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ON MONITORING RADIATION IN THE ENVIRONMENT DUE TO NUCLEAR REACTORS

Robert M. Graven and Robert J. Budnitz

January 4, 1974

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ON MONITORING RADIATION IN THE ENVIRONMENT DUE TO NUCLEAR REACTORS

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ABSTRACT

Nuclear reactors and the natural radiation background are discussed here with a view toward the instrumentation required to monitor radiation in the environment. A brief historical account of the use of nuclear reactors is presented to outline the magnitude of the environmental monitoring problem and its rapid rate of change. Various sources of radiation exposure are discussed, such as fuel handling, accidents, and waste storage. Measurement considerations and techniques used for area and environmental monitoring systems are briefly outlined.

The natural background is described, including the radiation due to cosmic rays, external gamma rays, and internal exposures. A summary compares the instrumentation for monitoring natural radioactivity and radiation due to the nuclear fuel cycle. Government regulations are referred to and a variety of references are cited to provide both general and detailed technical information to guide the reader into the maze of available literature.

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I. Introduction

Background information about the types and extent of radioactivity and radiation hazard due to the use of nuclear reactors will be presented, to be followed by a general discussion of the instrumentation available for its measurement. For detailed instrument information the reader is referred to Reference 1, where measurement considerations and techniques are discussed for the various levels, types, and locations of radiation.

A vast amount has been written documenting the environmental aspects of nuclear reactors. The United States Atomic Energy Commission (AEC) will soon have an "Environmental Report" available on each operating and proposed electrical power generating reactor. Upon completion, these documents will be available at AEC libraries or may be purchased from the Ordering Department, National Technical Information Service, Springfield, VA 22151. The docket number of the report for a specific reactor simplifies the search process.

Figure 1 illustrates the locations of the domestic civilian nuclear power plants as of June 1973 (Ref. 4). In addition to large scale commercial nuclear power reactors, there were about 259 smaller reactors in the United States at the beginning of this decade. The applications include experimental power systems, testing, teaching,

research, and naval propulsion. Many of the older reactors are quite small in comparison to the majority of new reactors which are rated to produce about 1000 MW of electrical power. The early power reactors served as pilot and demonstration plants for the large reactors now being built.

The U.S. electrical energy requirements for the near future and the estimated fraction that will be generated by nuclear power facilities are both expected to rise dramatically. Although projections for both short and long periods of time are at best only estimates and subject to new developments, nevertheless these predictions do form the basis for the construction of new electrical power generating plants. Since power plants require about eight years from original planning and financing until actual operation, the need for power must be anticipated. Similar growth patterns have been postulated for Western Europe, the U.S.S.R., and other parts of the world (Ref. 2, Spinrad, p. 57).

Most of the large power reactors are cooled with ordinary (light) water and are of either the Boiling Water Reactor (BWR) or the Pressurized Water Reactor (PWR) type. Other types include: High Temperature Gas Cooled Reactors (HTGR), Heavy Water Moderated, Pressure-Tube Reactors (CANDU), Liquid Metal Fast Breeder Reactors (LMFBR), and the Gas Cooled Fast Reactor (GCFR). There are also many new experimental and research reactors, including those used in nuclear fusion research.

This paper will only consider "area" and "environmental" radiation monitoring, rather than "process" monitoring. Area monitors are distributed within the reactor site and are intended for monitoring the ambient radioactivity to which the employees are exposed. Also included are instruments for monitoring gaseous stack effluents, water discharges, and particulates released during the normal and refueling operations.

Environmental radiation monitors are those designed to measure radiation in any environment where a human not employed by the plant might be exposed. Examples of environmental monitors (or "environs monitors") are those on fences surrounding a reactor site, or in rivers which might accidentally be contaminated. Process monitors can be used to determine the amount and time when activity will be released. Process instruments and techniques are often used for area and environmental monitoring (e.g., stack monitors).

II. Regulations

The U.S. Atomic Energy Commission licenses and regulates the operation of all domestic nuclear reactors. Laws, rules, regulations, and guidelines are periodically published in the Federal Register, Title 10, Code of Federal Regulations, Parts 20, 50, 70, and 100.

Since the operation of nuclear reactors involves many different phases (e.g., mining, milling, transportation, reprocessing, and waste disposal), a variety of regulations apply, depending on the situation. Regulations governing the operation of nuclear power reactors are constantly being reevaluated in light of new information. In addition to regulation of radionuclide emissions from reactors, regulations on heat, gas, noise, and aesthetic effects are in force or being formulated as a result of the National Environmental Policy Act and the Water Quality Improvement Act and the Occupational Safety and Health Act. The enforcement of, and compliance with, the stipulations to be imposed will require accurate and irrefutable data collected with reliable instrumentation.

The U.S. Environmental Protection Agency (EPA) has published a proposed guide for monitoring environmental radiation (Ref. 6).

