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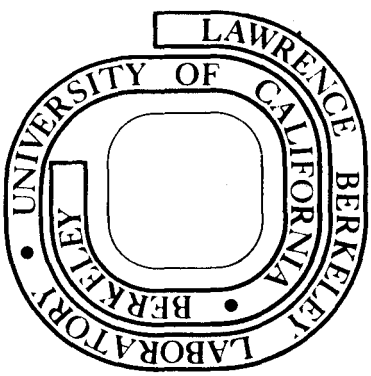

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ENVIRONMENTAL MEASUREMENTS AND MONITORING PROGRAMS AROUND REACTORS: PRE-OPERATIONAL, OPERATIONAL AND FOR ACCIDENTS

by

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I. INTRODUCTION

In this paper, a general overview will be given of instrumentation requirements for environmental monitoring around nuclear power reactors. We shall emphasize radiological measurements here, bringing other types of measurements into the discussion only briefly where appropriate. Three measurement situations will be discussed:

a) pre-operational measurements
b) operational measurements
c) instrumentation for accidents.

We shall treat the motivations and regulations; the broad categories of measurement problems; and some specific considerations in the choice, deployment, and use of instrumentation. For many measurements, proper sampling is as crucial as proper measurement, and we shall therefore discuss this aspect. We shall not treat actual instrumentation methods in detail, although mention of specific instrument types will be made as required.

A recent "Survey of Instrumentation for Environmental Monitoring" (Ref. 1), carried out at Lawrence Berkeley Laboratory, contains detailed discussions of the instrumentation itself, category by category. This Survey, which includes the parameters of commercially available instrumentation as well as instruments in use in government laboratories, should be consulted by the user interested in the detailed problems of the choice and use of instruments and instrument systems.

We shall emphasize measurements of radiological parameters in the unrestricted environment, although in some important cases measurements are actually made within the confines of the plant itself (for example, in the stack) rather than in the environment. We shall largely exclude measurements for radiation protection of operating personnel, as well as measurements for process control.

Except in particular cases, the broad measurement requirements are similar for all of the various reactor types now in commercial operation (PWR, BWR, HTGR). Because of the wide variety of possible sites, specific monitoring programs cannot be discussed here in detail; these are always tailored to the individual site.

II. PRE-OPERATIONAL ENVIRONMENTAL MONITORING PROGRAMS

A. Goals

A number of different goals determine the design of a pre-operational monitoring program. The major ones are these:

1) A program of monitoring must be designed for ultimate use in the operating stage.

2) Radiation and other background data must be accumulated to enable a comparison between pre-operational and operational situations in various environmental media.

3) Monitoring personnel must be trained.

4) Environmental sampling and measurement procedures, as well as laboratory analytical capability, must be developed and evaluated.

5) Two separate environmental reports must be filed, one at the AEC construction-permit stage and one at the AEC operating-permit stage. These must contain detailed descriptions of the potential environmental impacts of the proposed facility. The impacts in which measurements and monitoring instrumentation play a major role are:

   a) direct radionuclide emissions to various environmental media,
   b) direct doses delivered to humans and animals,
   c) pathways through the environment in which reconcentration can occur.

AEC regulations governing the pre-operational stage are contained in Regulatory Guides 4.1 ("Measuring and Reporting of Radioactivity in the Environs of Nuclear Power Plants," Ref. 2) and 4.2 ("Preparation of Environmental Reports for Nuclear Power Plants," Ref. 3). Most of the pre-operational measurements are identical to those ultimately carried out during routine operation; hence we shall omit detailed instrumentation discussions here, leaving them for the section on operational monitoring.

The pre-operational program is, in many of its facets, more far ranging than the post-operating program. Along with the building up of measurement capability, its main technical goals are identification of critical pathways and background measurements.

B. Critical Pathways Studies

The critical pathway concept implies that a certain identifiable, inter-connected system in the environment may provide an important route for transport of some hazard from its source to man. There may or may not be successively larger concentrations of the hazard in the chain. Perhaps the best known example in the reactor industry is the transport of iodine-131 in the chain: stack → air → grass → cow → milk → human → thyroid. Calculations and measurements have shown that if a human child continually drinks milk (1 liter per day) from a cow constantly grazing on grass exposed to air containing ^{131}I, he receives a thyroid dose about 1,000 times greater than the thyroid dose he would receive by merely breathing that same air (Ref. 1). The milk is clearly the key place in this chain for measurement of potential human dose.

For many sites, the pre-operational critical pathways studies may involve primarily a series of observational studies of the ecological networks. Trained ecologists can determine such things as which networks exist in the environs; how they interact; how their populations vary in time and from place to place; and how pathways to human exposure might occur. These observations, in turn, may have to be augmented by theoretical models to discover quantitative relationships (e.g., how a change in thermal properties will affect a natural population; how this in turn may alter some pathway to man). For many pathways reliance on experience elsewhere may be sufficient (e.g., the air-grass-cow-milk pathway); while for others, in situ studies at the actual site may be the only method for gaining the necessary information (e.g., meteorological or hydrological data to understand local dispersion of air or water).

