NIST COMMITMENT TO NATIONAL MQA PROGRAMS

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Abstract - The program of the Ionizing Radiation Division, Physics Laboratory is discussed, especially relating to standards, calibrations, and measurement quality assurance (MQA). The NIST program is "vertically integrated," meaning that activities extend from fundamental research to measurement research to supplying services and data. Typical methods NIST uses to assure the quality of the national standards are presented. Some of the programs in x-ray, gamma-ray, electron, neutron, and radioactivity research which support MQA are presented. Examples are given of MQA activities.

INTRODUCTION

The primary responsibility within NIST for MQA for ionizing radiations rests with the Ionizing Radiation Division, which is part of the Physics Laboratory, one of eight major Operating Units of NIST. In order to carry out its service missions, such as instrument calibration and measurement quality assurance, the Division is "vertically integrated." Vertical integration means activities stretch from fundamental research to measurement research to supplying services such as radioactivity standard sources (Standard Reference Materials or SRMs), evaluated data, calibrations, and MQA testing. All of these kinds of activities are located within the Division.

To carry out its mission, the Ionizing Radiation Division is organized into four groups, shown in the middle row of boxes in Figure 1. The Office of Radiation Measurements has the chief responsibility for outreach to the radiation community, and also provides MQA to a system of "reference laboratories" in various sectors, such as the federal government, state governments, industry, and the medical or health care industry. The major project of the Office of Radiation Measurements is MQA, as shown in the bottom row of boxes, where major projects are indicated. In the Division are three technical groups: Radiation Interactions and Dosimetry is responsible for research, measurements, and standards for x-rays, gamma-rays, and electrons. Neutron Interactions and Dosimetry is similarly responsible for neutrons, and Radioactivity for radionuclide metrology.

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CUSTOMERS

The Ionizing Radiation Division serves a diverse community of radiation users and measurers. As indicated in Table 1, the fields of diagnostic radiology and nuclear medicine are ubiquitous, and about 15% of us may expect to receive radiation therapy during our lifetime. Over one million radiation workers are badged for radiation protection. Public concerns focus on radon in homes and buildings and on environmental radioactivity, especially when it is found in food and water.

Industrial applications of radiation, shown in Table 2, include industrial radiation processing for sterilization of medical supplies, improvement of the properties of plastics, and curing of wire insulation and organic coatings; nuclear electric power provides 22% of U.S. electricity and represents a large capital investment. Smaller industrial applications include industrial radiography and the field of radiation effects on electronic devices, important for space and military applications.

Fundamental scientific research (see Table 3) in long-term support of measurements and standards programs is carried out on the physics of radiation interactions, especially at the nanometer level, and on resonance ionization spectroscopy for atom counting which, has important potential applications in environmental radioactivity assessment. Fundamental neutron physics is carried out at the Cold Neutron Source of the NIST nuclear reactor and includes neutron lifetime measurement, neutron interferometry for testing the bases of quantum theory, and experiments with polarized neutrons.

MEASUREMENT QUALITY ASSURANCE

The Office of Radiation Measurements, as indicated in Figure 1, has a major responsibility for MQA, especially for the creation of a national system of secondary, or reference, laboratories located where needed in both the governmental and private sectors (Inn et al. 1993). How the reference laboratory system works is indicated in Figure 2. A reference laboratory is accredited, not by the NIST Ionizing Radiation Division, but by other organizations such as the Conference of Radiation Control Program Directors (CRCPD), the Health Physics Society, the American Association of Physicists in Medicine (AAPM), or the National Voluntary Laboratory Accreditation Program (NVLAP), which operates out of NIST. The accrediting organization makes a decision whether or not to accredit a given reference laboratory based on a number of criteria, such as the technical qualifications of personnel, adequate equipment for the laboratory's job, an in-house quality control system, and, finally, satisfactory performance on MQA testing by NIST. The user's motivation for calibration or MQA testing is shown as the "driving force," which may be regulatory requirements, codes of good practice, assurance of legally defensible measurements, or simply a desire for high confidence in measurement.

A rough picture of the developing system of reference laboratories located in the state, federal, medical, and industrial sectors is shown in Figure 3. A summary of the current status of the national system of reference laboratories is presented in Table 4. The AAPM and CRCPD systems of laboratories have been well established for many years, whereas accreditation of the survey instrument laboratories by the Health Physics Society and of the federal laboratories by NVLAP is just getting underway. New programs for reference laboratories are underway for bioassay, high-level dosimetry, environmental radioactivity, and commercial radioactivity standards. The Accredited Dosimetry Calibration Laboratories of the AAPM are shown in Figure 4.

A different approach to measurement quality assurance is represented by the collaborative programs of the U.S. Council for Energy Awareness (USCEA) with the National Institute of Standards and

Technology (Gray, Golas, and Calhoun 1990). These programs are carried out by Research Associates from USCEA who are located at NIST and work closely with the NIST Radioactivity Group. The two traceability programs are Radiochemistry for the Nuclear Power Industry (see Figure 5) and for Radiopharmaceutical Manufacturers. As indicated in Figure 5, the driving force for the Radiochemistry program is regulatory requirements of the Nuclear Regulatory Commission. The program is primarily for electric power utilities and the laboratories that provide them with services, but commercial calibration source suppliers also participate. Some results from the Radiopharmaceutical program are shown in Figure 6. Largely as a result of this program, the vast majority of the proficiency test results are within 10% (the FDA requirement) of the NIST value.

Another NIST service for the radiation community is the calibration of neutron sources for neutron emission rate (McGarry and Boswell 1988). The most popular source is the ^{252}Cf spontaneous fission neutron source. Some of these sources are very intense, producing more than 10^9 neutrons/s in a capsule the size of a pencil eraser (the actual source material is much smaller). Consequently, special facilities are required for source handling. Figure 7 shows the 1.27-meter diameter manganous sulfate bath in which sources are calibrated by activation of ^{55}Mn, located behind a shielding window equipped with a remote handling arm.

STANDARDS AND RESEARCH ACTIVITIES

Methods for Assuring Quality of NIST Standards

The MQA services provided by NIST are of little value unless they are backed up by reliable, state-of-the-art standards, and transfer instruments or methods. How does NIST assure the quality of NIST standards? Four methods are indicated in Table 5. Intercomparisons with other national standards laboratories and leading research laboratories assure that we are all on the same international measurement scale. If the intercomparisons show disagreement, they show areas where more study is needed. Many of these intercomparisons are organized by the Consultative Committee for Measurement Standards of Ionizing Radiations (CCEMRI, from its French name), which meets at the International Bureau of Weights and Measures (Bureau International des Poids et Mesures or BIPM) in Sèvres, a suburb of Paris (see, for example, Caswell and Lewis 1992). Others are organized by the International Committee for Radionuclide Metrology (ICRM).

A second method for assuring the validity of national standards is to measure the value of the standard by several independent physical methods. For example, absorbed dose can be measured by calorimetry, ionization chamber methods, and Fricke (ferrous sulfate) dosimetry. This is perhaps the best way to gain information on systematic errors. If all methods agree, we assume the standard is fine. If methods disagree, we know where to look for problems.

A vigorous program of measurement research is necessary for developing new standards and transfer instruments and to have a deep understanding of the whole measurement process. Fundamental research helps in two ways: 1) to accomplish the goal of the fundamental research, measurement techniques of unprecedented accuracy are frequently needed—and developed and 2) fundamental research is a source of new ideas for primary standards. For example, many of our standards defined on an atomic basis have come from fundamental research. We shall now cite a few examples of the research carried out in the NIST Ionizing Radiation Division, which we expect to lead to better standards and transfer instruments on a shorter or longer time scale.

X-Ray, Gamma-Ray, and Electron Research

The simplest way in principle of measuring absorbed dose to a material is through the temperature rise, i.e., a calorimeter. Protocols for radiation therapy with ^{60}Co gamma-rays and high-energy x-rays call for the determination of the absorbed dose to water, from which the dose to the human body is determined by calculation. The usual method used for determining the absorbed dose to water has been by measuring ionization to air in an ionization chamber and correcting to water, a less direct method than the calorimeter. When calorimetric measurements were attempted, a graphite calorimeter was usually used. The graphite calorimeter, of course, has the problem of the correction from absorbed dose in graphite to absorbed dose to water. Steve Domen of NIST solved this problem by inventing the water calorimeter, shown in Figure 8. It would never have occurred to me that you could make a calorimeter out of water. The first water calorimeters did have a serious problem of calorimetric defect—excess heat produced by chemical reactions in the water. This was resolved by several workers by purifying the water to eliminate the reactions (Domen 1988). The water calorimeter is now taking its place as a primary standard for high-energy x-rays and gamma-rays.

A new idea coming out of NIST measurement research is the Laser Telemetering Dosimetry System, an R&D 100 Award winner by William McLaughlin and Marlon Walker. The experimental arrangement is shown in Figure 9. The key detector is the radiochromic dye film sensor located in the field of the radiation source. As the film is irradiated, it darkens with nanosecond time resolution, the increase in optical density being used as a measure of the radiation field. The dye film is interrogated with a He-Ne laser; the transmitted light impinging on a photodiode followed by appropriate electronics and a computer. This device has many possible applications for quick, easy, and inexpensive measurement of radiation fields in remote locations or which vary rapidly with time (Walker and McLaughlin 1990).

For many years NIST has calibrated beta-ray ophthalmic applicators used for radiation therapy of eye diseases. The usual calibration has been carried out with an extrapolation ionization chamber, the result being given in terms of absorbed dose rate averaged over an effective area for the applicator. However, the application of the laser-scanning microdensitometer (Soares 1992) to read the energy absorbed in a radiochromic dye film placed on the face of the applicator and backed by a tissue-equivalent plastic phantom has made it possible to provide the customer with much more detailed information about the applicator, as shown in Figure 10. In the lower part of the figure is an isodose plot for the applicator, giving information about the uniformity and location of the radiation dose from the applicator. The top part of Figure 10 shows a three-dimensional plot of the same information, the absorbed dose rate being given on the vertical axis. These plots are now routinely supplied with the calibration report for the applicator.

An advanced method of dosimetry now being pursued vigorously at NIST is Electron Paramagnetic Resonance (EPR) Dosimetry, also known as Electron Spin Resonance (ESR) dosimetry. This method, while not extremely sensitive, has the advantage of being suitable for post-irradiation dosimetry. Applications include radiation sterilization and processing, detecting irradiated foods, evaluating absorbed dose from irradiation accidents using bone samples or tooth enamel from the victims (Chernobyl), and measurements of bone biopsy samples in radiation beam therapy or radiopharmaceutical therapy. Figure 11 shows a typical EPR spectrometer (Kojima et al. 1993), the sample being placed in the microwave cavity in the field of a strong magnet. Figure 12 shows the typical signals received from a bone sample and an alanine sample, alanine being widely used for EPR dosimetry.