Regulations requiring specific identification of more and more radionuclides will greatly increase the amount of data which must be

taken and analyzed. Since radiation detectors are in some cases incredibly sensitive, there is a tendency to monitor radionuclides with extreme accuracy. We do not attempt either to justify or refute this tendency, but rather note it, since it has a major impact on the instrumentation required.

The public health department within each state has responsibility for monitoring, regulating, and enforcing the effluent emission regulations. The industrial safety department within each state usually specifies the safety codes for the employees of a nuclear power plant. Several interstate committees have been created for the case of reactors using interstate waterways or sharing air basins. The appropriate committee will usually have a statement included in the "Environmental Impact Statement" on the reactor. However, the ultimate responsibility rests on each individual utility for the operation of its plant and the protection of its employees.

III. Sources of Radiation

A reactor's core is the primary source of radioactivity at a nuclear power plant, but since the core is surrounded with adequate shielding, its contribution to environmental radiation is usually small compared to the natural background. Radiation is also produced by the decay of atoms which became activated due to the neutron and gamma flux within the reactor. If this occurs in cooling water or gas which is released into the environment it may represent a hazard. Fission products, activated water (tritium), activated air (^{13}N, ^{16}N), fuel rod cladding, and other activated materials will emit many different types of radiations in a wide spectrum of energies. The quantity of radiation produced by each reaction will depend on many variables (e.g., number of atoms present, cross-sections of interactions, the energy, binary or ternary decay).

The largest number of curies of radioactivity discharged by operating reactors is due to tritium, krypton, and xenon emissions. Tritium is commonly found in water as HTO which is purposely released to the air (in the form of water vapor) and to the cooling water at planned intervals. Tritium decays by emitting a very soft beta ray (E_{max} = 18.6 keV); it is thus usually not an external hazard in spite of its relatively long life (12.36 yr half-life). However, about 24,000 curies (Ref. 7) will be produced annually by each 1000 MWe reactor; if it is all eventually released to the environment, as is the current

practice, then during the next several decades a build-up can certainly be expected.

The isotopes of krypton (83m, 85m, 85, 87, 88, 89, 90) are commonly found in the gaseous output from boiling water reactors. The condenser output gas is treated and its release is delayed (holdup), which allows the short-lived isotopes to decay. An evaluation must be made and repeatedly checked (by monitoring) for each reactor during its normal operation to determine if its release of krypton and other gases is within the limits allowed by government regulations.

Xenon-133 represents a large amount of the activity expected to be released per year from a typical BWR in the gaseous effluent (Ref. 8). Its half-life (5.27 days) indicates it has a limited buildup potential, its decay mode (beta, E_{max} = 346 keV) indicates that a beta monitoring instrument must be used, its chemical characteristics (nonreactive noble gas), its biomedical properties (no serious reconcentration) and its occupational MPC (10 pCi/cc, 40-hour week) indicate its potential hazard is not as great as some more reactive elements. Some isotopes of xenon will be released at the reactor, and some at the Fuel Reprocessing Plant (FRP).

In considering the hazard to individuals, it is convenient to divide the exposure into classes, namely external and internal radiation.

A. External

External radiation is defined as radiation emanating from radioactive materials external to the body. Radiation from fuel rods, control rods, radioactive substances, and X-rays from high-voltage equipment are examples of external radiation.

In general, external radiation hazards are confined to rather specific areas close to the source of radiation. However, activated material released to the environment may be carried great distances in the atmosphere or water, in the form of a gas, liquid, or solid. To accurately determine the pathways and possible hazards, each nuclide must be individually identified and its quantity compared to the maximum permissible concentration.

B. Internal

Internal radiation is the radiation an individual receives from radionuclides which decay within his body. Isotopes which accumulate in the body from natural and manmade sources are ^{40}K in soft tissue, ^{90}Sr in bone, ^{3}H in water, ^{131}I in thyroid, and ^{85}Kr in fatty tissue.

Internal radiation from beta emitters such as ^{3}H and ^{90}Sr is more hazardous than external, since the protective layer of skin has been bypassed. Hence, most of the energy emitted from a decay will be deposited in the cells of the body. Some cells can be, and are, replaced during the normal cellular lifetime. For an adult, the red blood cells are usually completely replaced every 120 days, and the skin cells once every few days to few weeks. However, nonregenerating cells, such as nervous tissue, may never be replaced. If only a few cells are affected, they may be expelled by the body, but if a large number are destroyed or changed beyond the ability of the body to repair itself, serious deterioration may occur.

The dose to the population caused by nuclear reactors must be weighed against the natural background and the effects of alternative power sources. Studies of a "maximum person" (i.e., someone who drinks only effluent water from reactors and eats only the fish that reconcentrate various isotopes in their flesh, and drinks only milk from cows that graze on the grass downwind from a reactor, etc.) have been, and will continue to be performed. A meaningful estimate of the maximum dose received and its population distribution requires an accurate assessment of the dose pathways, using reliable monitoring and sampling techniques.

