRATION ~ 35.7%
SOURCE CAPSULE DIMENSIONS ~ CYLINDRICAL 7mm X 10mm (LENGTH
SOURCE DIMENSIONS ~ 5mm (SPHERICAL)



FOR 59.5 keV, μ_0/ρ (MASS ATTENUATION COEF) FOR SST ~ 1.2 cm^2/gm
FROM THE ATTENUATION EQUATION:

$$I = I_1 e^{-\frac{\mu_0}{\rho}\rho x}$$

I_1 = INTENSITY AT SOURCE SURFACE
I = INTENSITY AT X
μ_0/ρ = MASS ATTENUATION COEF., cm^2/gm
ρ = DENSITY OF ABSORBER, gm/cm^3
X = THICKNESS " " , cm

$$I/I_1 = e^{-1.2(8.026)(1/10)} = 0.382$$

$$I_0 = 200\,mCi \times 10^{-3} \frac{Ci}{mCi} \times 3.7\times10^{10} \frac{\text{DISINTEGRATIONS}}{\text{SEC}\cdot\text{Ci}} \times 0.357 \frac{\text{PHOTONS (59.5 keV)}}{\text{DISINT}}$$

$$= 2.642\times10^{9} \text{ 59.5 keV PHOTONS/s}$$

I_1 AND I_0 CAN BE RELATED BY APPROXIMATING THE SELF ABSORPTION IN THE SOURCE ie,

$$I_1/I_0 \cong e^{-0.75\mu R}$$

μ - ATTENUATION COEF. OF SOURCE MTL, cm^{-1}
R = SOURCE RADIUS cm

ASSUMING THE MATRIX TO BE MOSTLY SiO_2,

μ/ρ = 0.252 cm^2/gm AT hν = 60 keV
ρ = 2.64 gm/cm^3
R = 5/2 = 2.5 mm

$$I_1/I_0 = e^{-0.75(0.252)(2.64)\frac{2.5}{10}}$$
$$= e^{-0.125} = 0.883 \Rightarrow I_1 = 0.883\, I_0$$

$\therefore I = 0.382\, I_1 = 0.382(0.883\, I_0) = 0.337\, I_0$

ON A PER UNIT SOLID ANGLE BASIS,

$$I = \frac{0.337(2.642\times10^9)}{4\pi} = \underline{7.089\times10^{7}} \frac{\text{59.5 keV PHOTONS}}{\text{S - STERADIAN}}$$

THE MANUFACTURER'S RATING FOR THE SOURCE IS 7×10^7 SO THERE IS GOOD AGREEMENT.

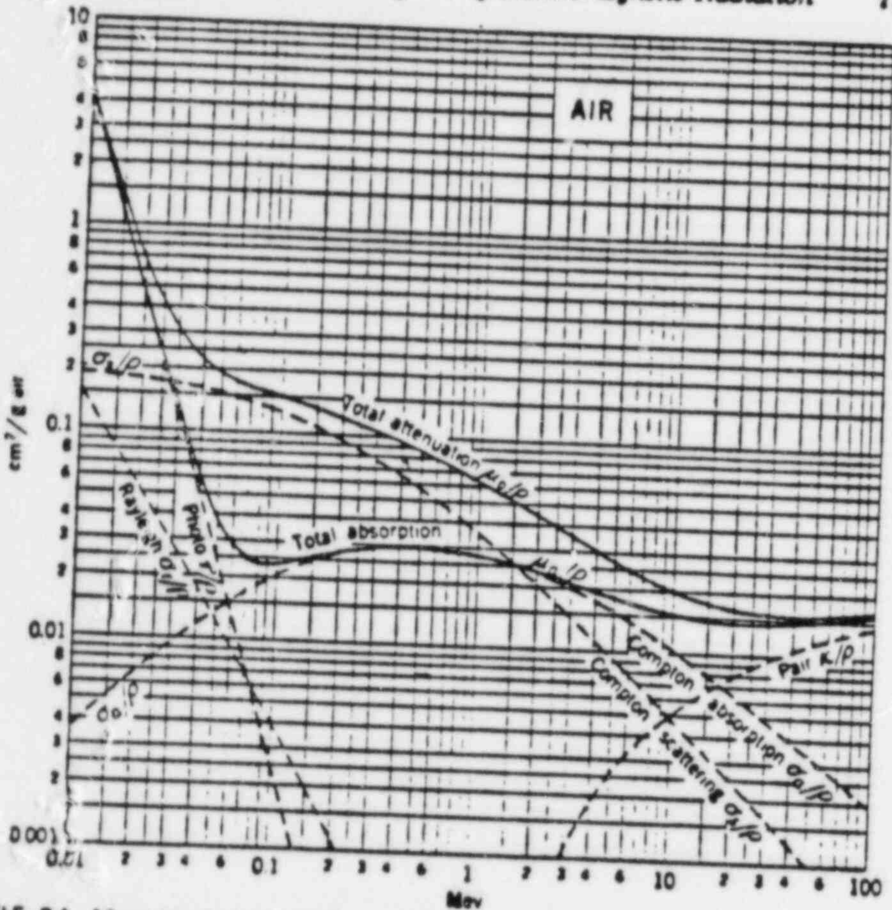


FIG. A1. Mass attenuation coefficients for photons in air, computed from the tables of atomic cross sections prepared by G. R. White (W38). The curve marked "total absorption" is $(\mu_a/\rho) = (\sigma_a/\rho) + (\tau/\rho) + (\kappa/\rho)$, where σ_a, τ, and κ are the corresponding linear coefficients for Compton absorption, photoelectric absorption, and pair production. When the Compton scattering coefficient σ_s is added to μ_a, we obtain the curve marked "total attenuation," which is $(\mu_0/\rho) = (\mu_a/\rho) + (\sigma_s/\rho)$. The total Rayleigh scattering cross section (σ_r/ρ) is shown separately. Because the Rayleigh scattering is elastic and is confined to small angles, it has not been included in μ_0/ρ. In computing these curves, the composition of "air" was taken as 78.04 volume per cent nitrogen, 21.02 volume per cent oxygen, and 0.94 volume per cent argon. At 0°C and 760 mm Hg pressure, the density of air is ρ = 0.001 293 g/cm³.