The second phase of the pre-operational critical pathways program is to calculate, from the expected releases of the various hazardous substances, the ultimate effects at the end-points (usually, the ultimate dose to man). Here two kinds of dose studies must be made: in the first, studies are done on the few 'persons at maximum risk' (e.g., the few fishermen catching fish for daily diets from the effluent water system); in the second, studies are done on average doses in the entire vicinity for a particular pathway.

The EPA's "Environmental Radioactivity Surveillance Guide" (Ref. 4) includes two figures which show overviews of many important pathways. These figures are reproduced here as Figures 1 and 2.

C. Pre-Operational Background Measurements

Background measurements are necessary to determine the ambient conditions for every pollutant or parameter which might be affected by plant operation. This involves measurements and calculations for radiological, chemical, thermal, meteorological, hydrological, ecological and demographic parameters. The measurements should be made for a period of at least one calendar year, and preferably for longer.

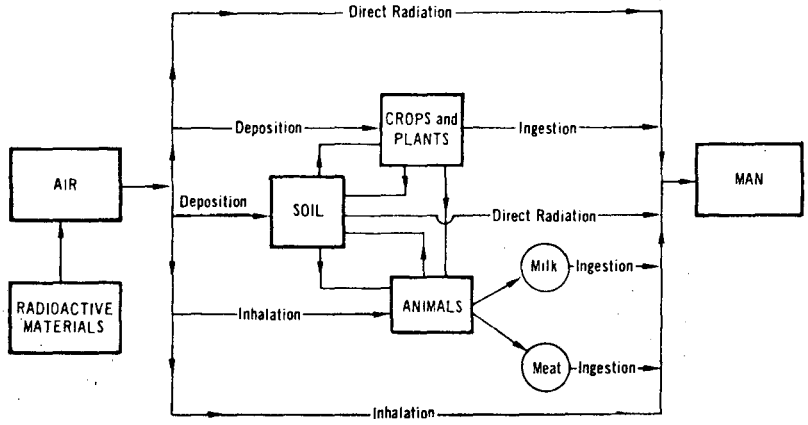

Figure 1. Pathways between radioactive materials released to the atmosphere and man

(from Ref. 4)

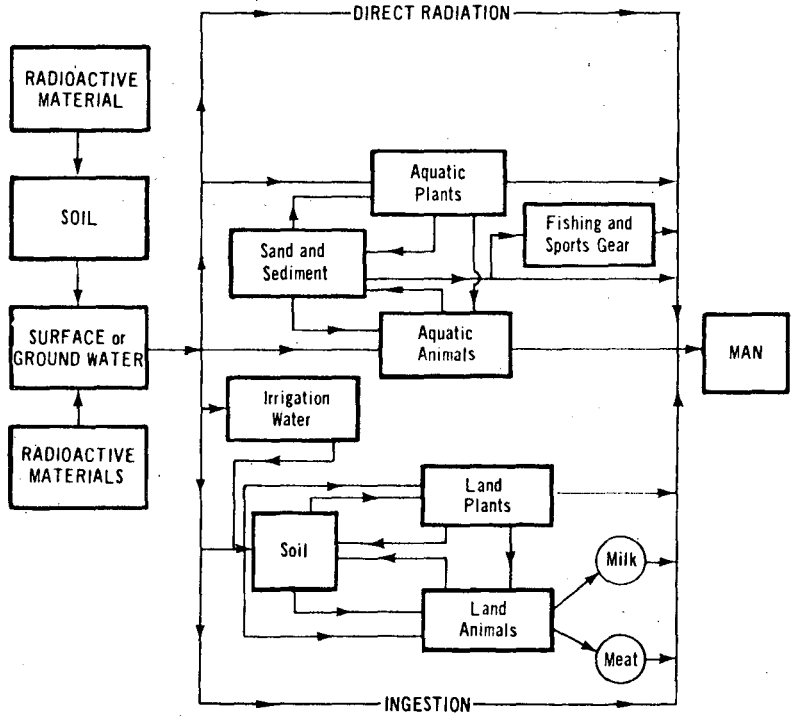

Figure 2. Pathways between radioactive materials released to ground and surface water (including oceans) and man

(from Ref. 4)

Every measurement which will later be 'required' in routine operations must be performed in this program. In addition, a wide variety of "indicator organisms" and other important measurement media should be sampled and measured. Details concerning these types of measurements will be discussed below under operational monitoring. Here we shall merely list the types of measurements involved. We will briefly summarize the pre-operational program suggested by EPA (Ref. 4):

1) Make gamma radiation dose rate measurements (e.g., film, thermoluminescent dosimeters, ion chambers) in various locations.

2) Apportion the total gamma dose among various radionuclides by in situ gamma spectrometric measurements [NaI(Tl), Ge(Li) spectrometry].

3) Measure gross-beta and gamma spectroscopic data on air filters.

4) Measure gamma spectra on various water, food, and biota samples.

5) Measure gross-alpha or alpha-spectroscopic data in various samples.

III. OPERATIONAL ENVIRONMENTAL MONITORING PROGRAMS

A. Goals

In an operational program of environmental monitoring around a nuclear power reactor, the various elements all have one common goal: to assure that the impacts of reactor operation on the whole long list of environmental parameters remain within regulations. We will assume here that the AEC regulations will soon include the "as low as practicable" doctrine; the goal also includes assurance that 'abnormal' emissions do not occur, or are detected and corrected if they do occur.