To carry out these NIST research programs, we need a wide variety of x-ray, gamma-ray, electron, and neutron sources, as well as many kinds of radioactive sources in solid, liquid, and gaseous forms. For the x-ray and electron program, an important new source is the Medical-Industrial Radiation Facility (MIRF), now being installed in the Radiation Physics Building. The basic accelerator is shown in Figure 13. It is an electron linear accelerator, push-button operable from 7 to 32 MeV in steps of 3 MeV. It will be used for dosimetry research in support of radiation therapy of cancer and industrial radiation processing, and also for development of new radiation processing technologies.

Neutron Research

Neutron measurements are particularly important for all forms of nuclear power and for worker protection. One of the approaches to neutron standardization is through creation of well-characterized standard neutron fields in which instruments or foils can be placed for calibration. One of these fields, the ^{252}Cf standard neutron field, is shown in Figure 14. The tiny neutron source is a small right circular cylinder located just above the small sphere located at the bottom of the figure. On either side of the source are located two NIST fission ionization chambers which are detectors used in many experiments. Use of two detectors at 180^{o} to each other makes the experiments less sensitive to actual source position. Neutron cross-sections for fissionable isotopes are often measured in this way. In the particular experiment shown, the sphere is filled with water, with the source placed at the center, and benchmark measurements are made to check computer codes used to assure the safety of large containers used to store aqueous solutions of fissionable isotopes (Gilliam et al. 1990). Other NIST standard neutron fields include pure ^{235}U and ^{252}Cf fission neutron fields and thermal neutron fields located in the thermal column of the NIST reactor, reactor-filtered neutron beams at 2, 24.5, and 144 keV, calibrated cold neutron beams, a D_2O-moderated ^{252}Cf neutron source, the Materials Dosimetry Reference Facility located at the University of Michigan reactor, and monoenergetic neutron beams at 0.1-1 MeV, 2-5 MeV, and 12-18 MeV can be made available from the NIST 3-MeV positive-ion Van de Graaff accelerator.

An example of advancing the state-of-the-art of precision neutron measurement comes from a fundamental neutron physics experiment being carried out on the Cold Neutron Research Facility. The experiment is a highly-accurate measurement of the neutron lifetime (Byrne et al. 1990). One of the most difficult quantities to measure in this experiment is the neutron fluence rate (often called flux) in a cold neutron beam. Figure 15 shows an apparatus designed for one of several independent methods of measuring the neutron fluence rate—in this case, by defined solid angle counting with four solid-state detectors viewing a boron foil of known boron content. The accuracy sought in fluence rate is 0.1 percent, an accuracy almost never achieved in neutron fluence measurement.

A novel new neutron personnel dosimeter is the bubble dosimeter, shown in Figure 16. The dosimeter is made of a supersaturated tissue-equivalent gel. When a single neutron interacts with a hydrogen atom in the gel, creating a recoil proton, a bubble is produced, such as are shown in the figure. The dose can be read visually, by counting the number of bubbles, or by detecting the audible "pop" made when a bubble is formed and recording that on an appropriate electronic scaler. The NIST role has been to test these instruments in both monoenergetic and distributed neutron sources (Perks et al. 1988). The bubble dosimeter at the present state of technology is a rather special purpose dosimeter for short-term measurements but lacking good long-term stability.

Radioactivity Research

We have previously mentioned the standardization of radioactive sources and MQA testing for the radiochemistry departments of nuclear power plants and for radiopharmaceutical manufacturers, which are done in collaboration with research associates from the USCEA. Quite a different problem is the standardization of radon measurements, important for quality control of the many small companies that provide radon measurements for homes and buildings. The primary standard for radon, an alpha-particle emitting colorless noble gas, is a pulse ionization chamber (Collé, Hutchinson, and Unterweger 1989), four of which are shown at the bottom of Figure 17. Each radon alpha decay produces a large pulse that can be counted and discriminated from other events. The gas handling system is used in conjunction with the pulse ionization chambers to prepare gas samples of known activity. Gas samples can be used for measurement traceability and for MQA testing. For example, in Figure 18 is shown the results of a measurement intercomparison carried out in 1990 between many of the leading radon measurement laboratories in the world. These are difficult measurements, but the spread of values is under 8%.

Radioactivity research and development activities sometimes are called on to address some very practical problems. For example, the military services needed a calibration source for large-area alpha survey meters. NIST developed the calibration device shown in Figure 19, which is supplied with both ^{239}Pu and ^{238}Pu sources (Unterweger, Hutchinson, and Hodge 1993). The calibration accuracy is in the range of 2-4%.

REMARKS

We believe that most critical dosimetry MQA needs are being met by NIST, but there are some new areas where the programs need to grow. We are looking to the Council on Ionizing Radiation Measurements and Standards (CIRMS), discussed in another paper at this meeting, for guidance on program direction and priorities. NIST is convinced that a strong research program is necessary to back up our calibration, standard reference material, and measurement quality assurance programs. We expect a steady expansion of MQA efforts, especially in the area of radioactivity. Information on radiation user needs and problems is most welcome.

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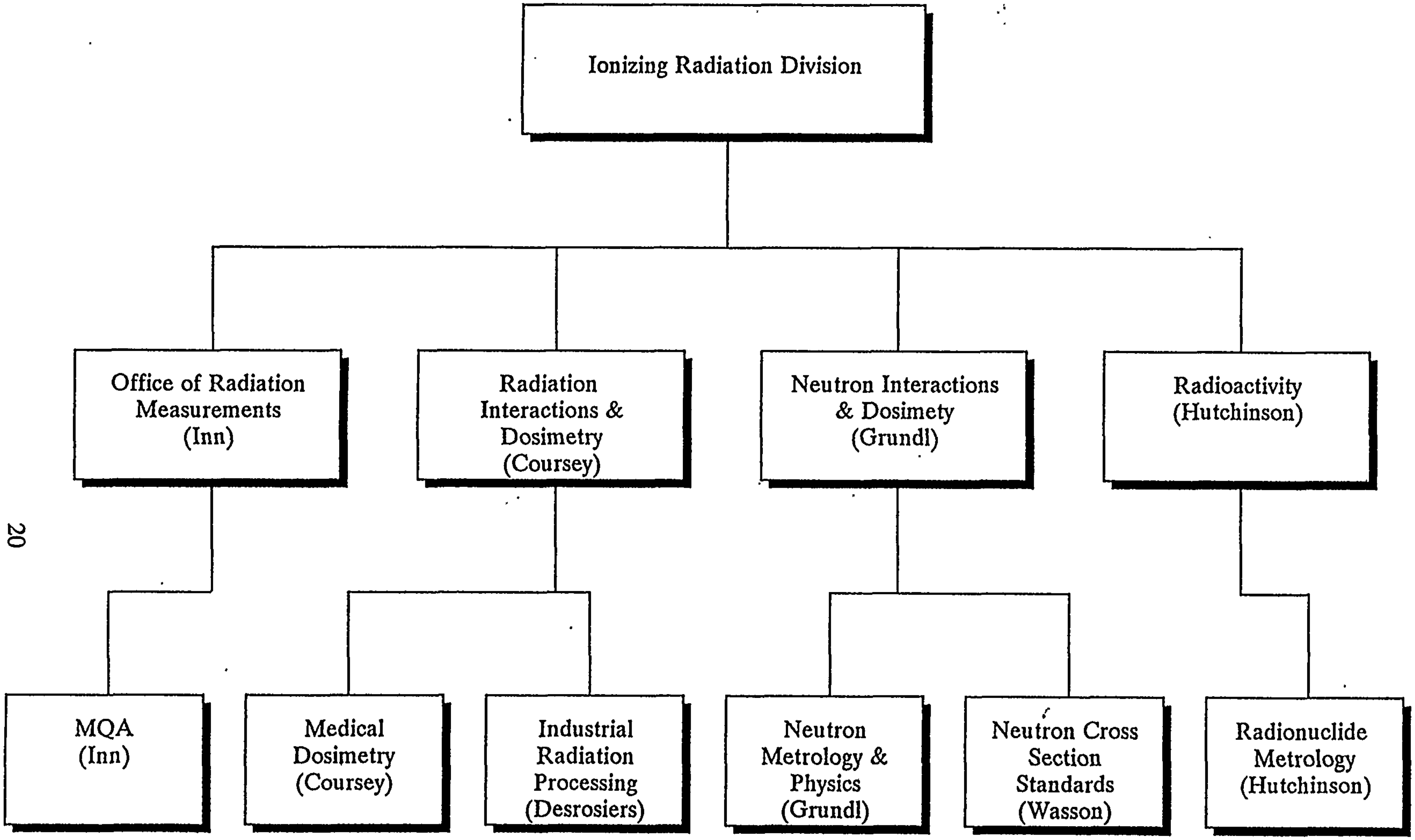


Figure 1 - Organization of the NIST Ionizing Radiation Division. Groups are shown in the middle row, and major projects in the bottom row.