C. Radionuclides

A number of radionuclides must be individually identified if a complete knowledge of the impact on the environment from nuclear reactors is to be assessed. A list summarizing the radionuclides found in the environment near nuclear facilities was given in Reference 9 and is reproduced here as Table 1. The question marks (?) imply that the results of the measurement were uncertain. For example, the level of ^{131}I in cattle thyroids was so low that a specific documentation of its concentration could not be made. All of these radionuclides must be considered; however, some will require more attention than others due to their half-lives, quantity of production, and toxicity.

Table 2 lists the half-lives and principal decay modes for isotopes from nuclear reactors which can pose an environmental radiation hazard due to their long half-lives and quantity of production. The energy and type of decay aids in determining the instrumentation required. The number of curies per year available at any typical new reactor (150 days after the fuel is removed from the core) provides an indication of the amount of activity of the various nuclides which will be transported through the environment.

Figure 2 graphically shows the production rate of radioactivity in curies per year as a function of time (Ref. 8). The elements from

Zirconium (Zr) to Antimony (Sb) and the rare earth elements (RE) dominate the energy released for the first 1000 days. The Cesium (Cs) and Strontium (Sr) are dominant for about the next 300 years. Eventually the Iodine-129 will remain due to its seventeen million year half-life. Note also that Zr^{93}, Nb^{93m} and Tc^{99} will still be producing about 1000 curies per year a few centuries from now. In order to appreciate the logrithmic scales it is instructive to assign dates for reactor fuel processed today. Furthermore, the decay of iodine by eight orders-of-magnitude requires about 150 days, while the same relative decay of strontium requires about 500 years. These curves should be considered with the relative biological effects of each radionuclide in mind.

The present use of plutonium and its "ultimate" accumulation and hazard should also be considered by the reader. The next calculation, not performed here due to the very large errors and speculation involved, is to multiply by the number of equivalent 1000 MWe plants, and by the number of years we expect each plant to operate. Radionuclide production is the major unique feature of burning uranium rather than coal, oil, or gas to produce electricity. Mindful of our responsibility to succeeding generations, we need to evaluate the rate at which we are destroying and dispersing our limited hydrocarbon inheritance. Tax incentives to develop solar, geothermal, coal gasi-

fication, or fusion power do not exist. Fission power will reduce our dependence on fossil fuels, and it is available now. However, other processes for energy conversion should receive much more financial support in order to provide an adequate energy supply which is compatible with the environmental limits of our globe for the entire future of mankind.

IV. Fuel Handling

The largest routine hazard of radiation exposure to individuals working at nuclear reactors is from refueling and maintenance operations. Whenever access is allowed to material that has been in the core of the reactor, extreme caution must be exercised. Very careful surviellance should also be maintained in the case of research reactors, since cavalier attitudes tend to develop when constantly handling radioactive materials. External radiation from spent fuel rods, from defective rods, or from leaks in the primary coolant system are potential major sources of radiation exposure. Hence, these operations must be closely controlled and the possibilities of accidents should be minimized. This fact is well known and the personnel responsible for radiation safety use a variety of different monitoring techniques and instruments to measure the dose (e.g., film badges, personnel dosimeters, ion-chambers, Geiger counters).

The operation of a nuclear power plant is somewhat similar to the operation of a refinery. It is an extremely complicated arrangement of pipes, tanks, bypasses, and safety systems. The personnel responsible for the reactor's operation must also be thoroughly familiar with all the possible problems which may occur and have occurred (e.g., broken fuel rods, leaks, corrosion, spills). Contingency plans covering any credible catastrophes must be detailed before a

reactor produces power. Refueling is a particularly critical period when strict adherence of safety procedures must be maintained.

Unique problems are associated with the handling or radioactive fuels. However, under normal conditions, exposure of the general public due to the mining, milling, refining, transporting, and handling of fresh fuel is quite small. Spent fuel presents a relatively greater hazard due to the decay of its fission products, but the instrumentation for monitoring fuel-handling operations is considered adequate. Air-pumps and filters to measure particulates and gas monitors (for radon) are necessary only to further substantiate that very little activity has been released. In the case of a transportation accident (rail or truck) where the fuel containment is breached, these monitors will be required to perform their task.

When considering the impact on the environment from nuclear power one should consider the entire fuel cycle. Figure 3 is a material and environmental release flow sheet for a typical 1000 MWe light water reactor (Ref. 8). The magnitudes of various gaseous, liquid, and solid wastes are also described for the fossil fuels in Reference 8.

V. Fuel Reprocessing

The growth in size and numbers of power-generating nuclear reactors has dramatically increased the total world inventory of many radionuclides. Fortunately, only a minute fraction of the total activity is released to the environment in routine reactor operation. The remainder stays essentially entirely within the spent fuel rods, which are normally stored for at least 150 days before shipment to a fuel-reprocessing plant.