APPENDIX B. DOSE RATE DUE TO ELECTROMAGNETIC RADIATION

DOSE RATES DUE TO ELECTROMAGNETIC RADIATION CAN CALCULATED FOR VARIOUS ASSUMPTIONS REGARDING THE SOURCE. IN THE FOLLOWING, THREE CASES ARE CONSIDERED TO ESTABLISH BOUNDS ON THE DOSE DUE TO ELECTROMAGNETIC RADIATION. THESE CASES INCLUDE:

1. BARE SOURCE (UNSHIELDED, UNENCAPSULATED) - ABSOLUTE UPPER BOUND BUT AN UNREALISTIC SITUATION.
2. DOSE DUE TO 59.5 KeV PHOTONS FROM ENCAPSULATED SOURCE. — SUCH AS DURING HANDLING
3. DOSE FROM SOURCE WHILE IT RESIDES IN THE SPOOL.

1. BARE SOURCE

THE DOSE FROM AN UNSHIELDED, UNENCAPSULATED SOURCE WILL ESTABLISH AN UPPER BOUND SINCE THE SOURCE IS ENCAPSULATED AND WILL RESIDE IN THE SPOOL PIECE*. THE DOSE (IN MILLIROENTGENS (mr)) DUE TO ELECTROMAGNETIC RADIATION FROM AN UNSHIELDED SOURCE IS GIVEN AS THE SUM OF THE PRODUCTS OF THE MASS ABSORPTION COEFFICIENT IN AIR AND THE INTENSITY OF EACH SIGNIFICANT PHOTON ENERGY ie

$$R = \sum_i I_i \frac{\mu_i}{\rho} \qquad (B.1)$$

WHERE

I – INTENSITY OF i^{th} ENERGY LEVEL

μ_a/ρ – MASS ABSORPTION COEFFICIENT IN AIR FOR THE i^{th} PHOTO PEAK.

* THE SPOOL PIECE WILL BE SHOWN TO BE AN EFFECTIVE SHIELD.

USING YIELD VALUES FROM TABLE 2 AND NOTING μ_a/ρ VALUES FROM FIGURE A.1, TABLE C.1 CAN BE CONSTRUCTED. AT 30 CM (1 FOOT) FROM THE EXPOSED SOURCE THEN,

$$R = \sum_i I_i \, \mu_a/\rho)_i$$

$$= \frac{3.7\times10^{10}}{4\pi(30)^2} \frac{\text{Disint}}{\text{s}\cdot\text{Ci}\cdot\text{cm}^2} \; \frac{9.23\,\text{keV}}{\text{Disint}} \; \frac{\text{cm}}{\text{gm air}} \; \frac{3600\text{s}}{\text{HR}} \; \frac{\text{r}\cdot\text{gm air}}{5.24\times10^{7}\,\text{keV}}$$

$$\cong 2.07 \frac{\text{r}}{\text{hr}\cdot\text{Ci}} = \frac{2.07\,\text{mr}}{\text{hr}\cdot\text{mCi}} \text{ at } 30\text{ cm}$$

FOR AN EXPOSED 200 mCi SOURCE THEN

$$R = 2.07 \times 200 = 415 \frac{\text{mr}}{\text{hr}} \text{ at } 30\text{ cm}$$

or

$$415 \times \left(\frac{30}{100}\right)^2 = 37.3 \frac{\text{mr}}{\text{hr}} \text{ at } 1\text{M}$$

A TOTALLY UNSHIELDED SOURCE WOULD THEN GIVE ONE THE PERMITTED YEARLY DOSE (5r) IN 12 HOURS AT A DISTANCE OF 30 cm (1 FOOT) OR IN ABOUT 5½ DAYS AT A DISTANCE OF 1 m (3.28 FEET). COMPARISON OF THIS TO SIMILAR CALCULATIONS FOR COMMONLY USED Co^{60} AND Cs^{137} SOURCES (20–30 Ci IN SIZE) WHICH PROVIDE THE PERMITTED DOSE IN LESS THAN 4 MINUTES AT 30 cm, ILLUSTRATES ONE OF THE SAFETY ADVANTAGES OF USING THE LOW ENERGY SOURCES RELATIVE TO HIGH ENERGY SOURCES.** NOTE THAT THE ABOVE CALCULATION IS UNREALISTIC SINCE THE SOURCE MATERIAL WILL <u>NEVER</u> BE EXPOSED (AS ARE Cs OR Co SOURCES) & AS WILL BE SHOWN IN THE NEXT SECTION, A SIGNIFICANT AMOUNT OF ATTENUATION TAKES PLACE IN THE SOURCE CAPSULE.

* HIGHER ENERGY GAMMA PEAKS ARE ALSO PRESENT BUT YIELDS ARE SO SMALL (<<0.04%) THAT THE CALCULATION IS NOT AFFECTED.