Two broad overviews must be consulted by anyone planning a monitoring program: (1) the AEC Regulatory Guide 4.1 ("Measuring and Reporting of Radioactivity in the Environs of Nuclear Power Plants"), which describes "an acceptable basis for designing a program to measure and report. . . ."; and (2) the EPA "Environmental Radioactivity Surveillance Guide" (Ref. 4), which "recommends methods for conducting a minimum level of environmental radiation surveillance outside the plant site boundary. . . ." In addition to these, one must consider the AEC's proposed Appendix I to 10CFR50 (Ref. 5), which, if adopted, would "provide numerical guides for design objectives. . . to keep radioactivity in effluents as low as practicable."

The AEC's Regulatory Guide 4.1 outlines five objectives for a radiological monitoring program, which can be paraphrased as follows:

1) The program should be based on the analysis of critical pathways.

2) It should consider the possible build-up of long-lived radionuclides.

3) It should facilitate estimating doses to the public.

4) It should consider the potential damage to important plants and animals.

5) It should be designed to establish correlations between environmental levels and releases from the plant.

The EPA's guideline, after repeating objectives (2) and (3) above, adds the following objective:

6) The program should provide data for public information purposes.

To these six we can add two others which are implied but not explicitly stated:

7) The program should provide data to compare with Federal or State regulations.

8) The program should continually confirm the pathway assumptions upon which the program itself is based, and verify the projections made in the pre-operational phase.

The relevant legal requirements are contained, essentially, in the AEC's published regulations, in particular 10CFR20 (Ref. 6) and 10CFR50, proposed Appendix I (Ref. 5). 10CFR20 tabulates maximum permissible concentrations of various radionuclides in air and water, which are related to certain limiting doses when humans are exposed to those radionuclides. These existing limits would be supplemented if the proposed Appendix I is adopted. Proposed Appendix I essentially states that, for LWR's, the "as low as practicable" concept can be met if the following guidelines are met:

a) Liquid releases, except tritium, should not exceed 5 curies/year.

b) Liquid releases, except tritium, prior to dilution in a natural body of water, should not exceed an average of 20 picocuries/liter.

c) Tritium liquid releases, prior to dilution in a natural body of water, should not exceed 5,000 picocuries/liter.

d) Gaseous releases of noble gases should not result in a dose rate at any off-site location above 10 mrem/year.

e) Gaseous releases of radioactive iodines, or radioactive particulates with half-life above 8 days, should not exceed the concentrations in 10CFR20, divided by 100,000.

f) The reactor operator is allowed to produce higher levels of emissions in liquid form, as gaseous radioiodine, or as gaseous particulates

if he can demonstrate that doses "to the whole body or any organ" are below 5 mrem/year for all individuals.

g) The AEC, on the other hand, may lower any of the above limits if exposure above 5 mrem/year is "likely".

We repeat here that all of the above is still proposed. However, another monitoring-program objective should be added to the list of 8 above:

9) To comply with Appendix I, which although only proposed is likely to be implemented sometime in the future.

It is important to understand the differing roles of the AEC and the EPA. In discussing its proposed Appendix I, the AEC has stated (Ref. 5) that

> "Under the President's Reorganization Plan No. 3 of 1970, the EPA is responsible for establishing generally applicable environmental radiation standards for the protection of the general environment from radioactive materials. The AEC is responsible for the implementation and enforcement of EPA's generally applicable environmental standards. . . . If the design objectives and operating limits discussed herein should prove to be incompatible with any generally applicable environmental standard hereafter established by EPA, the AEC will modify these objectives and limits as necessary."

B. Measurement Tasks and Categories

Measurement tasks fall roughly into the following categories:

a. Airborne radionuclides:
   i. in the stack;
   ii. in the environment.

b. Liquid-borne radionuclides:
   i. in the effluent streams;
   ii. in surface, ground, and drinking water.

c. Dosimetry in the environment.

d. Other environmental media:
   i. sediments near liquid effluent outfall;
   ii. plants, animals, microorganisms.

e. Foods:
   i. fish, shellfish;
   ii. milk;
   iii. meat and poultry;
   iv. fruits and vegetables.

f. Control and background data from sites distant from the plant.

Measurements themselves fall into the following broad categories:

a. Field measurements made in situ with portable or mobile instruments.

b. Measurements made by fixed instruments.

c. Measurements made on samples taken in the field and brought to a laboratory for analysis.

Table 1, reproduced from the EPA guide (Ref. 4), gives the EPA's "recommended minimum level environmental surveillance program." This program, dealing only with radiological offsite surveillance, must be supplemented by on-site measurements where appropriate, mainly in the stack and in the effluent water stream. The reader should study Table 1 before continuing here, since its contents will not be repeated in this text. It recommends detailed sampling media, sampling locations and sampling frequencies, and analysis requirements. We will discuss these various detailed considerations below.

The proper design of a sampling program is perhaps even more important than the measurements made on the samples: if a key item is not even sampled, then its significance is totally unrecognized!! We shall outline some considerations here for each medium requiring sampling. The sampling program must, of course, include consideration of the analytical and instrumentation capabilities.

1. Air: Sampling and Analysis

Three types of airborne activities normally require measurement: particulates; gases, principally noble gases; and halogens, principally iodine. A fourth, airborne tritium, should be measured occasionally.