The fuel-reprocessing plant (FRP) is then faced with the problem of coping with the activity. The basic idea is to reclaim as much useful fissionable fuel and other reusable materials as possible, while releasing as little radiation as possible to the environment. Another (perhaps overriding) factor for an FRP is economic viability: presumably the reclamation process must compete economically with the mining, milling, and treatment of virgin fuel.

The economic justification for fuel reprocessing is twofold: first the fraction of reusable fission fuel recovered in the FRP is about 50%; thus the reprocessing operation essentially doubles the amount of useful energy derivable from the original uranium. Second, reprocessing enables the radioactive fission products to be concentrated for easier and less costly handling. Of course the other

side of the coin is that these plants may release some radionuclides to the environment which presumably would be contained within the spent fuel rods if these were stored without reprocessing. Since four of the most important nuclides (krypton-85, tritium, strontium-90, and cesium-137) have half-lives from 10 to 30 years, storage for decay is practical only on a century-based time scale. Present FRP plants can be viewed as operational prototypes for those needed in the future to provide sufficient fuel reprocessing capacity for the reactors now being built.

In the United States in 1973 there was only one operating commercial FRP: the Ashford, N.Y. plant of Nuclear Fuel Services Inc. (NFS). This plant began operation in April 1966. The NFS plant has closed for remodeling to increase its fuel reprocessing capacity. Two other commercial plants are in advanced stages of construction: the Midwest Fuel Recovery Plant (MFRP) in Morris, Illinois, and the Barnwell Nuclear Fuel Plant (BNFP) in Barnwell, South Carolina. Others are in the planning stage.

To illustrate the magnitude of the FRP problem, we take one estimate (from Oak Ridge National Laboratory, Ref. 10) for the future expansion of nuclear electrical generating capacity. While it must be emphasized that future projections such as this are based upon debatable assumptions, they do indicate at least future trends which

must be considered. In this light, Figure 4 shows the estimated installed nuclear generating capacity (megawatts) from 1970 to 2020. Figure 5 shows the projected discharges of spent fuel in tonnes (metric tons) for the same time period. Since the capacities of the three plants mentioned above are about one tonne per day each for NFS and MFRP, and six tonnes per day for BNFP, it can be concluded from Figure 5 that extensive additional FRP construction will be needed merely to meet the extrapolated fuel usage in 1980, a date for which present estimates of nuclear capacity are reasonably accurate.

The radionuclide fission products contained in the irradiated fuel of a light water reactor are shown in Table 3 (assuming a specific power level of 30 megawatts/tonne and a total fuel exposure of 33,000 megawatt days/tonne (Mwd/t)). From this table, it can be seen that the activities are prodigious indeed. FRP design has evolved around extremely careful analyses of the problems associated with these activity levels. Also, AEC licensing and operating restrictions have forced plant designers and operators to meet increasingly more stringent emission limits. Also shown in Table 3 are data for spent fuel from the liquid-metal fast breeder reactor, for a specific power level of 58 megawatts/tonne and burnup of 33,000 Mwd/t.

A. Liquid and Solid Wastes

MFRP plans to solidify wastes directly after production, to avoid the necessity for on-site retention of high activity wastes in liquid form. BNFP plans to use sedimentation and caking to

concentrate the liquid wastes into solid form, over a period of years. Both plants plan eventually to ship these wastes to a federal repository for perpetual care. The NFS experience has been different: low level liquid wastes are stored in lagoons for various periods before release to the environment via Cattaragus Creek. The environmental impact of the storage systems planned at the other sites is mainly related to the integrity of the container vessels, a subject which we shall not treat here.

B. Radiation Doses to Individuals

One important way of viewing the radiological impact of any radiation source is through radiation doses delivered to individuals living near the site. Studies have been made of some of the important components of this impact; in this section, a brief summary will be given of some of the conclusions.

For the MFRP and BNFP, calculations have been done on the main pathways of exposure to the general public. For MFRP, a few individuals in nearby cottages could receive as much as a few percent of technical specifications limits, and the estimated total man-rem is 35/year, integrated over a 50-mile radius containing over six million people (Ref. 11). For BNFP, the corresponding estimated annual figures (Ref. 12), integrated over about 200,000 people, are about 20 man-rem (whole body), 27 (bone), 200 (thyroid), and 200 (skin).

Shleien (Ref. 13) performed a 1968 study of exposure levels near NFS. His study concluded that "the presence of Nuclear Fuel Services, based on data presently available, did not significantly increase the radiation dose to the 'typical individual' in 1968 above that due to fallout and natural radiation." When Shleien considered a hypothetical "maximum individual" whose diet consisted of 50 kg of deer meat and 40 kg of fish per year (all killed near NFS), he found that such an individual might receive a whole-body dose of $\simeq$250 mrem/year, mostly from ^{137}Cs and ^{134}Cs in deer meat. The overall conclusion seems to be that normal FRP operations do not presently contribute a significant dose to humans.