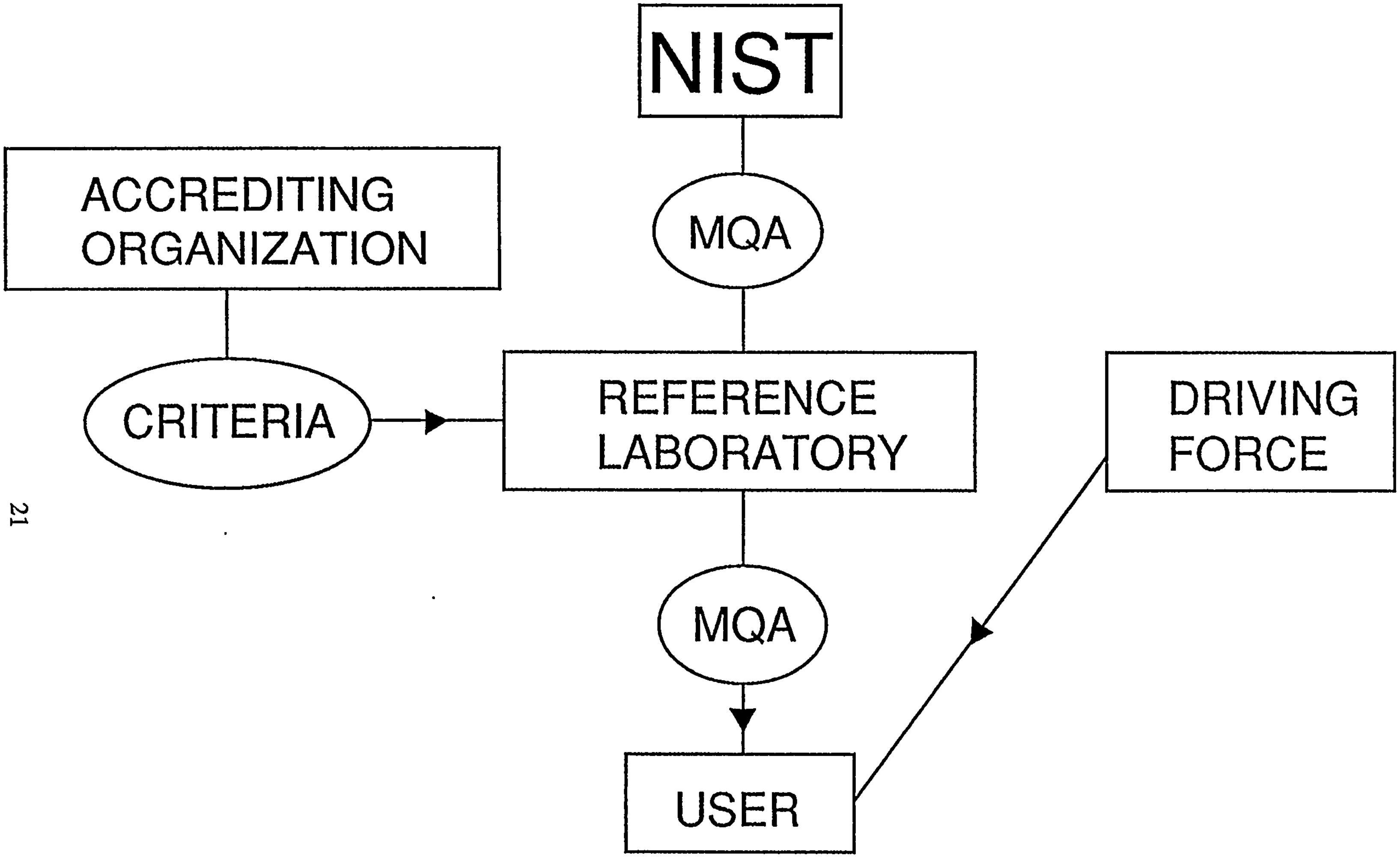


Figure 2 - Usual Structure for Measurement Quality Assurance. (See text for discussion of how this system works.)

ASSURING RADIATION MEASUREMENT QUALITY

We Help the Nation Achieve Quality Control for Health and Safety, Industrial Productivity, and Defense and Aerospace

NATIONAL MEASUREMENT SUPPORT SYSTEM

- **Approximately a quarter million ionizing radiation sources and detectors require calibration or measurement standards in this country.**
- **There are 100,000 dental, 135,000 diagnostic, and 5,600 industrial x-ray facilities in the U.S.**

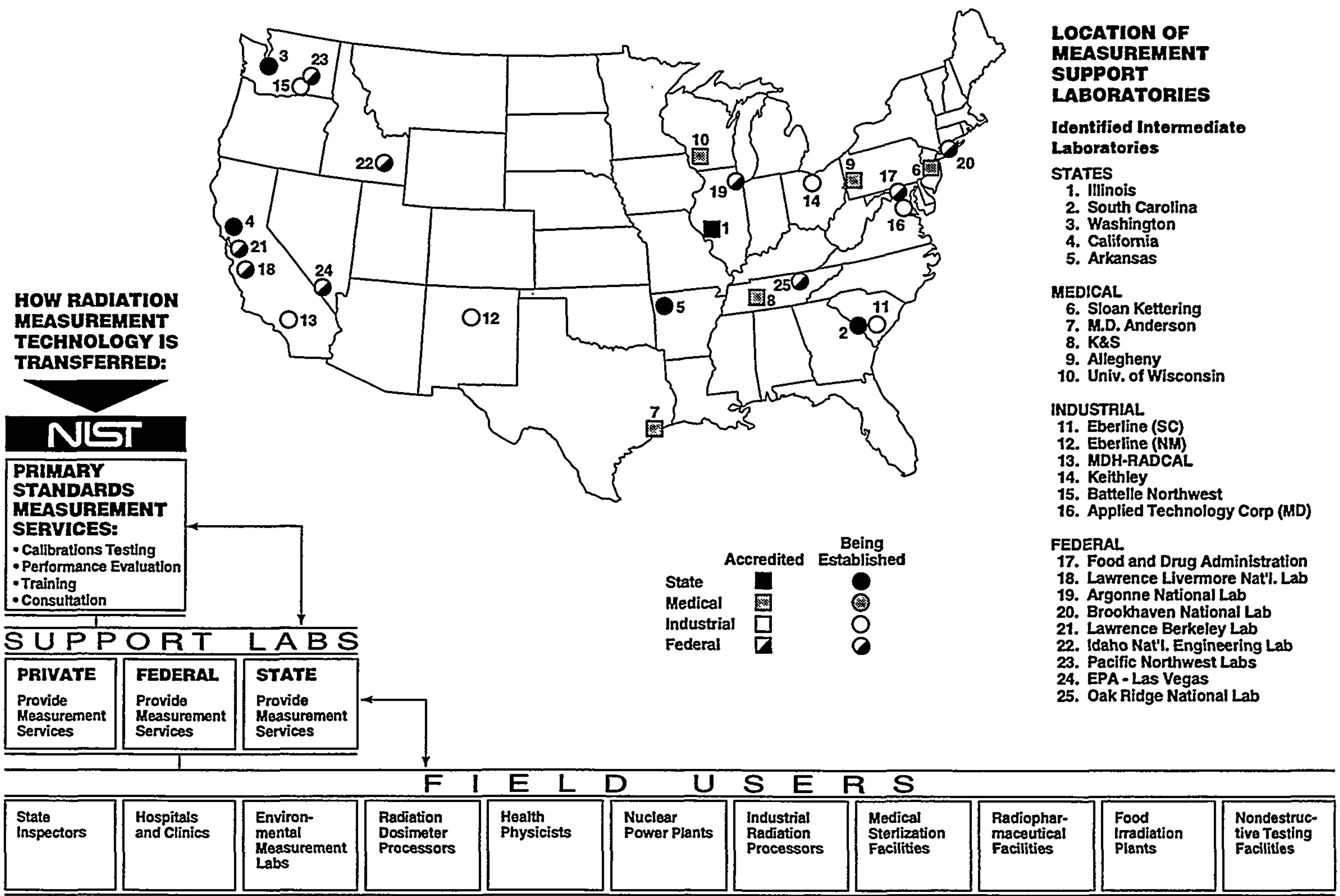


Figure 3 - System of Reference Laboratories in the United States (not current). Also called the National Measurement Support System.

American Association of Physicists in Medicine (AAPM) Accredited Dosimetry Calibration Laboratories (ADCL's)

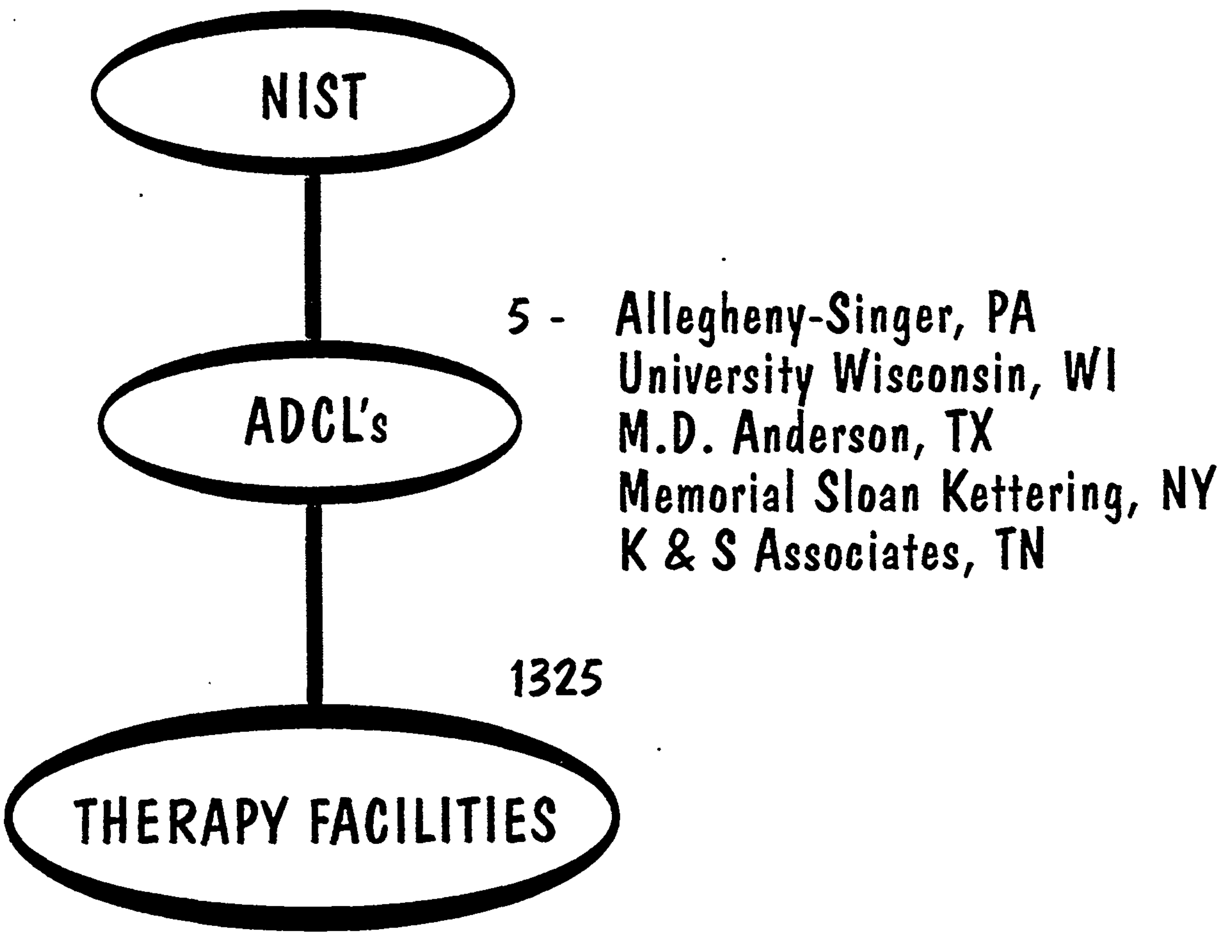


Figure 4 - Accredited Dosimetry Calibration Laboratory System of the American Association of Physicists in Medicine.