Considerable judgment must be used to deploy air-sampling sites appropriately in the environment. For example, knowledge of a variety of meteorological parameters is important in order to understand how stack-measured activities relate to ultimate dose depositions in the general environment. The EPA Guide contains detailed discussions on this issue which we shall omit here. Another good reference is the discussion of measurements of airborne radioactive clouds in a recent Battelle Northwest study (Ref. 7).

Airborne particulates are normally sampled on filters in the stack, and also on filters collected using hi-vol blowers in several (perhaps ten) off-site locations. In the stack, the difficult problem is assuring a properly representative sample of the total stack flow. In the environment, concentrations are usually so low that large volumes are required. The EPA recommends weekly samples at flow rates of about 1 ft^3/minute, yielding total weekly samples of about 300 cubic meters. These filters are typically measured for gross beta in a 2π internal gas proportional counter and for gamma activity by gamma spectroscopy. Individual radionuclide analyses, such as radiostrontium determinations, are done occassionally by chemical concentration followed by specific procedures.

(Reproduced from Ref. 4, U.S. Environmental Protection Agency Report ORP/SID 72-2)

Table 1. Offsite surveillance of operating light-water-cooled nuclear power facilities

Operation or sample type	Approximate number of samples and their locations	Collection frequency	Analysis type[a] and frequency
Air particulates	1 sample from the 3 locations of the highest offsite ground level concentrations 1 sample from 1-3 communities within a 10-mile radius of the facility 1 sample from a location greater than a 20-mile radius in the least prevalent annual wind direction[d]	Continuous collection—filter change as required	Gross long-lived β at filter change[b] Composite for gamma isotopic analysis and radiostrontium analysis[c] quarterly
Air iodine	Same sites as for air particulates	Continuous collection—canister changes as required	Analyze weekly unless absence of radioiodine can be demonstrated
Direct radiation	2 or more dosimeters placed at each of the locations of the air particulate samples which are located at the 3 highest offsite ground level concentrations 2 or more dosimeters placed at each of 3 other locations for which the highest annual offsite dose at ground level is predicted[e] 2 or more dosimeters placed at each of 1-3 communities within a 10-mile radius of the facility[f] 2 or more dosimeters placed at a location greater than a 20-mile radius in the least prevalent annual wind direction[d]	Quarterly	Gamma dose quarterly
Surface waters[g]	1 upstream 1 downstream after dilution (e.g., 1 mile)	Monthly (Record status of discharge operations at time of sampling)	Gross β, gamma isotopic analysis[h] monthly. Composite for tritium and radiostrontium analysis[c] quarterly
Ground water	1 or 2 from sources most likely to be affected	Quarterly	Gross β, gamma isotopic analysis[h] and tritium quarterly
Drinking water	Any supplies obtained within 10 miles of the facility which could be affected by its discharges or the first supply within 100 miles if none exists within 10 miles	Continuous proportional samples[i]	Gross β, gamma isotopic analysis[h] monthly. Composite for tritium and radiostrontium analysis quarterly[c]
Sediment, benthic organisms and aquatic plants	1 directly downstream of outfall[j] 1 upstream of outfall[j] 1 at dam site downstream or in impoundments[j]	Semiannually	Gamma isotopic analysis semiannually
Milk	1 sample at nearest offsite dairy farm in the prevailing downwind direction 1 sample of milk from local dairy representative of milkshed for the area	Monthly	Gamma isotopic analysis and radiostrontium analysis monthly[c]
Fish and shellfish	1 of each of principal edible types from vicinity of outfall 1 of each of the sample types from area not influenced by the discharges	Semiannually	Gamma isotopic analysis semiannually on edible portions
Fruits and vegetables	1 each of principal food products grown near the point of maximum predicted annual ground concentration from stack releases and from any area which is irrigated by water in which liquid plant wastes have been discharged 1 each of the same foods grown at greater than 20 miles distance in the least prevalent wind direction	Annually (At harvest)	Gamma isotopic analysis annually on edible portions
Meat and poultry	Meat, poultry, and eggs from animals fed on crops grown within 10 miles of the facility at the prevailing downwind direction or where drinking water is supplied from a downstream source	Annually during or immediately following grazing season	Gamma isotopic analysis annually on edible portions
Quality control[k]	Samples as required for accurate sampling and analysis		Minimum frequency—annually

[a] Gamma isotopic analysis means identification of gamma emitters plus quantitative results for radionuclides that may be attributable to the facility.

[b] Particulate sample filters should be analyzed for gross beta after at least 24 hours to allow for radon and thoron daughter decay.

[c] Radiostrontium analysis is to be done only if gamma isotopic analysis indicates presence of cesium-137 associated with nuclear power facility discharges.

[d] The purpose of this sample is to obtain background information. If it is not practical to locate a site in accordance with the criterion, another site which provides valid background data should be used.

[e] These sites based on estimated dose levels, as opposed to ground level concentrations where the dose may be affected by sky shine, high plumes, or direct radiation from the facility being monitored.

[f] These locations will normally coincide with the air particulate samplers used in the monitored communities.