** The calculation is PRESENTED HERE ONLY FOR COMPARISON PURPOSES.

2. DOSE FROM ENCAPSULATED SOURCE.

THE DOSE RATE EXPECTED FROM THE ENCAPSULATED SOURCE CAN BE ESTIMATED BY APPROXIMATING THE INTENSITY OF ALL RADIATIONS AT A DISTANCE x FROM THE CAPSULE. AT A DISTANCE X FROM A POINT SOURCE, THE INTENSITY IS GIVEN BY

$$I_i = \frac{n_i h\nu_i}{4\pi x^2} \qquad \text{B.2)}$$

WHERE:

I_i - intensity OF i^{th} ENERGY LEVEL
n_i - NUMBER OF PHOTONS WITH ENERGY $h\nu$
$h\nu_i$ - PHOTON ENERGY LEVEL

IN APPENDIX A, n_i WAS ESTIMATED FOR THE 59.5 KeV PHOTO PEAK. SIMILAR CALCULATIONS INCLUDING ATTENUATION IN THE CAPSULE WALL AND SELF ABSORPTION ARE SHOWN IN TABLE B.3 ASSUMING, FOR CONSERVATISM, A 250 mCi SOURCE. THE RESULTS IN TABLE B.3 SHOW THAT ONLY THE PHOTONS WITH ENERGY GREATER 20.8 KeV NEED BE CONSIDERED AS EVERYTHING ELSE IS EFFECTIVELY ATTENUATED IN THE CAPSULE WALL. THE DOSE CAN BE CALCULATED FROM EQN B.1), THE VALUE GIVEN IN TABLE B.3, AND AIR MASS ABSORPTION COEFFICIENT

VALUES FROM TABLE B 1. Ie.

$$R = \sum I_i \, \mu_a/\rho$$

$$= \frac{1.4845E5}{4\pi X^2} \cdot \frac{MeV \; ~~cm^2~~ \; r \text{-} ~~gm~~ \; ~~4\pi~~ ~~str~~ \; 3600s}{~~s~~ \cdot ~~str~~ \; cm^2 \cdot 5.24 \times 10^7 \; ~~MeV~~ \; ~~gm~~ \; m}$$

$$= \frac{10.2}{X^2} \frac{r}{hr}$$

AT A DISTANCE OF 10cm THEN

$$R_{10} = \frac{10.2}{10^2} \times 10^3 \frac{mr}{hr} = 102 \frac{mr}{hr}$$ AT 10cm FOR 250 [illegible] SOU[illegible]

AND AT 30cm,

$$R_{30} = \frac{10.2 \times 10^3}{(30)^2} = 11 \frac{mr}{hr}$$ AT 30cm FOR 250 [illegible] SOURCE

AND AT 100cm

$$R_{100} = \frac{10.2 \times 10^3}{100^2} = 1.02 \frac{mr}{hr}$$ AT 1M FOR 250 mC[illegible] SOURCE

USING ANSI/ANS STANDARDS, THE FLUX-TO-DOSE RATE CAN BE ESTIMATED USING VALUES IN (REF. 4) AND THE 59.5 KeV PHOTON QUOTED OUTPUT RATE. FROM REF. 4, FOR GAMMA RAYS,

$$\ln(DF_n(E)) = A + Bx + Cx^2 + Dx^3$$

WHERE:

$DF_n(E)$ = (rem/hr)/(photon/cm^2-s)

E = PHOTON ENERGY, MeV

X = $\ln(E)$

A = -13.626

B = -0.57117

C = -1.0954

D = -0.24877

(A–D: VALUES FOR $0.03 \le E \le 0.5$)

SUBSTITUTING :

$$\ln(DF_n(0.0595)) = -13.626 + (-0.57117)\ln(0.0595) + (-1.0954)(\ln(0.0595))^2 + (-0.24897)(\ln(0.0595))^3$$

$$= -15.14$$

$$\therefore DF_n = e^{-15.14} = 2.65 \times 10^{-7} \frac{\text{rem}}{\text{hr}} \frac{\text{cm}^2\text{-s}}{\text{photon}} \times 10^3 \frac{\text{mrem}}{\text{rem}}$$

$$= 2.65 \times 10^{-4} \frac{\text{mrem}}{\text{hr}} \frac{\text{cm}^2\text{-s}}{\text{photon}}$$

IF $n = 70E6 \frac{\text{PHOTONS}}{\text{S-STER}}$ (59.5keV) $\times 1.25$ (ACCOUNT FOR UPPER BOUND ON SOURCE STRENGTH)

$$= 87.5E6 \frac{\text{PHOTONS}}{\text{S}\cdot\text{STER}}$$

$$N = \frac{87.5E6 \times 4\pi}{4\pi X^2} \frac{\text{PHOTONS}}{\text{S-STER}} \frac{\text{STER}}{\text{cm}^2} = \frac{87.5E6}{X^2} \frac{\text{PHOTONS}}{\text{S-cm}^2}$$

$$R = DF_n \cdot N = 2.65 \times 10^{-4} \left(\frac{87.5E6}{X^2}\right) = \frac{23213.37}{X^2} \frac{\text{mrem}}{\text{hr}}$$

$X = 10\text{cm} \Rightarrow R = 232.13$ mrem/hr
$X = 30\text{cm} \Rightarrow R = 25.79$ mrem/hr
$X = 100\text{cm} \Rightarrow R = 2.32$ mrem/hr

} Assuming 250mCi Source

THESE VALUES CLEARLY INDICATE THAT THE SOURCE MUST BE HANDLED WITH TONGS!