RADIOCHEMISTRY MEASUREMENT ASSURANCE PROGRAM FOR THE NUCLEAR POWER INDUSTRY

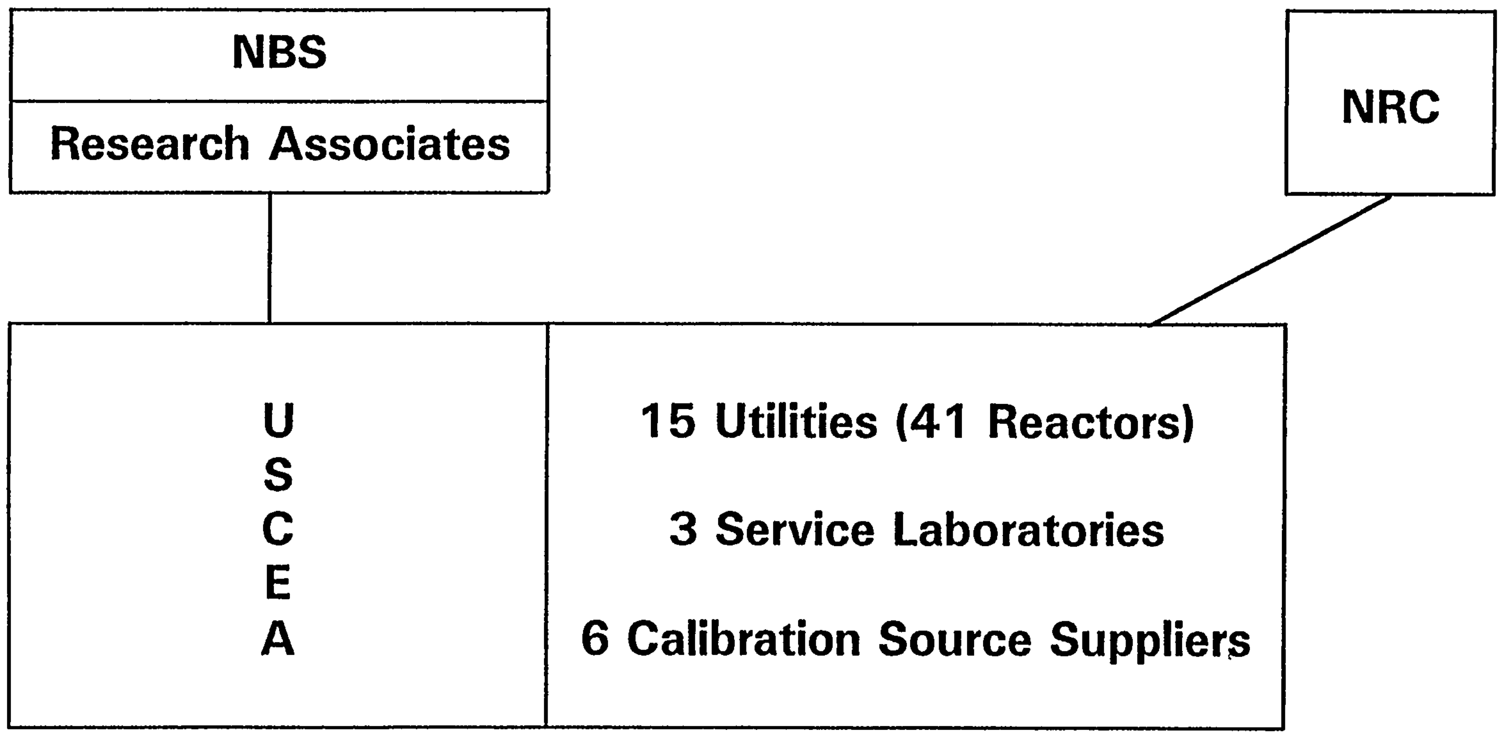


Figure 5 - Radiochemistry Measurement Assurance Program for the Nuclear Power Industry, a Collaboration Between the NIST Radioactivity Group and the USCEA.

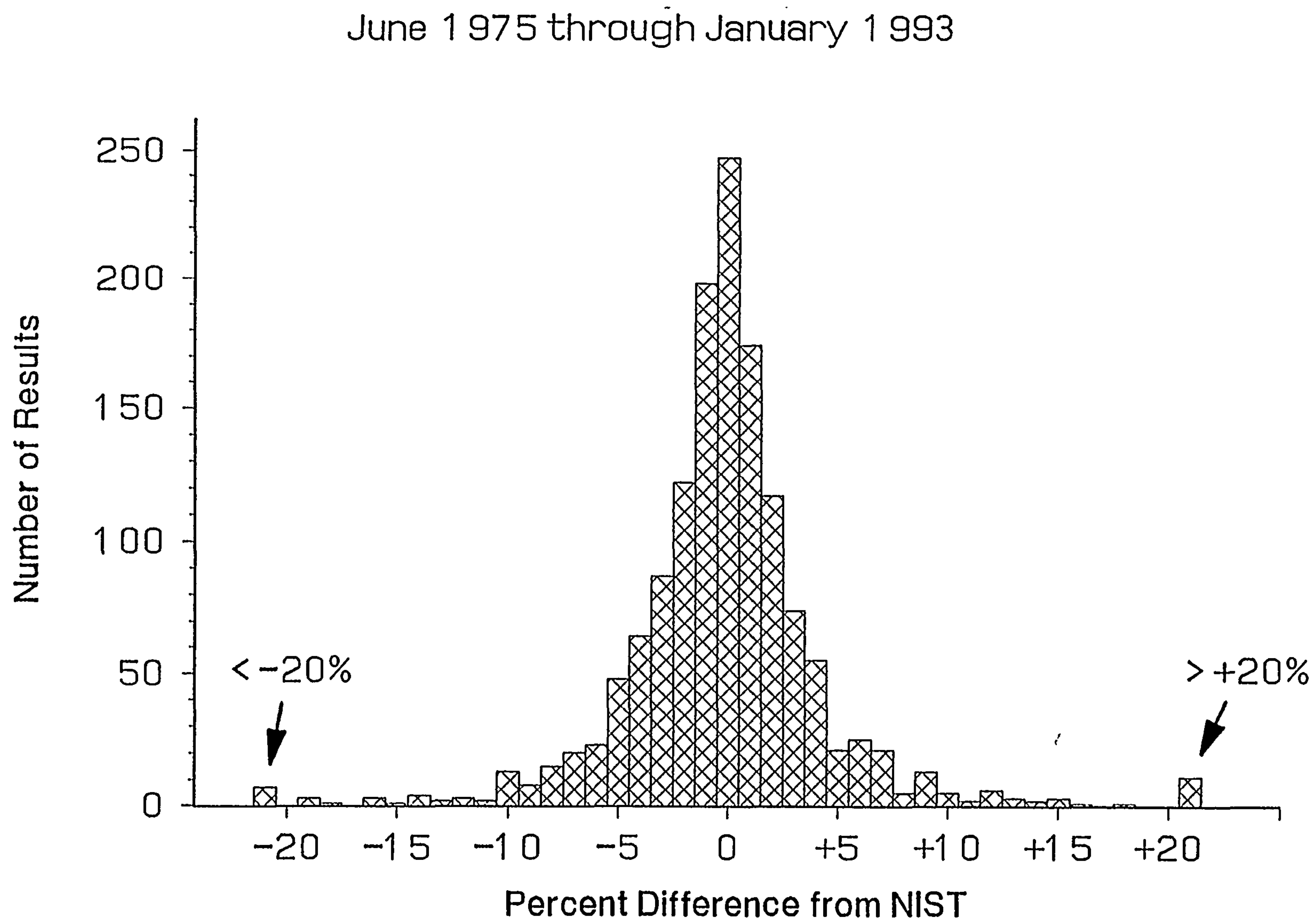


Figure 6 - Results of the Radiopharmaceutical Measurement Quality Assurance Program, Jointly Sponsored by the NIST Radioactivity Group and USCEA.

Figure 7 - Manganous Sulfate Bath for Neutron Source Calibration, Shown Behind Shielding Window and Showing Master-Slave Arm Used for Source Handling.

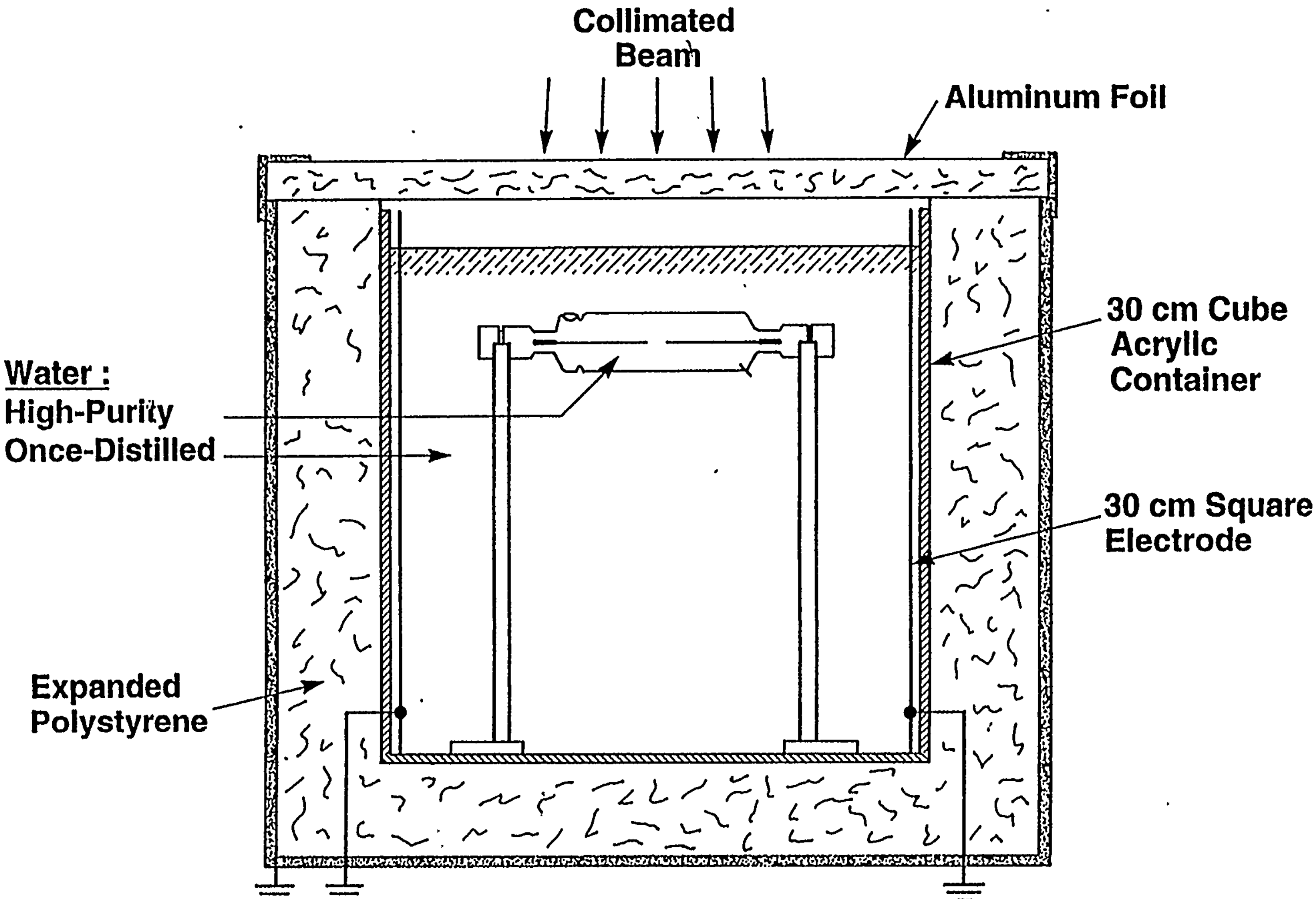


Figure 8 - Water Calorimeter, a Proposed NIST Measurement Standard for Absorbed Dose for ^{60}Co Gamma-Ray Beams and Megavoltage X-Rays.