[g] For facilities not located on a stream, the upstream sample should be a sample taken at a distance beyond significant influence of the discharges. The downstream sample should be taken in an area beyond the outfall which would allow for mixing and dilution. Upstream samples taken in a tidal area must be taken far enough upstream to be beyond the plant influence when the effluent is actually flowing upstream during incoming tides.

[h] If gross beta exceed 30 pCi/liter.

[i] Drinking water samples should be taken continuously at the surface water intake to municipal water supplies. Alternatively, if a reservoir is used, drinking water samples should be taken from the reservoir monthly. If the holding time for the reservoir is less than 1 month, then the sampling frequency should equal this holdup time. Increases in concentration of activation and/or fission products at these sources necessitate the analysis of tap water for the purpose of dose calculations. Additional analyses of tap water may be necessary to satisfy public demand.

[j] See figure 6 for locations on a stream. For facilities located on large bodies of water, sampling sites should be located at the discharge point and in both directions along the shore line.

[k] The Analytical Quality Control Service of the Surveillance and Inspection Division (SID) provides low-level radiochemical standards and interlaboratory services to State and local health departments, Federal and international agencies, and nuclear power facilities and their contractors. The Service operates several types of cross-check programs for the analysis of radionuclide in environmental media, such as milk, food, water, air, and soil. The samples are submitted on a routine schedule designed to fit the needs of each laboratory. Technical experiments are undertaken to permit detailed analyses of the accuracy and precision obtained by participating laboratories. In addition, low-level radioactivity standards are provided to the agencies participating in the various programs. Primary and secondary standardization is also performed as needed on those radionuclides not used on a routine basis.

Airborne iodine-131 is normally sampled with charcoal cartridges. In environmental locations the cartridge normally follows the particulate filter, while in the stack it is a separate set-up. These cartridges are typically analyzed by gamma spectrometry, usually directly but sometimes after chemical separation. The ultimate in sensitivity, perhaps two orders of magnitude below that of ordinary gamma spectrometry, is achievable with beta-gamma coincidence spectrometry (Ref. 8) and 1000-minute counting times. With this added sensitivity, it is just barely possible to measure 10^{-15} microcuries/cm^3, which is the Appendix I proposed ^{131}I concentration limit in environmental air. Hence, stack measurements are usually required; for them, ordinary gamma spectrometry should be sufficient.

Airborne noble gases are normally measured in the stack with flow-through gas proportional counters or ion chambers. Radioxenons can be collected on charcoal for gamma-spectroscopic analysis (Ref. 9), but this procedure is not usually done in routine sampling systems; neither is collection of krypton and xenon by cryogenic means for laboratory analysis in flow-through instruments. Because environmental concentrations of these gases are usually exceedingly small, their environmental effect is usually measured by their contribution to total whole-body external dose, measured with instruments discussed separately below.

Airborne tritium (normally as tritiated water vapor) should be measured occasionally by sampling the stack using a desiccant such as silica gel; heating the gel; collecting the condensate; and measuring in a liquid-scintillation system. If differentiation between HT (gas) and HTO (water vapor) is desired, these can be separately collected by a chain involving desiccation of HTO, combustion to HTO of the HT, and a second desiccation (Ref. 10).

The air sampling program just outlined will differ slightly depending upon the reactor type. Specifically, BWR's may emit significantly greater short-lived activities than PWR's. Recent improvements in scrubbing of the halogens (iodine) from BWR effluent have altered this picture, but the short-lived xenons and kryptons will still be greater for BWR's. This consideration affects sampling frequency; for example, the 30-day typical hold-up before airborne release from PWR's reduces most of the short-lived activities to insignificant levels. It also mandates careful sampling in environmental air near PWR's immediately after the planned releases.

2. Water: Sampling and Analysis

Most liquid (water) measurements are made by samples taken in the environment and returned to the laboratory for analysis. The only exception is direct in-stream measurements in the liquid effluent channel.

Samples of surface water, ground water, and drinking water are typically taken as indicated in Table I. It should be noted that drinking water must meet U.S. Public Health Service standards (Ref. 11) separate

from those of the AEC and EPA. Laboratory analyses include gross beta measurements in a low-background internal proportional counter, after chemical treatment to eliminate the sample water itself; tritium determinations by liquid scintillation; radiostrontium (^{89}Sr, ^{90}Sr) by any of various chemical separations followed by beta counting; and gamma spectroscopic analysis. Occasional gross-alpha and alpha-spectroscopic analyses are also suggested, as are occasional specific analyses for a few other nuclides such as ^{140}Ba-La, ^{14}C, ^{95}Zr-Nb, and ^{131}I.

In-stream monitors are useful for continuous tritium and continuous gamma-spectral measurements. A continuous tritium liquid-scintillation flow-cell system has been recently developed to enable on-line (less than a few minutes) detection of small changes in tritium concentration (Ref. 12). A sensitive NaI(Tl) gamma spectrometer may also be used to examine the liquid effluent continuously. With the advent of Appendix I's release limits on total liquid-borne curies, such instruments will be needed to augment the batch-sampled measurements now performed.

3. Food, Milk, Biota, Other Media: Sampling and Analysis

In Table 1, the EPA's recommended sampling programs are set down for many of these other media. Two different goals are involved: (1) some media are indicative of pathways to human exposure, either directly or indirectly; (2) some media may indicate long-term build-up phenomena for effluents with long half-lives.