3. DOSE DUE TO ELECTROMAGNETIC RADIATION WITH SOURCE CAPSULE INSTALLED IN FORGING

THE DOSE RATE DUE TO ELECTROMAGNETIC RADIATION AT THE FORGING SURFACE CAN BE ESTIMATED BY ASSUMING THE CAPSULE TO BE A POINT SOURCE IN AN ISOTROPIC MEDIUM OF STAINLESS STEEL. TWO CALCULATIONS WILL BE PRESENTED IN ORDER TO BOUND THE DOSE RATE. THE VARIABLE IN THESE CALCULATIONS IS THE PATH LENGTH OF STAINLESS STEEL. THE MINIMUM PATH IS, AS SHOWN IN FIGURE 2, FROM THE SOURCE THROUGH THE BACKSIDE OF THE CAPSULE AND THROUGH THE 0.953 cm (3/8 IN) LONG SET SCREW HOLDING THE SOURCE IN PLACE. ON THE OTHER EXTREME, FIGURE 2 SUGGESTS THAT, BY AND LARGE, 2.54 cm (1 IN) OF STAINLESS STEEL SURROUNDS THE SOURCE CAPSULE. IN BOTH CASES, SPHERICAL MEDIUM APPROXIMATIONS ARE USED. THE INTENSITY AT A DISTANCE x FROM A POINT SOURCE IS ESTIMATED FROM

$$I = \frac{\sum_i n_i (h\nu)_i e^{-\mu_{oi} x}}{4\pi x^2} = \frac{3.7 \times 10^{10}}{4\pi x^2} \sum Y_i (h\nu)_i e^{-\left(\frac{\mu_0}{\rho}\right)_i \rho_i x_i} \qquad \text{(B.3)}$$

WHERE:

n_i - # OF PHOTONS EMITTED WITH ENERGY $(h\nu)_i$
$h\nu)_i$ - PHOTON ENERGY AT i^{th} PHOTO PEAK
μ_{0i} - LINEAR ATTENUATION COEFFICIENT IN STAINLESS STEEL
x - SPHERE RADIUS
ρ - STAINLESS STEEL

MAXIMUM PATH

USING TABLE B.2 VALUES OF MASS ATTENUATION COEFFICIENT FOR IRON, A STAINLESS STEEL DENSITY OF 8.026 gm/cm³ (501 LBM/FT³), YIELD VALUES FROM TABLE B.1, AND AN x OF 2.54 cm GIVES THE RESULTS SHOWN IN TABLE B.4a FOR THE MAXIMUM PATH LENGTH CASE. THE DOSE RATE FROM EQUATION B.1) IS

$$R = \Sigma I_i \left(\frac{\mu_a}{\rho}\right)_i = \frac{3.7\times10^{10}}{4\pi x^2} \sum_i \left[Y_i (h\nu)_i \, e^{-\left(\frac{\mu_0}{\rho}\right)_i \rho x} \left(\frac{\mu_a}{\rho}\right)_i \right] \qquad B.4)$$

FROM TABLE B.4, THE VALUE OF THE SUMMATION IS 2.87×10^{-15} MeV - cm² /(DISINT. - gm AIR) SO.

$$R = \frac{3.7\times10^{10}}{4\pi(2.54)^2} \cdot \frac{2.87\times10^{-15}}{5.24\times10^{7}} \, 3600 \; \frac{DIS.}{S \cdot Ci} \; \frac{MeV\text{-}cm^2}{cm^2 \; DIS \cdot gm\,AIR} \; \frac{r\text{-}gm\,air}{MeV} \; \frac{s}{hr}$$

$$= 9\times10^{-11} \frac{r}{hr\text{-}Ci} = 9\times10^{-11} \frac{mr}{hr\;mCi}$$

FOR THE 250 mCi SOURCE THEN,

$$R = 250 \times 9\times10^{-11} = \underline{2.25\times10^{-8} \frac{mr}{hr}}$$ AT THE SPOOL SURF

MINIMUM PATH

FOR THE MINIMUM PATH, THE SKETCH IN APPENDIX A AND FIGURE 2 INDICATE THAT THE TOTAL PATH LENGTH IN STAINLESS STEEL IS ABOUT 1.099 cm (4 mm (BACK SIDE OF CAPSULE) + 0.953 cm (SCREW) − 0.254 cm (VOID IN SCREW HEAD). USING THE SAME VALUES OF ATTENUATION COEFFICIENT ETC AS IN THE PREVIOUS CALCULATION, GIVES THE RESULTS SHOWN IN TABLE B.4b. THE VALUE OF THE SUMMATION FOR USE IN EQN B.4) IS 7.694E-9 SO THE DOSE IS

$$R = \frac{3.7\times10^{10}}{4\pi(1.099)^2}\;\frac{7.694E-9\,(3600)}{5.24E7}$$

$$= 1.289\times10^{-3}\ \frac{r}{hr\text{-}Ci} = 1.289\times10^{-3}\ \frac{mr}{hr\ mCi}$$

FOR THE 250 mCi SOURCE THEN

$$R = 250 \times 1.289\times10^{-3}\ \frac{mr}{hr} = 0.322\ \frac{mr}{hr}$$

THESE CALCULATIONS INDICATE THAT IN GENERAL, THE DOSE AT THE SURFACE OF THE SPOOL PIECE IS NEGLIGABLE, WITH THE EXCEPTION OF AN AREA DIRECTLY OVER THE TOP OF THE

SET SCREW WHERE THE DOSE COULD BE OF THE ORDER OF 0.322 mr/hr FOR A SOURCE ON THE HIGH SIDE OF THE SOURCE STRENGTH RANGE.