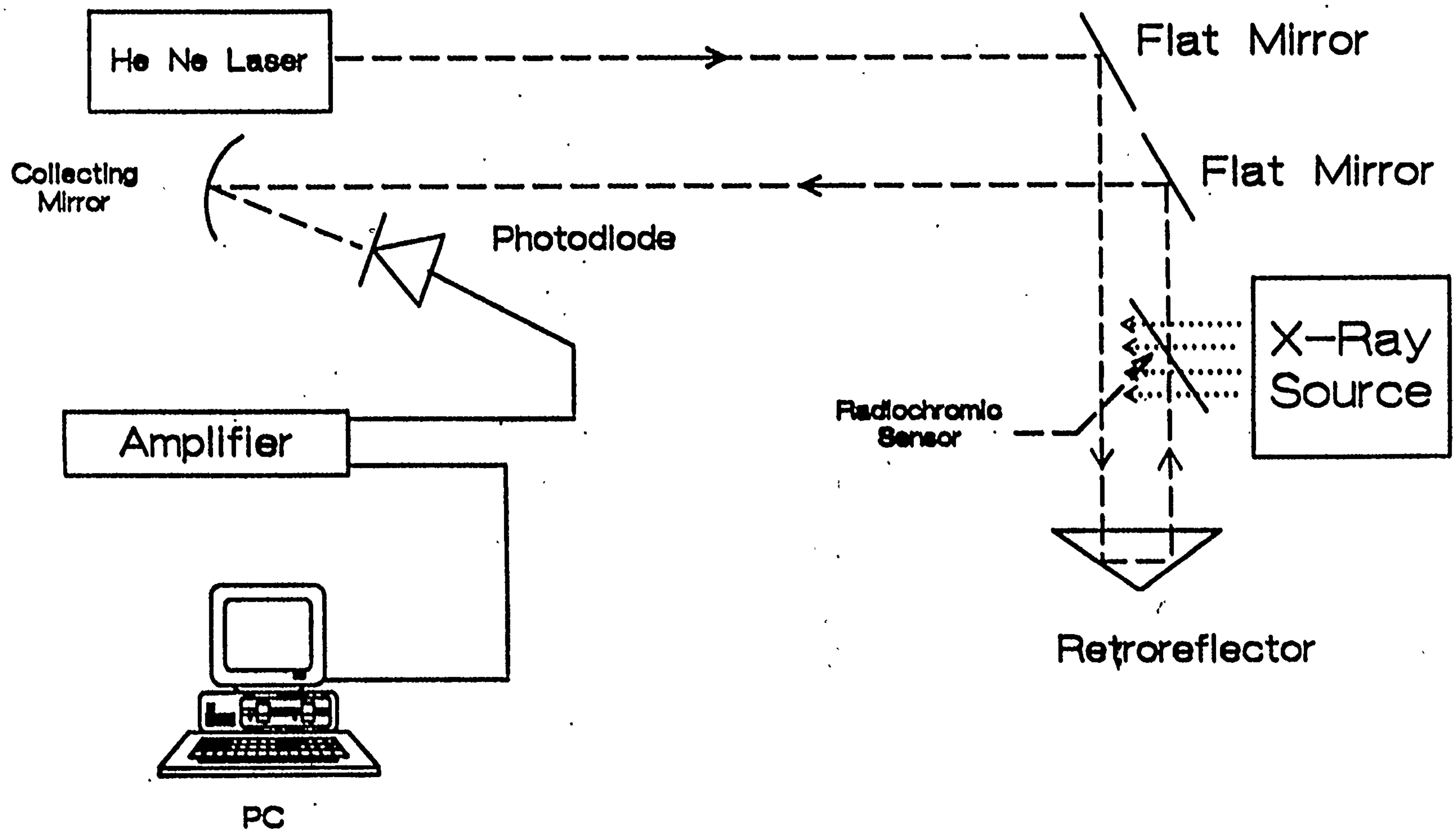


Figure 9 - Laser-Telemetering Dosimetry System.

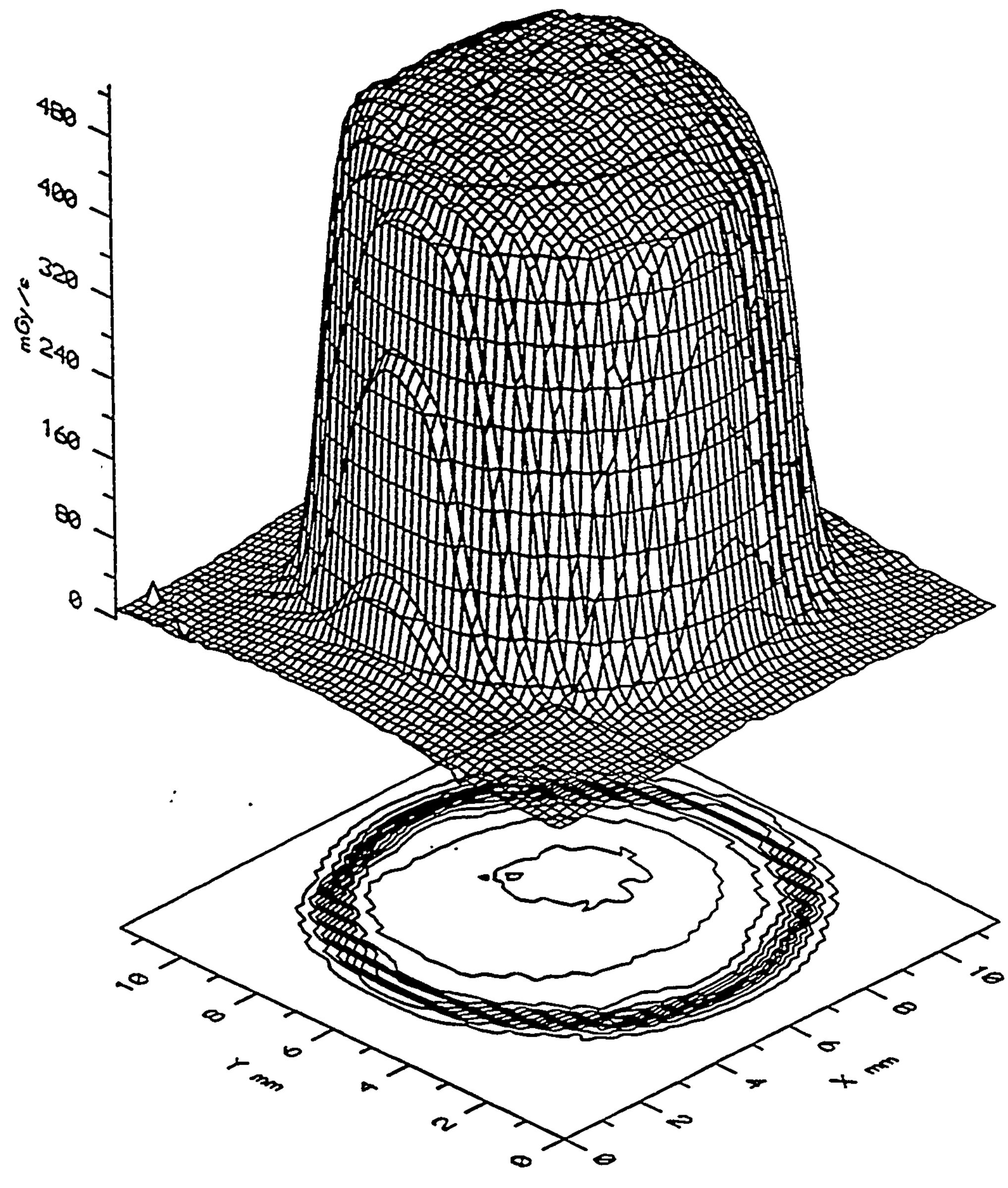
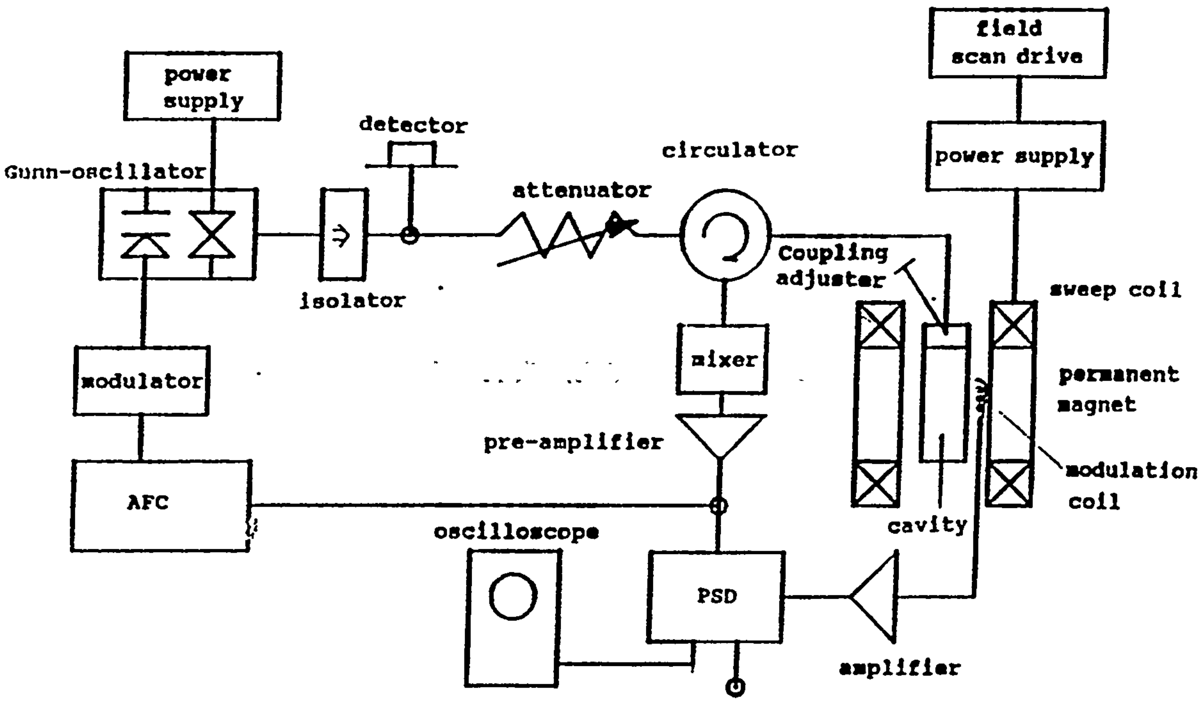


Figure 10 - Isodose Plot and Three-Dimensional Dose Plot for ^{90}Sr-^{90}Y Ophthalmic Applicator.