For example, stream-bottom sediments and certain soil samples are taken to indicate if these media are acting as deposition sites for effluents. Microorganisms and the like are sampled regularly when they constitute indicators in food chains, and occasionally to check on the validity of the overall sampling program. Milk and food are sampled if they are produced in the neighborhood; suitable samples produced nearby (but in areas which should not be affected by plant operations) are also needed for comparison purposes. Fish and shellfish are sampled either because they may be important commercially or for sport, or less often because of their role in a wider pathway.

Analytical procedures for milk are well documented in the literature (Ref. 13, 14). The AEC is now suggesting ^{131}I measurements in milk at the 0.5 pCi/liter level, which is very difficult even under the best analytical conditions; the EPA's suggested 10 pCi/liter detection limit is more easily achieved. These milk measurements involve chemical concentration (ion exchange, for example) followed by gamma or beta-gamma spectrometry. Strontium-89 and -90 are measured in milk by any of several chemical procedures followed by beta counting. ^{137}Cs and ^{134}Cs are measured by gamma spectrometry.

For other media, procedures are not as widely documented, although compilations of radiochemical procedures exist which among them contain methods for nearly all of the usual media (Ref. 15 - 19). Gamma or beta spectrometry is the usual counting technique, typically after complicated chemical separations.

4. Environmental Dosimetry

The EPA (Ref. 4) recommends "a network of integrating or continuously recording dosimeters (thermoluminescent dosimeters, film, or ion chambers)," placed at several sites in the environs. When integrating dosimeters (TLD, film) are used, they should be deployed in pairs, and if possible each unit should independently measure both the penetrating (gamma) and the non-penetrating (beta, x-ray) components. The network should obviously emphasize dosimetry where demographic studies indicate the most likely exposures might occur.

The pre-operational program should include in situ gamma spectrometry to determine the principal radionuclides contributing to the dose, as well as the contribution from cosmic radiation. This type of measurement ought to be repeated from time to time after operation begins, and whenever the dose rate changes.

5. Instrumentation and Analytical Requirements

Given the large number and variety of radiological measurement tasks in the environment around power reactors, it may seem as if the instrumentation and analytical requirements are beyond the capability of a typical utility company. In actual fact, this is often the case: many utilities have contracted out some or all of their measurement needs to commercial laboratories. Others have gradually built up in-house expertise to perform the required measurements. Sampling is more often performed by in-house personnel, albeit with important periodic outside review. We shall not argue here the pros and cons of in-house vs. contracted capability: there is more than mere expense involved in the decision. We shall present here an overview of the types of equipment needed to do the very best job of measurement and analysis. Detailed discussions of instruments are found in the LBL Survey (Ref. 1).

Laboratory equipment begins with a gamma spectrometer. There are two kinds in common use: NaI(Tl) crystal spectrometers with high efficiency and low energy resolution; and anti-coincidence-shielded Ge(Li) semiconductor spectrometers with superb resolution but lower efficiency. A well-equipped analytical laboratory would need one of each type: the Ge(Li) system for 'peak-hunting' to determine all of the various gamma-emitting isotopes in an unknown sample, and a NaI(Tl) system for the ultimate in single nuclide sensitivity (for example, to perform ^{131}I analyses of milk at minute concentrations). An added beta-coincidence feature inside a NaI(Tl) well is required for the very greatest sensitivity for ^{131}I. Unfortunately, these systems are all very expensive, since they all must include electronic accessories such as multi-channel analyzers and data-recording devices. These systems are also not easy to operate at maximum sensitivity, and may require computer analysis of the data for ultimate performance. If a choice had to be made, perhaps the better instrument for this set of tasks would be a Ge(Li) system for 'peak-hunting'; in that case some very-low-activity samples would have to be measured on a NaI(Tl) system elsewhere.

The second key laboratory instrument is the low-background beta internal gas proportional counter. This instrument, useful for gross-beta as well as beta-spectrometry measurements, is much easier to operate and maintain than the gamma spectroscopy equipment. It can also be used, with minor changes, for gross-alpha measurements.

An alternative or supplement to the beta proportional counter is a silicon surface-barrier detector, for alpha and beta spectroscopy. This instrument has superb resolution, but cannot accommodate as large samples as the gas counter. Either type must be accompanied by a multi-channel analyzer system.

Tritium measurements are performed with a liquid scintillation/photo-multiplier set-up. These are commercially available as complete units, or can be had at less cost (and less reliability, perhaps) by assembling the parts separately.

A wide variety of analytical-chemical instruments must be available for the individual measurement problems: ion-exchange columns, wet- and dry-ashing apparatus, organic chemistry supplies, and so on.

Dosimetry is done either with film (requiring development and reading); thermoluminescent dosimeters (TLD reader systems are commercially available); or pressurized ion chambers for field deployment.

Sampling equipment includes air-filter and charcoal-trap samplers; hi-vol blowers; grab-sample equipment for water sampling; core samplers for soil; and other specialized equipment such as cryogenic samplers for noble gases.

Fixed samplers include in-stream tritium and gamma spectrometry [NaI(Tl)] equipment; automatic air samplers for particulates; flow-through ionization chambers or proportional counters for noble gases; and pressurized ion chambers for dosimetry.