4. Dose Due to (α,n) Reaction

MANUFACTURER QUOTES INDICATE A NEUTRON COUNT OF 10^4 n/s-Ci DUE TO (α,n) REACTIONS. TABLE B.4 GIVES RESULTS OF MONTE-CARLO CALCULATIONS CONDUTED TO CALCULATE NEUTRON FLUXES CORRESPONDING TO 1 REM (ROENTGEN EQUIVALENT MAN). THESE CALCULATIONS ACCOUNTED FOR THE RELATIVE BIOLOGICAL EFFECTIVENESS (RBE) OF NEUTRONS AND MULTIPLE COLLISIONS. USING THE MOST CONSERVATIVE CASE, ie 10 MeV neutrons AND A FIXED (WITH ENERGY) RBE, A NEUTRON FLUX OF 1.3×10^7 n/cm^2 CORRESPONDS TO 1 rem. FOR THE 200 mCi Am^{241} SOURCE AT A DISTANCE OF 10 cm THEN,

$$R_N = \frac{10^4 (0.2)\, 3600\, 10^3}{1.3\times10^7\, 4\pi\, 10^2}$$

$$= 0.44 \frac{\text{mrem}}{\text{hr}}$$

TABLE B.1. DOSE RATE CALCULATIONS FOR EXPOSED SOURCE IN AIR.

$E = h\nu$ (keV)	Yield (%)	μ_a/ρ (cm^2/gm)[a]	$h\nu \times$ Yield $\times \mu/\rho$
11.89	0.85	4.	0.404
13.9	13.3	1.5	2.773
17.8	19.3	1.4	4.81
20.8	4.93	0.45	0.461
26.35	2.4	0.25	0.158
33.195	0.103	0.13	0.004
43.42	0.057	0.055	0.001
59.5	35.7	0.029	0.616
			$\Sigma = 9.23$

a. MASS ABSORPTION COEF. IN AIR

TABLE B.2. MASS ATTENUATION COEF. FOR IRON AND SiO_2

	Fe[b]	SiO_2[b]
$E = h\nu$ (keV)	μ_0/ρ (cm^2/gm)	μ_0/ρ (cm^2/gm)
10	173	19.0
15	56.4	5.73
20	25.5	2.49
30	8.13	0.859
40	3.62	0.463
50	1.94	0.318
60	1.20	0.252
80	0.595	0.194

b. DATA FROM "RADIOLOGICAL HEALTH HANDBOOK", JAN 1970, USDHEW, pg 138

TABLE B.3

$h\nu$ (keV)	$\frac{\mu_0}{\rho}$ (1) STAINLESS	$e^{-\frac{\mu_0}{\rho}\rho x}$ (2)	YIELD (%)	I_0 (PHOT/S)	μ (cm⁻¹) (3) SiO_2	$e^{-0.75\mu R}$ (4)	I_1 (PHOT/S)	I (PHOT/S-STR)	$n h\nu$ (MeV/S-STR)	$n h\nu$ (MeV/…)
11.89	128.9	1.175E-45	0.85	7.863E7	36.92	0.0010	7.748E4	7.244E-42	–	–
13.9	82.05	2.513E-29	13.3	1.23E9	22.83	0.014	1.722E7	3.444E-23	–	–
17.8	39.1	2.35E-14	19.3	1.785E9	10.34	0.144	2.57E8	4.807E-7	–	–
20.8	24.1	3.977E-9	4.93	4.56E8	6.23	0.311	1.418E8	4.488E-2	9.335E-4	4.21[illegible]
26.35	14.48	8.970E-6	2.4	2.22E8	3.84	0.487	1.081E8	7.716E1	2.033	0.5[illegible]
33.195	6.69	4.657E-3	0.103	9.528E6	1.93	0.696	6.631E6	2.457E3	81.56	10.6
43.423	3.05	0.08647	0.057	5.273E6	1.09	0.815	4.297E6	2.957E4	1.284E?	70.6
59.537	1.237	0.371	35.7	3.302E9	0.67	0.882	2.912E9	8.598E7	5.116E6	1.48
										Σ = 1.48

EQUATIONS USED:

$$I = \frac{I_1}{4\pi} e^{-\frac{\mu_0}{\rho}(\rho x)} \quad \frac{\text{Photons}}{\text{S-STR}}$$

$$I_0 = 250\,\mu\text{Ci} \times 10^{-3}\,\text{Ci}/\text{mCi} \cdot 3.7\times10^{10}\,\frac{\text{DIS}}{\text{S-Ci}} \times \text{YIELD} \; \frac{\text{PHOTONS}}{\text{S}} = 9.25\times10^{9} \times \text{YIELD}$$

$$I_1 = I_0\, e^{-0.75\mu R}$$

1. VALUES FOR STAINLESS STEEL FROM TABLE B.2 BY INTERPOLATION
2. x = 1mm (CAPSULE WINDOW THICKNESS) ρ = 8.026 gm/cm³ for STAINLESS
3. VALUES FOR SiO_2 FROM TABLE B.2 ρ_{SiO_2} = 2.64 gm/cm³
4. R = 2.5 mm (SOURCE MATERIAL RADIUS)