C. Required Instrumentation

From the above discussion, it is clear that unique instrumentation is needed to monitor the environmental impact of radiation around FRP's. We have excluded instrumentation required in process control.

The largest source of exposure is normally due to ^{85}Kr and tritium in gaseous effluent. Clearly instrumentation is required to determine their distributions in the environment. Usually the amounts actually emerging from the stack are determined from calculation. In-stack monitors are nevertheless essential to check on the "normality" of the releases. The environmental impact is depen-

dent as well upon external effects such as meteorological conditions, and instruments are required at the site boundaries and beyond to determine the ultimate fate of the released activity, and to verify continuously the validity of dose-commitment calculations.

Airborne iodine is also a potential problem. Normally the iodines are removed by filtration before the gas is emitted. Instrumentation is required to determine iodine levels downstream of the filters, since it is very important to detect abnormalities immediately. Also, routine surveillance of cow's milk via the air-grass-cow-milk-human pathway is required.

Airborne particulates should be monitored in the stack, since they are so difficult to detect and quantify in the environment. In addition, gross beta and gross alpha determinations should be performed periodically in environmental locations.

Liquid effluent monitoring is also required. A continuous stream monitor is required to detect rapidly any possible faults in the system. Also, routine sampling and analysis for gross α, β, and γ should be performed, along with spectrometric measurements if necessary.

Monitoring in the vicinity of the high and low level waste storage containers is also essential. Possible pathways whereby leakages can

find their way into the environment must be studied and measurements carried out to confirm the integrity of the containment systems.

Finally, in the event of an accidental emission of radiation, there must be instrumentation present with wide dynamic range to perform critical-pathways measurements affecting a rather broad geographical area. These include sampling instruments for air, water, particulates, grass, and milk.

VI. Accidents

We restrict this section to a brief outline of some of the considerations in the choice of instrumentation for monitoring environmental releases in the event of a reactor accident. To summarize, the instrument should have an extremely large dynamic range, fail-safe operation, alarms, remote read-out, remote calibration, and long life (weeks if possible) on self contained power supplies. Reference 14 provides justifications and recommendations for an on-line data acquisition system capable of monitoring the accidental release of radionuclides to the environment.

Sabotage is an important consideration. A disgruntled employee, or a misguided fanatic could cause a tremendous amount of damage to society, individuals, and the energy supply of any nuclear nation. It can also be assumed that all large electrical generators will be considered primary targets in time of war. Further, acts of extortion, similar to skyjacking, are also possible from misinformed, unstable individuals or organizations.

A large amount of public and private discussion has occurred over the assumptions and predictions concerning "credible accidents". The primary example is a Loss of Coolant Accident which has been in the public spotlight. Wilson and Jones (Reference 15) provide details and some history concerning the assumptions, calculations, and pre-

dictions. Statistics and comparisons to the hazards associated with large amounts of other highly concentrated forms of energy in a volatile form (e.g., oil super tankers, liquified natural gas) are also presented, along with benefit-risk comparisons of alternative ways of producing electricity (e.g., fossil fuels). A comparison of the relative danger of BWR's and PWR's (hot steam under high pressure) is also assessed. HTGR's, LMFBR's, naval, and research reactors must also be considered in attempting to evaluate the risks associated with converting mass into energy.

The potential hazard from any credible accident must be seriously evaluated from several points of view. It is essentially impossible for a BWR or PWR to produce a nuclear explosion; however, if all redundant safety systems are breached, a serious accident could occur (i.e., the core could melt). If such an accident were to occur, a large amount of radioactivity would be present in a volatile form.

A number of general statements can be made to summarize the radioactive hazard to man from the nuclear fuel cycle:

1. Excluding accidents, the present dose to the general population due to <u>external</u> radiation from routine nuclear reactor operation is negligible.

2. Excluding accidents, the present dose to the general public due to <u>internal</u> radiation from nuclear reactor operation is also negligible.

3. Accidents are extremely improbable but cannot be completely excluded; therefore, the consequences of all possible accidents must be very seriously considered based on reasonable assumptions.

4. Long-term storage (perhaps thousands of years) of large amounts (tonnes) of high activity radioactive wastes (megacuries) will require accident-proof means of perpetual storage.

A small number (38) of radiation injuries has occurred in the U.S. during the 27-year period 1943-1970 (Ref. 16). None of these involved an electrical power generating reactor, a testimony to an appreciation of the requirement for a meticulous attention to details. The accidents have usually involved careless handling of fuel by the employees. Many of the accidents occurred at small reactors where experiments were being conducted that required a variety of fuel configurations. Naturally, the situation at an operating reactor used for power generation is quite different, since such a reactor is usually much larger with rigidly controlled operating procedures.