Portable and mobile equipment includes possible mobile gamma-spectrometry equipment for in situ measurements; and any of a long list of portable, hand-held meters (Geiger-Muller counters, ion chambers, proportional counters, etc). Calibration sources, shielding, reagents, and other items must also be included.

The list could go on and on, yet not be complete. The reader should understand that all of this equipment is necessary only for a complete, self-sustaining laboratory. More likely, as mentioned above, at least some of the required measurements will be made by shipping samples off-site for analysis elsewhere.

IV. ACCIDENTS AND ACCIDENTAL EMISSIONS

A. Goals

It is widely accepted that even a 'small' reactor accident (one whose radiological significance is minor compared to that of the Design Basis Accident class) can still prove to be a disaster from a number of points of view. Over and above the need to protect public health, the costs, delays, and uncertainties involved before normal operations can be resumed should be sufficient cause to take every reasonable precaution to avoid even minor accidental events. Furthermore, certain types of minor accidents could have repercussions throughout the nuclear industry, perhaps even resulting in wide suspension of operations pending an investigation.

Given this fact, it should strike the reader as surprising that instrumentation for use in the event of accidents is not widely installed around commercial reactors. This fact is well documented (Ref. 20). The AEC has not specifically required the installation of instrumentation adequate to achieve the several goals outlined below for accident situations, and many reactor operators have not done this on their own iniative.

There are several crucial goals for accident-monitoring instrumentation. In nearly every case the information required must be available quickly, at a necessary sacrifice in high accuracy:

(1) To aid in implementing life-saving, property-saving, and evacuation measures;

(2) To assure safety for investigators or rescuers working near the site;

(3) To characterize the radiological situation within the containment vessel itself;

(4) To detect releases from any breach of the containment;

(5) To characterize releases to the environment through normal effluent channels (stacks, water pipes, etc.);

(6) Finally, to aid in reconstructing the sequence of events and in determining the effectiveness of engineered safeguards and natural removal processes.

Considering the wide variety of accidental events which might be imagined, it is obvious that instrumentation cannot easily be designed to cover all contingencies. Instead, a choice must be made. Here we shall discuss those types of instruments which most thoroughly provide for the widest range of situations. In our discussions below we shall rely for much of the material on a recent AEC-sponsored study (Ref. 20, 21).

B. Instrumentation Requirements

Before discussing the particular instruments themselves, a word about their sensitivity is in order. In most cases, instrumentation installed for routine monitoring is capable of measuring in the range up to, say, about 1000 times greater activity or flux than normal levels. Accident-monitoring instruments must be able to take over above this level, and must be operative for perhaps 8 or 9 more orders-of-magnitude (up to, say, 10^{11} or 10^{12} times normal release levels). This implies, among other parameters, either logarithmic read-out or scalars with very large numbers of digits. Other requirements for accident-monitoring are ruggedness, isolation from failures in AC power, fail-safety, and insensitivity to extremes of heat, humidity, and radiofrequency energy.

The most obvious need is for instrumentation to protect the public health in the event of a release. In most situations, the airborne release mode will be by far a more important vehicle than the liquid release mode in carrying hazards to the general public. This is because liquid releases generally travel into and in well-defined channels, with a slower rate, less dispersion, and easier control. Also, it is easier to avoid human exposure to radioactive waters than is the case for airborne radioactivity.

We shall discuss instrumentation roughly in the following categories:

a) For airborne radioactivities
   i. inside the containment;
   ii. in the stack and ventilation systems;
   iii. to follow an airborne cloud (meteorological and radiological instrumentation);
   iv. for dose assessment.

b) For liquid radioactivities in the effluent channels.

c) For personnel protection
   i. portable (hand-carried);
   ii. mobile (airplanes, boats, trucks, vans).

It should be emphasized that there are five ways in which emergency measurements differ from routine measurements:

a) The radioactivity levels may be higher than usual.

b) Measurements must be made more quickly than usual.

c) Many more measurements may be required than usual.

d) Areas and media requiring measurement may be more varied than usual.

e) Personnel called in for assistance may be less skilled than usual.

To understand accidental airborne releases, one needs information in the following categories:

a) the total quantity of airborne activity within the containment;

b) the total quantity released either by breach of the containment or by the stack;

c) the parameters characterizing a radioactive cloud travelling in the environment;

d) the radiation dose distribution from airborne radioactivity.

The total quantity of airborne activity must be measured. It has been estimated (Ref. 21) that about 80% ± 10% of the activity in airborne releases within a few hours of any reactor turn-off will be noble gases (mainly krypton and xenon). Nearly all of the remainder will be halogens (bromine, iodine); only ≈ 2% will be other species. Some measurement devices must be present within the containment vessel, and others within the ventilation system and the stack to determine total airborne activities. Calculations (Ref. 21) have shown that measuring all gamma rays between 2 and 2.5 MeV provides an excellent determination of total short-lived krypton isotopes, and from this a good proportional determination of all airborne activity, for periods up to 10 hours after reactor turn-off. Because of harsh conditions, both in the containment and in the stack, filter and charcoal trap samples should be taken in the containment or stack, automatically removed, and then measured outside. Gaseous samples fed directly to a flow-through ion chamber or G-M counter should be used to measure noble gases. Air filters for particulates should be measured with a rugged Geiger-Mueller counter. Activated charcoal traps for halogens should be measured for gamma activity by a NaI(Tl) single-channel analyzer system, and for gross beta by a thin window proportional counter.