TABLE B.4a

$h\nu$ (keV)	Yield, Y (%)	μ/ρ (cm^2/gm) [a]	$e^{-\frac{\mu_0}{\rho}\rho x}$ [c]	$I' = h\nu \cdot Y \cdot e^{-(\frac{\mu_0}{\rho})\rho x}$ (MeV/DISINT)	μ_a/ρ (cm^2/gm) [b]	$I' \times \frac{\mu_a}{\rho}$ (M.../DI...)
11.89	0.85	128.9	0.	0.	4.	0.
13.9	13.3	82.05	0.	0.	1.5	0.
17.8	19.3	39.1	0.	0.	1.4	0.
20.8	4.93	24.1	0.	0.	0.45	0.
26.35	2.4	14.48	0.	0.	0.25	0.
33.195	0.103	6.69	5.9 E-60	2.02E-64	0.13	2.63E·
43.423	0.057	3.05	9.92E-28	2.46E-32	0.055	1.35E·
59.537	35.7	1.28	4.65E-12	9.88 E-14	0.029	2.87E·
						Σ = 2.87E

a. VALUES FOR IRON FROM TABLE B.2 (BY INTERPOLATION)
b. VALUES FOR AIR FROM FIGURE A.1
c. For x = 2.54 cm
d. For x = 1.099 cm

TABLE B.4b

$h\nu$ (keV)	Yield (%)	μ_0/ρ ($\frac{cm^2}{gm}$) [a]	$e^{-\frac{\mu_0}{\rho}\rho x}$ [d]	$I' = h\nu \times Y \times e^{-(\frac{\mu_0}{\rho})\rho x}$ ($\frac{MeV}{DIS.}$)	$\frac{\mu_a}{\rho}$ ($\frac{cm^2}{gm}$) [b]	$I' \times \frac{\mu_a}{\rho}$ ($\frac{MeV\text{-}c...}{DIS\text{-}g...}$)
11.89	0.85	128.9	0	0	4	0
13.9	13.3	82.05	0	0	1.5	0
17.8	19.3	39.1	0	0	1.4	0
20.8	4.93	34.1	4.78E-93	4.702E-96	0.45	—
26.35	2.4	14.48	3.397E-56	2.14[illegible]E-59	0.25	—
33.195	0.103	6.69	2.357E-26	8.059E-31	0.12	1.048E-31
43.423	0.057	3.05	[illegible]E-12	5.126E-17	0.055	2.82E-18
59.537	35.7	1.28	1.749E-5	2.653E-7	0.029	[illegible]E-9
						Σ = 7.694E-9

CONTROL NO. [illegible] 8 4 0

TABLE B.5 **Flux of Neutrons Corresponding to 1 Rad or 1 Rem**

Neutron energy, Mev	First-collision calculation of flux						Multiple-collision calculation of flux †		
	n/cm²/rad	n/cm²/rad *	Using fixed RBE		Using NBS Handbook 59 values of RBE		n/cm²/rad	Using fixed RBE	Using NBS Handbook 59 values of RBE
			n/cm²/rem	n/cm²/rem *	n/cm²/rem	n/cm²/rem *		n/cm²/rem	n/cm²/rem
10	1.78×10^8	1.78×10^8	1.55×10^7	1.55×10^7	2.86×10^7	2.86×10^7	1.4×10^8	1.3×10^7	2.2×10^7
5	2.23×10^8	2.23×10^8	2.04×10^7	2.04×10^7	3.45×10^7	3.45×10^7	1.8×10^8	1.7×10^7	2.5×10^7
4	2.33×10^8	2.33×10^8	2.10×10^7	2.10×10^7	3.33×10^7	3.33×10^7	2.1×10^8	1.9×10^7	2.7×10^7
3	2.72×10^8	2.72×10^8	2.54×10^7	2.54×10^7	3.77×10^7	3.77×10^7	2.3×10^8	2.2×10^7	2.9×10^7
2	3.23×10^8	3.23×10^8	3.01×10^7	3.01×10^7	4.00×10^7	4.00×10^7	2.5×10^8	2.4×10^7	2.9×10^7
1	4.05×10^8	4.05×10^8	4.05×10^7	4.05×10^7	3.85×10^7	3.85×10^7	2.6×10^8	2.5×10^7	2.5×10^7
0.5	6.13×10^8	6.13×10^8	5.50×10^7	5.50×10^7	5.56×10^7	5.56×10^7	4.4×10^8	4.2×10^7	4.5×10^7
0.1	1.61×10^9	1.61×10^9	1.54×10^8	1.54×10^8	1.25×10^8	1.25×10^8	1.0×10^9	1.4×10^8	1.3×10^8
0.01	1.00×10^{10}	1.04×10^{10}	1.06×10^9	1.05×10^9	9.00×10^8	9.09×10^8	1.8×10^9	6.9×10^8	6.5×10^8
10^{-4}	7.63×10^{11}	8.13×10^{10}	7.52×10^{10}	4.12×10^{10}	6.67×10^{10}	3.85×10^{10}	1.4×10^9	7.3×10^8	7.2×10^8
2.5×10^{-8}	4.64×10^{10}	1.28×10^9	4.50×10^9	1.09×10^9	4.35×10^9	1.08×10^9	3.0×10^9	1.0×10^9	1.0×10^9

* The values of flux for first-collision calculation, as given in columns 3, 5, and 7, were obtained by assuming all the gamma energy produced in the element of tissue is absorbed in the element and contributes to the absorbed dose.

† These values of flux were obtained by W. S. Snyder by applying a Monte Carlo calculation to obtain the absorbed dose at various depths in a large-tissue phantom 30 cm thick. The values of flux correspond to the absorbed dose at a position in the phantom where it is a maximum.