Transportation of increasing amounts of radioactive material may present a source of possible accidental exposure of the general public to radioactivity. The material should be transported in a solid form if possible. Some low-level liquid wastes (essentially contaminated water) can be solidified into concrete, which does not spill or leak. When a transportation accident does occur, a trained radiation hazard

inspector could fly to the scene and evaluate the hazard. At least one health physicist, or public health employee, or office, in each state (or regional area) should be responsible and available (24 hr/day) to determine the extent of any possible radioactive hazard. The radiation survey crew should have available calibrated, reliable, immediately usable, portable instruments to detect the activity. Dosimeters should be worn by the inspectors as well as by the transportation workers in order to measure their dose. The dose received by the general public, or any specific individuals involved in any accident, would be determined from calculations based on the measurements.

Breeder reactors, presently being developed, will require special safety considerations. Liquid sodium is a very volatile element which reacts with air and burns violently in water. Furthermore, a remote possibility of a violent chain reaction exists for fast-neutron breeders.

VII. Waste Storage

The storage of large volumes of high-level radioactive wastes for extremely long periods is a crucial consideration when discussing radiation and the environment. A list of the projected high-level and alpha emitting wastes is given in Table 4 as an indication of the quantities and activity of radioactive wastes that will require handling and storage (Ref. 3).

Geological stability, isolation from ground water, economics, activity of the waste, and distance from fuel reprocessing plants are just a few of the considerations involved in the decision of where and how to store radioactive wastes. Large tanks, either above or below ground, supported so they can be visually checked for leaks on the bottom and all sides, should be designed to withstand earthquakes and severe weather. Automatic leak detectors and area monitors containing alarm circuits would be required to continuously monitor each tank. Reference 10 presents a detailed discussion of waste storage, management, transportation, economic, and siting considerations.

The uncertainties associated with this aspect of nuclear power emphasize our dilemma. Should we leave future generations tons of activated fuel or should we leave them no fossil fuels? Clearly, other alternatives need to be developed.

VIII. Measurement Considerations

A. Process

Instrumentation for monitoring the operation of a reactor is beyond the scope of this report; however, the information from these instruments will provide a reference for correlating environmental contamination. Since sensors near the core must measure and withstand a massive amount of radiation, their design considerations are quite different from instruments intended to monitor low-level radionuclide signals immersed in a noisy, dynamically varying, natural background environment.

B. Area

Instrumentation for monitoring radiation within the reactor building should consist of a combination of various types. Measurements of gross beta and gamma activity provide a denominator or overall reference. Specific attention to the various components of radiation due to individual sources is not always necessary, although it is certainly useful information when attempting to diagnose a leak and document its history.

Wall-mounted ion-chambers should have sufficient sensitivity to measure daily variations (down to about 1 μR/hr). Separate detectors having a large range capable of measuring an accidental release

(up to about 10,000 R/hr) are also required. Fail-safe audible and visual alarms and provisions for recording the measurements are always desirable features. Periodic calibration and regularly scheduled maintenance procedures are necessary.

Stack and effluent monitors should have means for providing a temporal record of the emissions, in addition to multiple "fixed filters" for integrating the radioactivity released during various time periods.

Dosimeters for measuring the dose received by each employee should be pocket ion-chambers worn outside of any heavy clothing, as well as an integrating dosimeter (film, thermoluminescent dosimeter) changed periodically, in order to provide a measurement of both the long (integral) and short term dose received by an employee.

Remotely controlled or portable radioactive sources should be used routinely to check the calibration and operation of permanently installed monitoring instrumentation. A programmable calibrated electronic test pulse can also be used to rapidly isolate instrument failures.

C. Environment

The main consideration of instrumentation for monitoring environmental radiation is sensitivity. If the instrumentation is sensitive

enough to measure the expected emissions, then it will also respond to hourly, daily, and seasonal variations in the background levels. Typical background levels are presented in Table 5 (Ref. 17). Fluctuations in local background radiation leads to a dose which varies from about 75 to about 150 mrem/yr. In addition, daily variations can be as high as ±50%. Therefore, it will be rather difficult to measure the additional dose from a properly operating reactor, since that dose is typically not expected to exceed 5 mrem/yr at the fence.

Additional primary considerations for environmental monitors are reliability and precision. The instrument must be capable of performing the measurement (say, ≤3% error) over a wide range of temperature, humidity, pressure, dust, wind, snow, rain, and other adverse environmental factors.

Presently, TLD's and film are the backbone of environmental monitoring systems. These systems provide a valuable historical record of the emissions and a convenient mechanism for archival storage. As the quantity of required measurements increases, the need for automated procedures will also increase.

A large amount of meteorological data should be collected to determine the effect of an effluent discharge. For example, in a PWR this information could be used to determine when and at what

rate gas could be discharged to maximize dispersion, and hence to minimize any localized environmental impact.