AFC: Auto-frequency control

PSD: Phase sensitive detector

Figure 11 - Block Diagram of a Portable ESR Spectrometer (Kojima et al. 1993).

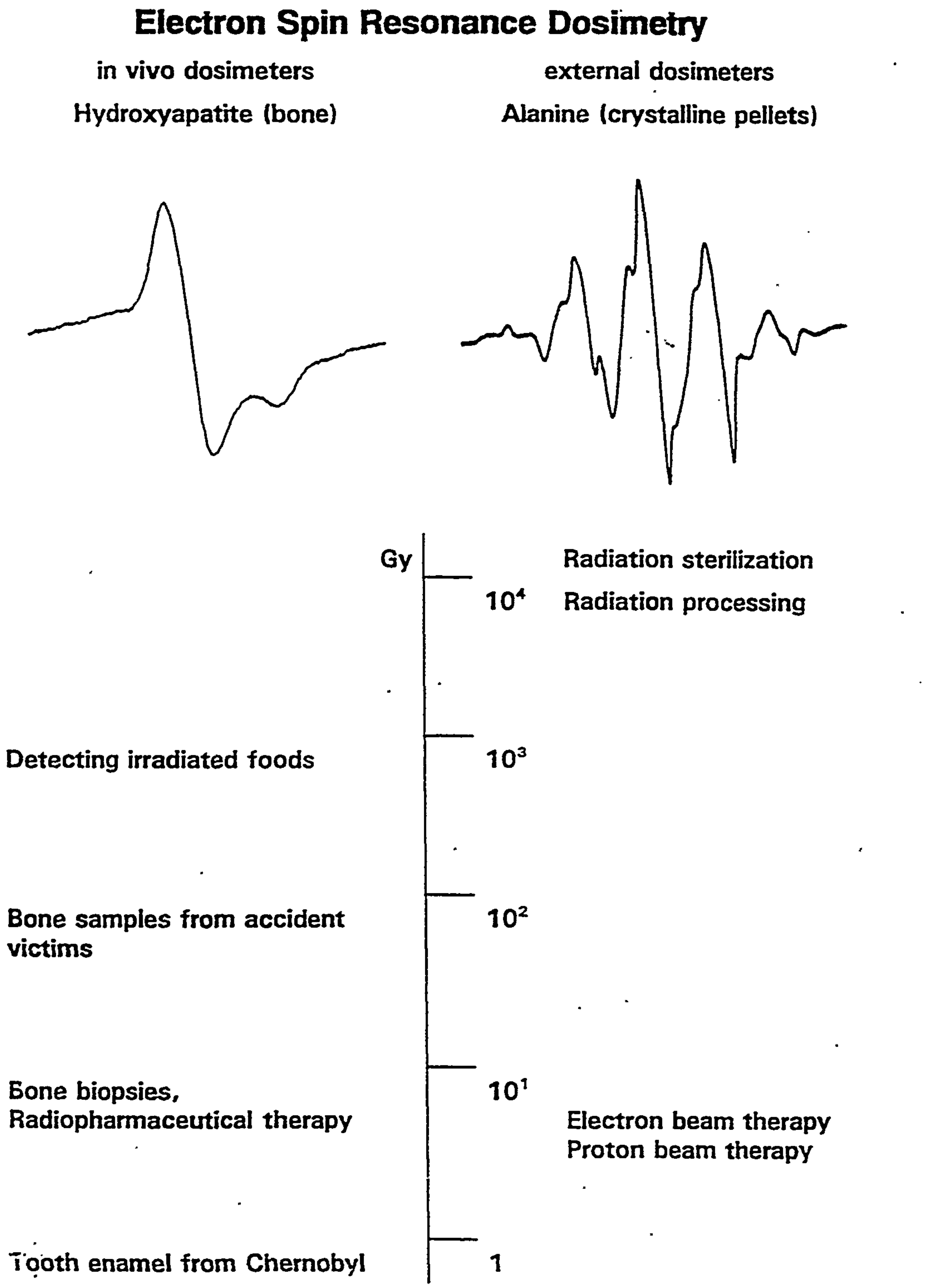


Figure 12 - Electron Spin Resonance Dosimetry (also known as Electron Paramagnetic Resonance Dosimetry), Shown for In Vivo Dosimetry in Bone and for Alanine Crystals.

MIRF

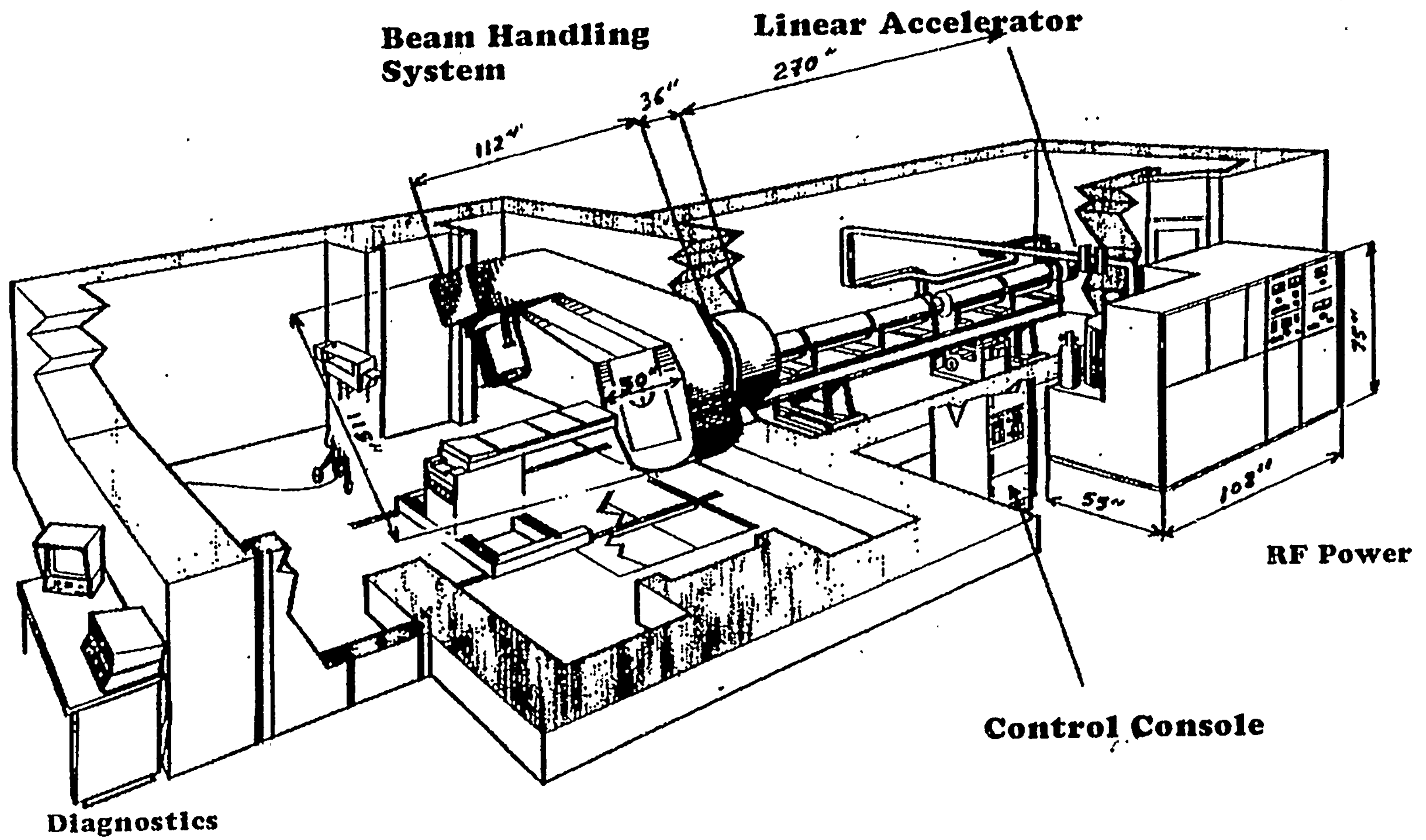


Figure 13 - Layout Diagram for the Sagittaire Linear Accelerator Being Used for the NIST Medical-Industrial Radiation Facility (MIRF). Layout at MIRF is Modified, and Will Have a Horizontal Beam Only.

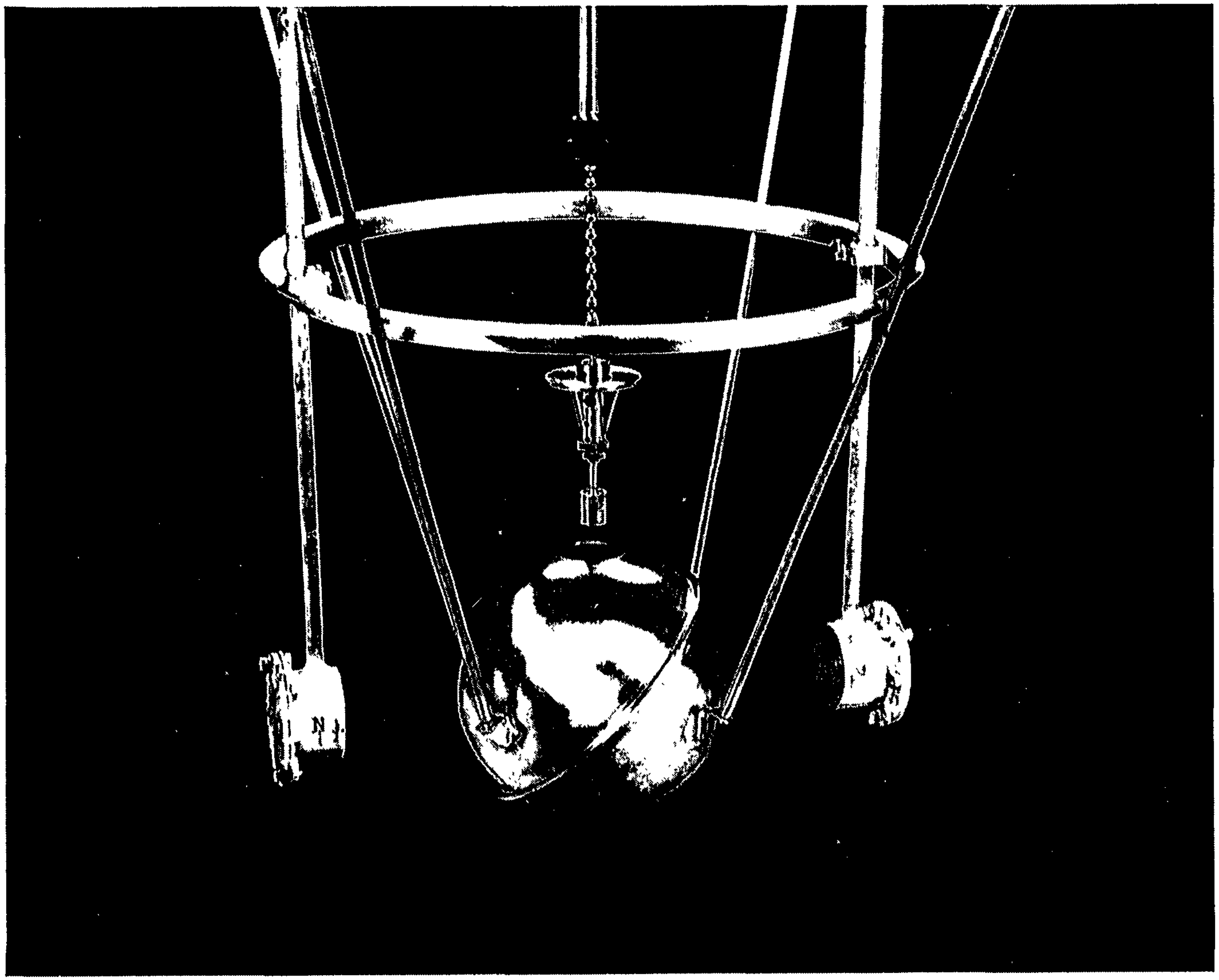


Figure 14 - Low-Scatter ^{252}Cf Irradiation Facility Shown with Source, Paired Fission Ionization Chamber Detectors, and Moderating Sphere, which is Filled with Water in the Particular Experiment Shown.