APPENDIX C. EXPECTED PHOTON COUNT RATE AT DETECTOR SURFACE

THE PHOTON COUNT AT THE DETECTOR SURFACE FOR EACH SYSTEM CAN BE ESTIMATED BY CONSIDERING THE PATH LENGTHS IN EACH MATERIAL (Be, WATER-STEAM MIXTURE, AIR, ALUMINUM ETC) AND THEN APPLYING THE APPPOPRIATE ATTENUATION EQUATIONS. THE SKETCH SHOWN IN FIGURE C.1 SHOWS THE RELEVANT MATERIALS AND DIMENSIONS (LINEAR) TRAVERSED BY EACH BEAM FOR EACH SYSTEM.

THE TOTAL ATTENUATION OF A COLLIMATED BEAM IS

$$I = I_0 e^{-\sum \mu_i x_i} = I_0 e^{-\sum (\mu/\rho)_i \rho_i x_i} \qquad (C.1)$$

WHERE:

- I - ATTENUATED COUNT RATE
- I_0 - COLLIMATED BEAM COUNT FOR NO ATTENUATION
- μ/ρ_i - MASS ATTENUATION COEFFICIENT FOR MATERIAL i
- ρ_i - DENSITY FOR MATERIAL i
- x_i - LINEAR PATH LENGTH IN MATERIAL i

TABLE C.1 GIVES RELEVANT PARAMETERS CALCULATED FOR EQUATION C.1.

I_0 IS THE BEAM COUNT RATE THAT THE DETECTOR CAN ACTUALLY "SEE" FOR NO ATTENUATION. BASED ON THE COLLIMATOR DIAMETER, SOURCE TO COLLIMATOR DISTANCE, AND SOLID ANGLE, THE DETECTOR WILL SEE AN I_0 CALCULATED AS

$$I_0 = n\, d\omega = n \frac{dA}{r^2} \qquad (C.2)$$

WHERE:

- n — # OF 59.5 KeV PHOTONS PER SECOND PER STERADIAN PRODUCED AT THE SOURCE
- $d\omega$ — SOLID ANGLE SEEN BY THE DETECTOR

dA – COLLIMATOR AREA
r – SOURCE TO COLLIMATOR DISTANCE (SEE FIG C.1)

FOR THE SITUATION IN FIGURE C.1, r IS GIVEN AS

$$r = L_{B,S} + L_{B,S} + X + L_{B,D} + L_{B,D} - Z \qquad (C.3)$$

$$dA = D_c^2 \frac{\pi}{4}$$

TABLE C.2 GIVES r AND I_o VALUES FOR EACH BEAM CALCULATED FROM EQNS C.2 & C.3. AND USING THE SOURCE PHOTON FIELD OF 70×10^6 PHOTONS/S-STER COMPUTED IN APPENDIX A.

USING THE VALUES IN TABLES C.1 AND C.2 IN EQN (C.1) GIVES THE RESULTS SHOWN IN TABLE C.3. WHERE I_f AND I_g ARE THE CALCULATED ALL LIQUID AND ALL VAPOR COUNT RATES. AS SHOWN, THE CALCULATED ALL VAPOR COUNT RATE IS GREATER THAN 50000 IN ALL CASES. THIS BEAM CAN BE FULLY ATTENUATED BY A 0.635 cm (1/4 IN) STAINLESS STEEL PLATE IE

$$I = I_o e^{-\frac{\mu}{\rho})_i \rho_i X_i}$$

$$= 71180\ e^{-1.2 \times 8.026 \times 0.635}$$

$$= 71180 \,(2.208 \times 10^{-3})$$

$$= 157. \ \frac{\text{PHOTONS}}{\text{s}}$$

TABLE C.1. PARAMETERS FOR EQN C.1.

	MTL(i)	$(\mu/\rho)_i\left(\frac{cm^2}{gm}\right)$	$\rho_i\,(gm/cm^3)$	x_i (cm)[c] Beam 1	x_i (cm)[c] Beam 2	$\mu/\rho\,\rho_i\,x_i$ Beam 1	$\mu/\rho\,\rho_i\,x_i$ Beam 2	$e^{-(\mu/\rho)_i\rho_i x_i}$ Beam 1	$e^{-(\mu/\rho)_i\rho_i x_i}$ Beam 2
1½"	Air	0.189	8.36E-4[a]	1.397	2.032	2.21E-4	3.21E-4	0.99978	0.99968
	Be	0.15	1.85	1.27	0.508	0.35243	0.14077	0.70298	0.86852
	Water/Steam	0.207	1.0, 1.39E-2[b]	5.359	5.9	1.109/0.0153	1.2213/0.0185	0.32979/0.9848	0.2948/0.9817
	Be	0.15	1.85	0.508	0.508	0.14097	0.14097	0.86852	0.86852
	Air	0.189	8.36E-4	8.636	7.62	0.00136	0.0012	0.99864	0.9988
	Al	0.284	2.7	0.0528	0.0508	0.04049	0.03895	0.96032	0.9618
	Air	0.189	8.36E-4	0.37	0.36	5.846E-5	5.688E-5	0.9999	0.9999
2"	Air	0.189	8.36E-4	1.397	2.032	2.21E-4	3.21E-4	0.99978	0.99968
	Be	0.15	1.85	1.27	0.508	0.35243	0.14077	0.70298	0.86852
	Water/Steam	0.207	1.0/1.39E-2	4.158	4.925	0.8607/0.0088	1.0194/1.42E-2	0.42284/0.9988	0.36018/0.98603
	Be	0.15	1.85	0.508	0.508	0.14097	0.14097	0.86852	0.86852
	Air	0.189	8.36E-4	8.636	7.62	0.00136	0.0012	0.99864	0.9988
	Al	0.284	2.7	0.0533	0.0508	0.02724	0.03875	0.97313	0.96180
	Air	0.189	8.36E-4	0.373	0.36	5.894E-5	5.688E-5	0.99994	0.99994