Another primary consideration for an environmental monitoring system is versatility. One proposed system (Ref. 14) provides a facility for evaluating new monitoring instruments and is capable of a variety of test site configurations. Sufficient computer power for rapid collection, reduction, correlation and display of information, and a mechanism for easy distribution of both the raw and reduced data based on a time-sharing architecture was outlined. Dynamic, synergistic, and antenogistic studies of how a contaminant travels, disperses, concentrates, or reacts with the environment will need to be performed for many radionuclides and other contaminants. The system design is also capable of responding to an emergency situation.

IX. Measurement Techniques

A variety of techniques is used to measure the environmental and occupational radiation levels from nuclear power reactors. For example, grab samples, continuous monitors, dosimeters, and radionuclide identification equipment are all used to evaluate the operation of a nuclear power reactor. It is only possible to mention here that sampling plays a major role in environmental studies.

Each reactor will require different items which need to be sampled (e.g., fish, birds, corn, cows, thyroids, milk, water, air), different isotopes which should be measured (^{131}I, ^{90}Sr, ^{85}Kr, ^{3}H), different sampling intervals (daily, weekly, monthly, yearly), and different sampling locations (upwind, downstream, nearest city). Environmental sampling is used to provide backup and redundant data, to check the primary data sources (i.e., process monitors, stack concentrations, and meterological information).

Some of the sampling and analysis should be independently performed by at least two organizations to ensure confidence in the measurements. A typical environmental surveillance program is given in Reference 18.

Measurement techniques, instrumentation, and procedures for determining individual radionuclides in the gaseous, liquid, and particulate states are discussed in Reference 1. Grab samples and chemical

separation procedures are used for some of the gas and liquid phase measurements. Particulate concentrations are usually determined by independent laboratories analyzing filter paper on a monthly basis. Instrumentation for each of the following radionuclides is treated separately in Reference 1: Tritium, Krypton-85, Strontium-90, Iodine-131, Radon-222, Radium, Uranium and Plutonium.

X. Natural Radiation Backgrounds

This section will be concerned with a brief summary of the various components of the natural radiation background dose. By "natural background" we refer to radiation which is not man-made, including exposure affected by a man's activities as in airplane flight or by the use of radioactive building materials. Exposures to naturally occurring radiation from some activities, such as mining of naturally radioactive ores is excluded from the discussions in this section since that is considered an occupational exposure.

Depending on his location on the earth (or above it in aircraft) a man is exposed to varying levels of natural radioactivity. The sources include cosmic radiation, terrestrial radioactivity, air-borne radionuclides and internal radiation from ingestion of normal air and food. For many of the numbers presented here, we shall rely upon a recent EPA summary of natural background levels (Ref. 17). Another fine source is The Natural Radiation Environment, edited by Adams and Lowder (Ref. 19). A variety of sources were used for fallout data; many of the measurements presented here have been reported by the U.S.A.E.C. Health and Safety Laboratory.

A. Cosmic Radiation

The composition of primary cosmic radiation entering the atmosphere is about 85% protons, 14% alpha particles, and 1% heavier

nuclei. There seem to be few electrons and high energy gammas, and those mostly at the lower energies, where they comprise a few percent of the flux. The primary energy spectrum follows an inverse power law, falling off approximately as $1/E^2$ from about 10^9 to 10^{18} eV (Ref. 20).

At the earth's surface, the flux is predominately muons from the decay of pions produced by the primary protons in the upper atmosphere; these muons are accompanied by an equilibrium mixture of electrons and gammas. There is also a small flux of neutrons. For our purposes, it is adequate to assume that the total dose to tissue from cosmic radiation is almost entirely from relativistic charged particles.

Cosmic radiation dose levels vary significantly with altitude, and less strongly with latitude. Figure 6 shows a vertical profile from 10,000 to 80,000 feet which was measured in balloon flights by U.S.A.E.C. Health and Safety Laboratory personnel in 1969-70 (Ref. 21). Note the latitudinal variations at the higher elevations. From this figure, it can be seen that higher doses will be experienced in aircraft.

Table 5 shows the state-by-state breakdown of cosmic-ray annual per capita doses in the U.S. Note that while the average does in the U.S. is 45 mrem/year, the does rates range from 35-40 mrem/year (at sea level in the continental U.S.) to 115-130 mrem/year (in the Rocky

Mountain states). The sea-level rates at more southern latitudes (Hawaii, Canal Zone, Samoa) are smaller: about 30 mrem/year. It is estimated that at an altitude of 40,000 feet (conventional jet aircraft) the dose is as large as 0.7 mrem/hour, and about 1.1 mrem/hour at 60,000 feet (possible supersonic transport SST altitudes (Ref. 22)); thus a round-trip transcontinental flight will yield total doses of about 6 to 8 mrem, in either conventional or SST aircraft. Assuming 310 million passenger miles flown in 1970 (Ref. 23), the total man-rem accumulated by passengers in that year was about 200,000 (or an average dose to the entire population of 1.0 mrem per capita). In addition, approximately 15,000 air crew members received an average of 670 mrem/year in 1970, for a total of about 10,000 man-rem (Ref. 17).