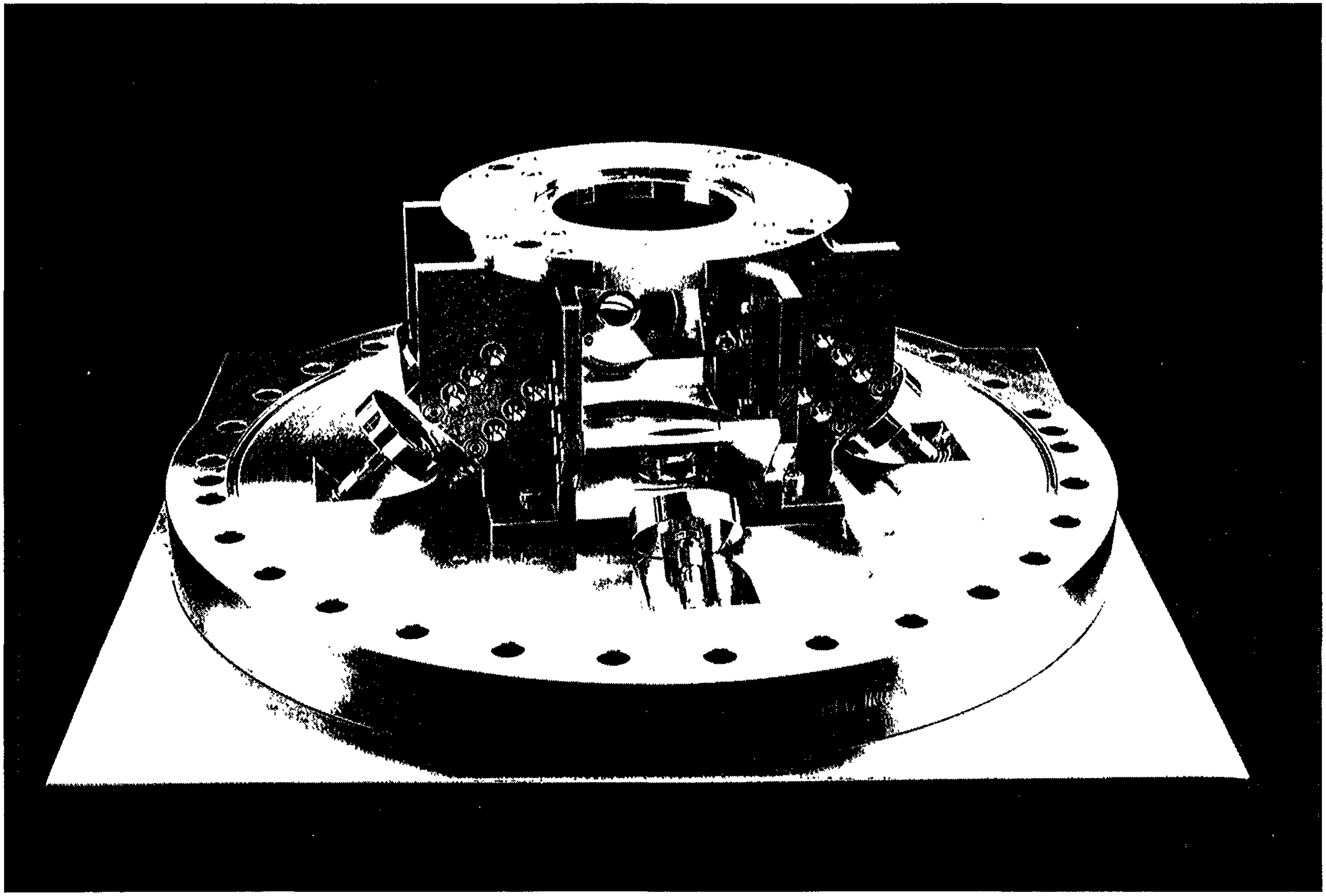


Figure 15 - Neutron Fluence-Measuring Apparatus, Using Boron Film and Known Solid Angle Alpha-Particle Semiconductor Detectors.

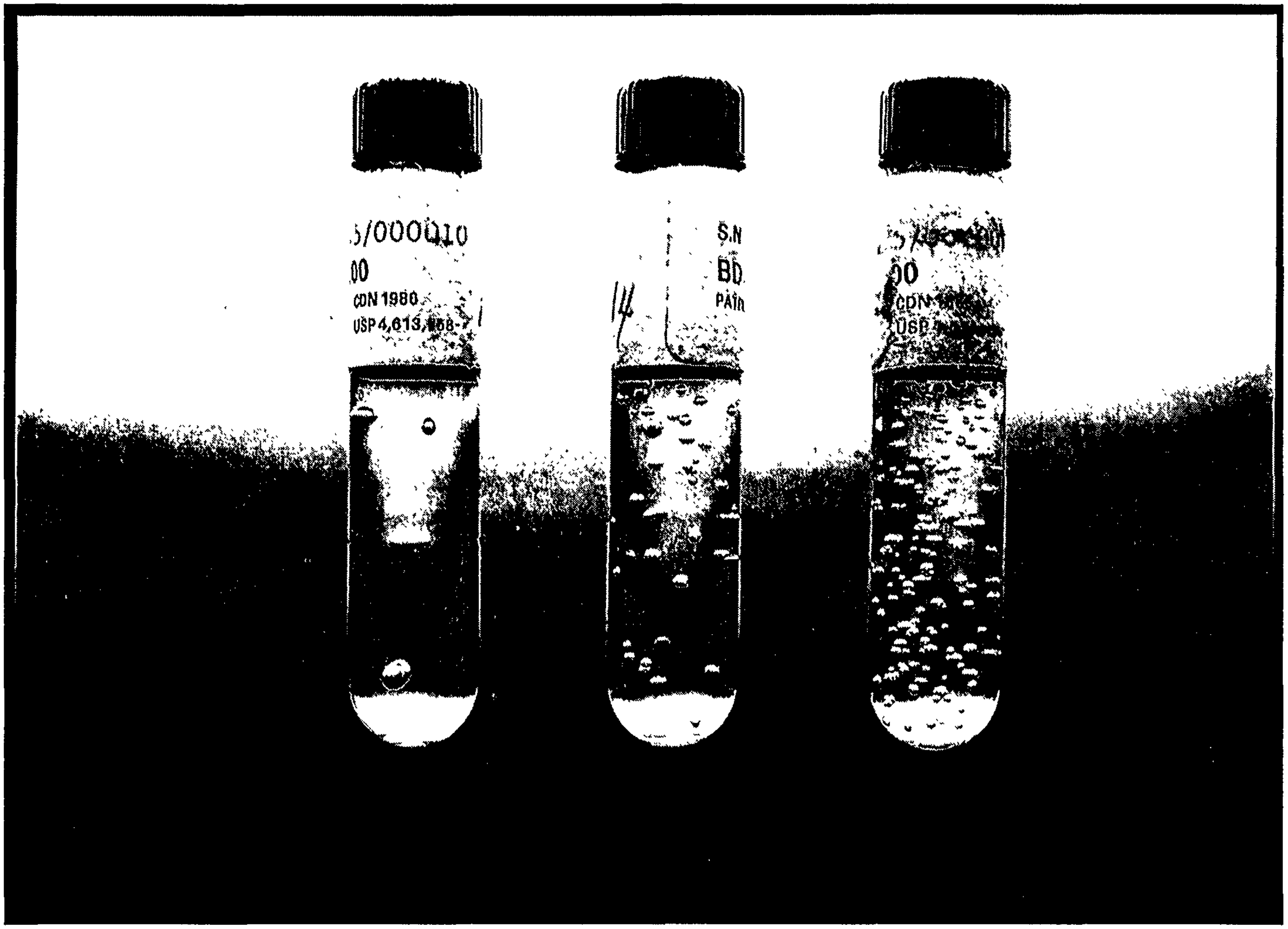


Figure 16 - Neutron-Sensitive Bubble Detectors, Showing Three Levels of Exposure.