The direction, speed, radioactivity, and dispersion of the radioactive cloud must be assessed. This is vital to enable an understanding of how the cloud will travel in the environment. To perform the meteorological function, a tower should be constructed and instrumented in a location representative of the reactor site, yet far enough away from the reactor itself that it is not much affected by local weather disturbances from the buildings. Instrumentation should be placed at several heights, up to at least the height of the release stack. Measurements of wind components, temperature, and turbulence are needed to enable emergency personnel, using a previously constructed mathematical model, to predict the likely space/time spread of a release cloud and hence to call for evacuation if required in zones likely to be affected. As well as being vital in real time, these measurements are needed to enable post-accident reconstruction. This implies capability for recording the data (e.g., strip charts or magnetic tape recordings). To measure the duration and radioactivity of the plume, it is necessary to deploy a concentric ring of at least 10 small NaI(Tl) counters, set to count gammas above 2 MeV and shielded by at least 10" of lead from the reactor core. Even better would be a series of concentric rings, but these could prove to be costly. In any event, the exact deployment of these detectors requires separate study for each reactor site.

Measurements of the airborne radioactivity in the environment distant from the site should include determinations of both halogens and particulates.

The dominant short-lived activity is from noble gases, but these deliver dose almost entirely as external whole-body radiation, which is detected by the dosimeters covered in the section below. The halogens and particulates, on the other hand, may be a greater problem because of biological reconcentration than from whole-body external dose. Instrumentation for this task should include hi-volume (filter) samplers as well as continously recording air monitors.

The radiation dose distribution delivered by the airborne route to the environment should be measured. This can be done using inexpensive integrating dosimeters deployed widely throughout the surrounding environs. Self-developing film, thermoluminescent dosimeters, or pocket-type ionization chambers are among the choices for this measurement task. It is important to know how much of the measured dose is of the penetrating type (gamma radiation) and how much is non-penetrating (betas, x-radiation); to perform this task, instruments should be paired, one thick-walled and the other thin-walled.

Liquid releases are easier to instrument. For on-site measurements, only a few well-defined channels are normally available for liquid flow. Direct measurement of activity flowing in each of these channels is preferred. Small sealed NaI(Tl) systems, directly immersed in the flowing liquid and set to count all gammas above a few hundred keV, are the best choice for this task. For the wider environment, grab sampling ought to be sufficient, since the short-lived nuclides will have decayed. A sampling pattern to allow for understanding the time evolution of the radioactive releases is essential, and must be laid out beforehand. The use of boats for the sampling task may be appropriate for sites near large bodies of water.

Personnel protection is the third category for which instrumentation is required. Among those requiring protection are rescue, firefighting, and security personnel; investigators; and monitoring and operational personnel. Instrumentation for this task is similar to that used in normal radiation protection, except that it ought to be capable of performance in more extreme situations (heat, etc.) and for high-level measurements. Portable monitoring rate-meters and personnel integrating dosimeters are the two obvious classes of instruments. Among others are instruments for immediate bio-assay of exposed personnel: capability should include at the minimum whole-body gamma counters and tritium urinalysis equipment.

Among commercially available portable instruments, two general design concepts exist: some instruments are specialized units, while others allow the use of a wide variety of probes attachable to a common electronic package. Each concept has both pluses and minuses: If individual units are used, the number of any one functional type required in an emergency may be very large. If a multiplicity of probes is used with a common electronic unit, its use may require more sophistication than might be available in an emergency. It appears that both design concepts have a place in applications to accident-monitoring. Whichever design is chosen, the availability of both rate mode and integration mode is an important requirement.

Personnel dosimeters for this purpose must have immediate read-out capability. This rules out film and thermoluminescent dosimeters; pocket ion chambers and portable survey meters are acceptable, but for this application some sort of pre-set alarm feature (both for integrated dose and for dose-rate) is essential.

C. Summary: Accident Monitoring

This discussion has attempted to outline the broad considerations involved in the choice of accident-monitoring instrumentation. As mentioned above, the AEC has no specific regulations covering this area; however, an excellent presentation of the issues can be found in a recent study at Battelle Northwest (Ref. 20, 21). This study includes a large number of detailed criteria for instrument performance, deployment, and use.

V. SUMMARY

In this paper, a general overview has been given of the requirements for environmental monitoring programs around nuclear power reactors. The emphasis has been on radiological measurements in three types of environmental measurement situations: (a) pre-operational; (b) operational; (c) during accidents and accidental releases. The goals of the various programs have been outlined, along with the relevant regulations. Discussions of the sampling part of each program have been included, along with some comments on the choice, deployment, and use of instrumentation. Other sources must be consulted for detailed discussions of instruments (Ref. 1) and analytical techniques (Ref. 15-19).

The goal of this paper has been to give the interested but inexpert reader some insight into the complexities of environmental monitoring programs. The difficulties involved in establishing a viable program should not be thought of as insurmountable: on the contrary, many skilled personnel are easily capable of carrying out these sampling and measuring programs, including the occurrance of unexpected demands from time to time.

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