TABLE C.2. CALCULATED UNATTENUATED COUNT RATES[d]

	1½" Spool Beam 1	1½" Spool Beam 2	2" Spool Beam 1	2" Spool Beam 2
dA (cm^2)	0.2818	0.2818	0.2818	0.2818
r (cm)	14.732	15.044	13.531	14.069
dA/r^2 (STER)	0.0013	0.00125	0.00154	0.00142
I_0 (counts/s)	90890	87159	107741	99658

a Air assumed to be a perfect gas at P=1 ATM & 422K (300°F)

b Sat. steam at 2.76 MPa (400 PSIA)

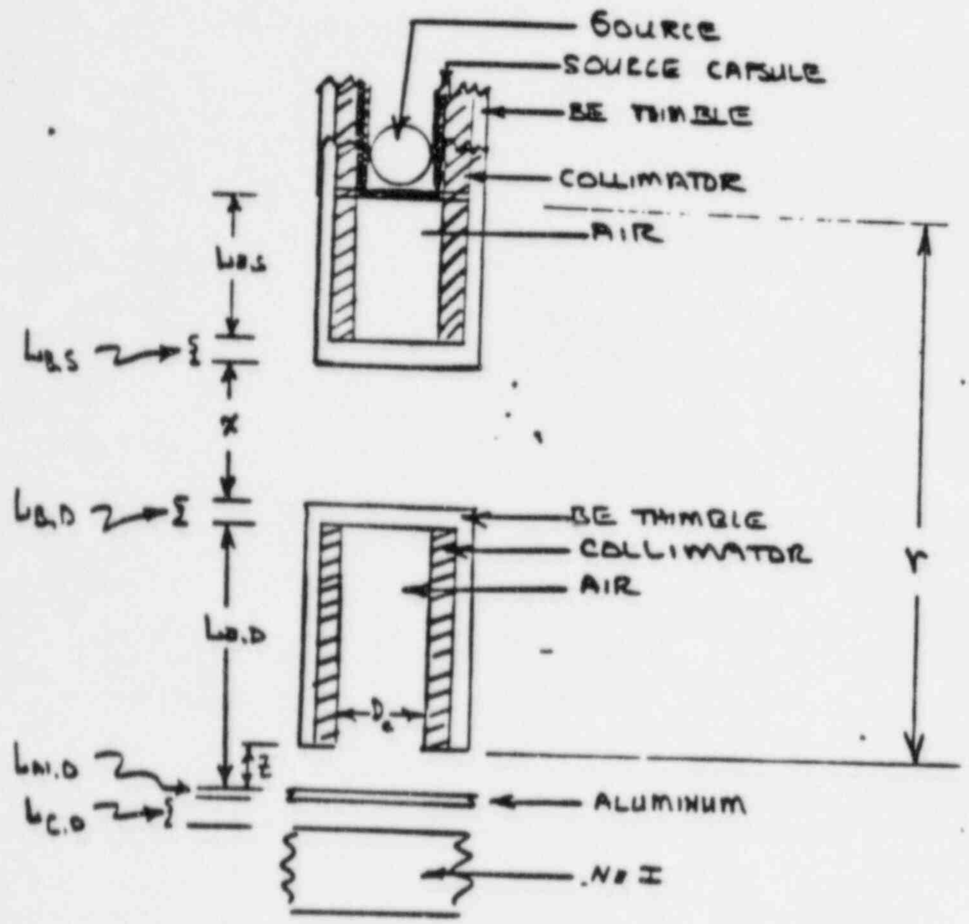
c Beam 1 is the off-diameter beam; Beam 2 is the diametral beam

d Not accounting for detector efficiency

TABLE C.3 CALCULATED ALL GAS AND ALL LIQUID COUNT RATES RECEIVED AT DETECTOR SURFACE.[a]

	2½" Sch 80 Spool		2" Sch 80 Spool	
	BEAM 1	BEAM 2	BEAM 1	BEAM 2
I_f (PHOTONS/s)	17545	18615	27025	26044
I_g (PHOTONS/s)	52389	62078	63142	71180

a. IE, DETECTOR EFFICIENCY NOT FACTORED IN.



		2½" Sch 80*		2" Sch 80	
		Beam 1	Beam 2	Beam 1	Beam 2
(Air)	$L_{a,s}$ (cm)	1.397	2.032	1.397	2.032
(Be)	$L_{B,S}$ (cm)	1.27	0.508	1.27	0.508
(H_2O)	X (cm)	5.359	5.9	4.158	4.925
(Be)	$L_{B,D}$ (cm)	0.508	0.508	0.508	0.508
(Air)	$L_{a,D}$ (cm)	8.636	7.62	8.636	7.62
(Al)	$L_{Al,D}$ (cm)	0.0528	0.0508	0.0533	[illegible]
(Air)	$L_{C,D}$ (cm)	0.37	0.36	0.373	0.36
	D_c (cm)	0.599	0.599	0.599	0.599
	z (cm)	2.438	1.524	2.438	1.524

* BEAM 2 DENOTED AS THE DIAMETRAL BEAM

CONTROL NO.

FIGURE C.1 APPROXIMATE PATH LENGTHS - SOURCE TO DETECTOR