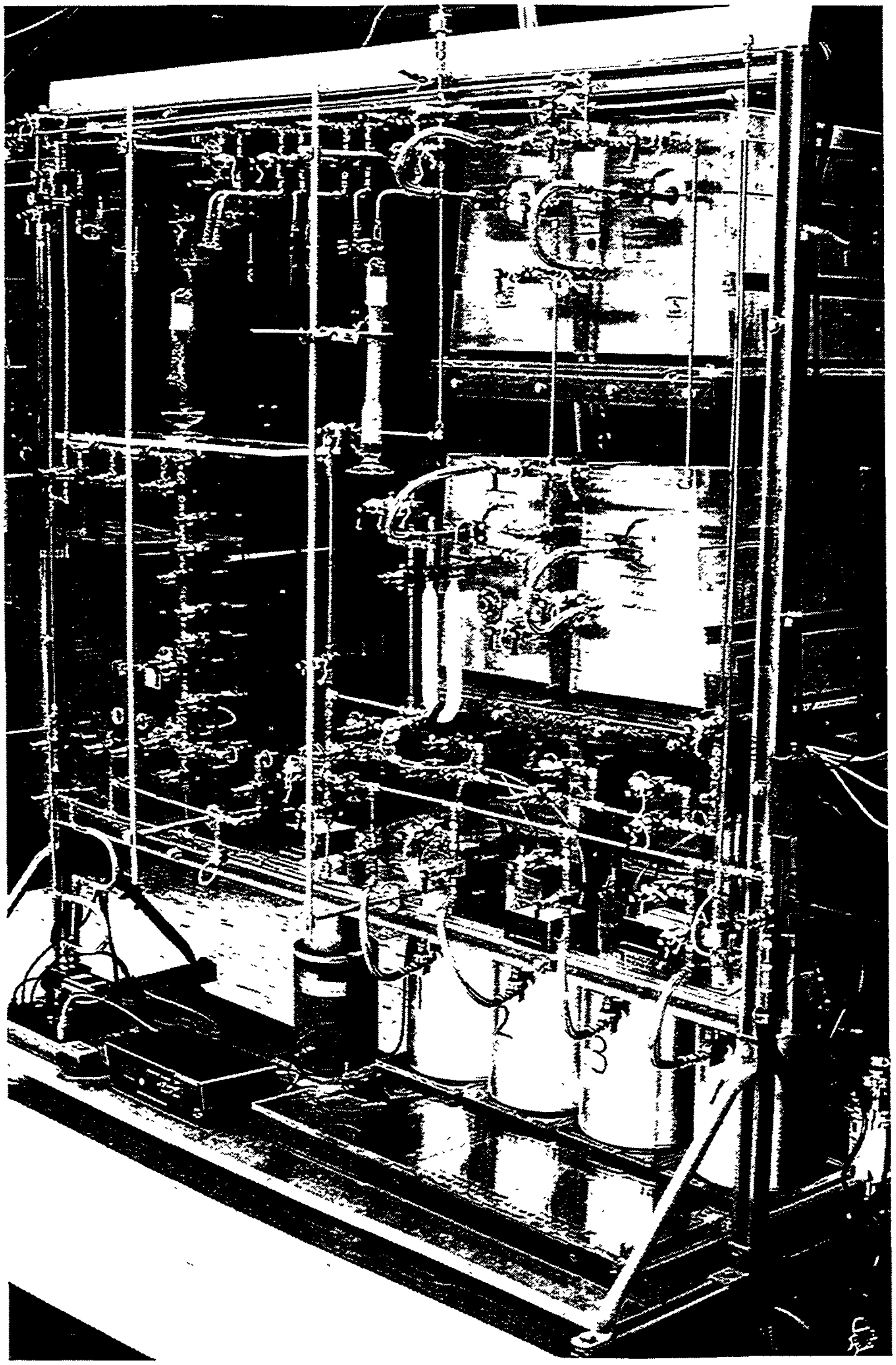


Figure 17 - Gas-Handling Apparatus for Radon Measurements. Showing the Four Pulse-Ionization Detectors (near bottom) which Serve as Primary Standards.

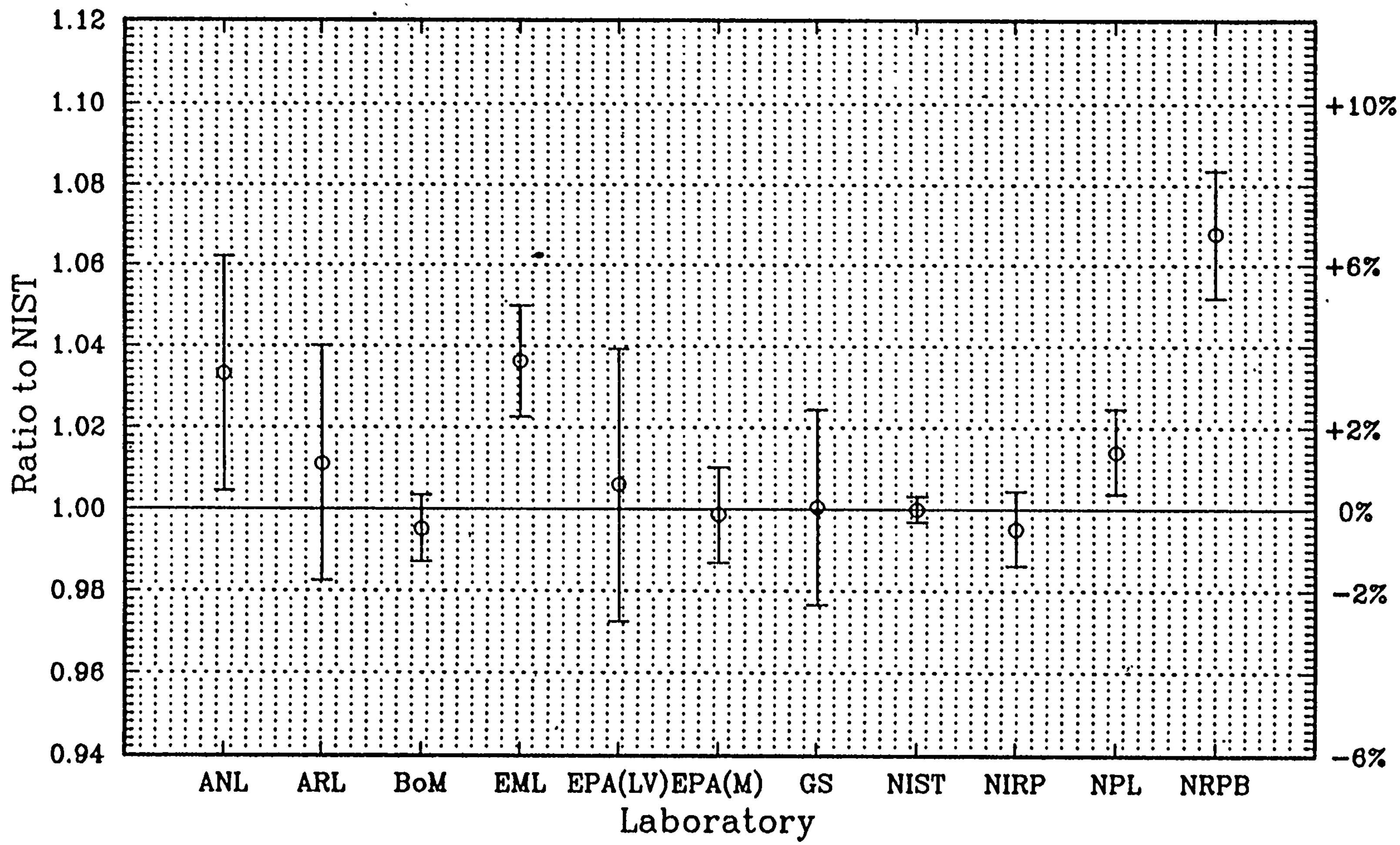


Figure 18 - Results of International Radon Intercomparison Sponsored by NIST Among Major Laboratories.

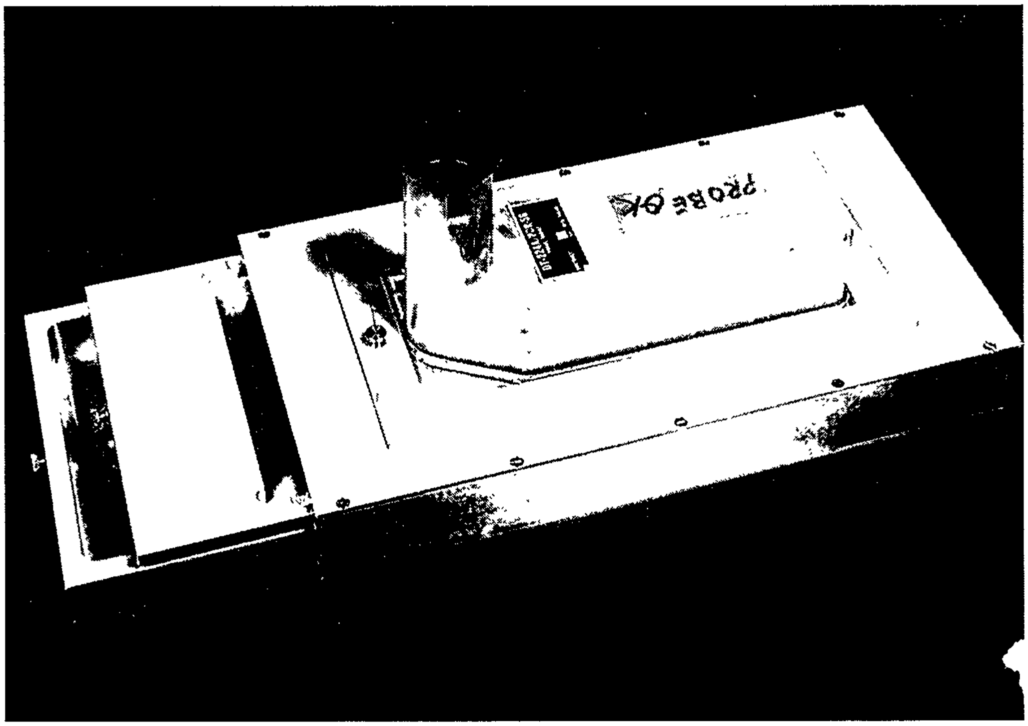


Figure 19 - NIST-Developed Calibration Source for Large-Area Alpha Survey Meters.

Table 1 - Safety, Health, and Environment

Diagnostic Radiology	125 million people receive 200 million x-ray examinations/year; 200 million dental x-rays/year; Imaging equipment 2.5 B$/year
Radiation Therapy	1 person in 4 gets cancer, 60% treated with radiation therapy; Accuracy: 5% dose to tumor, 3% physical dosimetry; 600,000 patients per year; 10 B$ at 1325 facilities
Nuclear Medicine	1 person in 4 entering hospital has radionuclides used as part of the diagnostic procedure
Occupational Radiation Protection	1.3 million radiation workers badged
Public	Radon Environmental radioactivity (esp. food, water)

Table 2 - Industry

Industrial Radiation Processing	5 B$/y
Nuclear Electric Power	22% of U.S. electricity (30 B$/y) Replacement cost of 108 reactors ~500 B$
Industrial Radiography	0.5 B$/y
Radiation Effects on Electronic Devices	~1 B$/y

Table 3 - Science

- Physics of radiation interactions at the nanometer level
- Resonance ionization spectroscopy—atom counting
- Fundamental neutron physics

Table 4 - Office of Radiation Measurements National Measurement Support System for Ionizing Radiation

Radiation Therapy	5 laboratories [AAPM]
States	Illinois, South Carolina, California, (Arkansas) [CRCPD]
Personnel Radiation Dosimetry	1 testing lab, PNL, 89 processors [NVLAP] 1 testing lab, RESL, ~12 processors [DOELAP]
Survey Instrument Calibration	Eberline, New Mexico [HPS]
Federal Laboratories	CDRH, (ORNL), (PNL), (Navy SC) [NVLAP]
Under Development	Bioassay High-level dosimetry Environmental radioactivity Radioactivity standards

Brackets [ ] indicate accrediting organization.
Parentheses ( ) indicate "in progress."

Table 5 - Assurance of NIST Standards

- Intercomparisons with other National Standards Laboratories and Leading Laboratories
- Comparisons of Independent Standardization Methods
- Measurement Research
- Fundamental Research