B. External Gamma Radiation

Naturally occurring radionuclides produce external gamma exposures which vary with location, time, and meteorological conditions. Reviews of these levels have been complied (Ref. 24, 25). Also, Reference 12 contains detailed discussions of some localized "hot spots" in various terrestrial locations, such as in Brazil and the Rocky Mountains, where levels may reach several thousand mrem/year. Table 5 (Ref. 17) also shows the state-by-state external whole body doses, which average about 60-mrem/year over the U.S. The dominant contributions are from radon and its daughters (ultimately from the uranium and thorium deposited in rocks) and from potassium-40. When measurements of low

level gamma emitters are made using gamma spectroscopy, potassium-40 in particular can provide a significant background.

C. Internal Exposures

The contributions of the dominant radionuclides to internal radiation are shown in Table 6 (from Ref. 17). Doses to the whole body, to endosteal cells, and to bone marrow are considered. The total is dominated by ^{40}K, ^{210}Po, ^{222}Rn, ^{226}Ra, and ^{14}C. The average whole body dose is approximately 25 mrem/year, and except for the ^{222}Rn contribution (through inhalation) it is all received through food ingestion. Because agricultural produce in the U.S. receives wide distribution, these figures probably do not fluctuate as significantly from place to place as do the external or cosmic radiations. In fact, ^{226}Ra concentrations seem to vary more due to dietary differences at a given location than due to geographical effects (Ref. 17).

D. Summary of Natural Radiation

The overall "average" U.S. doses from natural radiation can be summarized as follows:

SOURCE	AVERAGE DOSE	RANGE IN U.S.
Cosmic Rays	45 mrem/year	30 to 130 mrem/year
External Gamma Radiation	60 mrem/year	40 to 115 mrem/year
Internal Exposures	25 mrem/year	----------
Total	130 mrem/year	

XI. Summary

One of the objectives of this paper has been to provide the reader with an incentive to review the status of nuclear power generating plants. Their location, growth, and operation were discussed from the environment hazard point of view. The problems of fuel handling, fuel reprocessing, accidents, and waste storage were also outlined. A brief discussion of the sources of radiation exposure was intended to point out those problem areas which require attention. Various general measurement considerations were described for monitoring radiation in the area and environment surrounding a reactor. Measurement techniques used to determine concentration, dose, and hazard were briefly mentioned. Summary information on natural radiation backgrounds was included to illustrate the "signal to noise" problem. References were chosen based on their clarity and usefulness to the task at hand.

The use of an on-line computer-controlled monitoring system allows programmable calibration procedures, rapid response, and aids in controlling the process. The primary consideration for purchasing instrumentation for nuclear reactors is often price; however, sensitivity, dynamic range, calibration, and accuracy should receive higher priorities. In general, the instrumentation now being used for gross gamma and neutron measurements is adequate. As new guidelines require more specific determination of individual

radionuclides, increased use of spectrum analyzers will be required. It is unfortunate that instrumentation budget requests receive such low priority, and seem to require a strong legal stimulus for any increases.

The total average natural dose of 130 mrem/year corresponds to about 15 μrem/hour. Of this, about 105 mrem/year (~12 μrem/hour) is from cosmic radiation and external sources. This constant, irreduceable background, along with fallout radiation in some circumstances, can hinder dose measurements at external levels significantly below a few μrem/hour. In particular, one of the difficulties is that the natural levels may have diurnal and seasonal fluctuations due to meteorological changes. These variations can sometimes mask the presence of small man-made contributions to the total radiation environment. Measurements of the natural background levels per se can be made today for most of the parameters of interest. An example of instrumentation developed specifically for use in the environment and for low-level measurements is the pressurized-argon ionization chamber used by the U.S.A.E.C. Health and Safety Laboratory (Ref. 28). Finally, measurements of man-made radionuclides in various samples (e.g., rocks or soils) can be significantly affected by natural background activities from such radionuclides as potassium-40 and the heavy natural alpha-emitting chains.

During normal operation, environmental monitoring instruments need not concentrate on the "short-lived" isotopes. A question that

must be addressed is the assessment of how much (curies), how long (half-life), how energetic (energy), how hazardous (MPC), and how probable is the release of each isotope. Unfortunately, a detailed quantitative calculation will never produce an absolutely certain answer for a specific case, only a better estimate of the probability. Hence, there is a reliance on the environmental monitoring program of a reactor to predict future release probabilities and distributions.

XII. Acknowledgment

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Figure 1	Nuclear Power Reactors in the United States (Ref. 4)
Figure 2	Radioactivity produced in one year by a 1000 MWe Light Water Nuclear Power Plant (Ref. 8)
Figure 3	Material and environmental release flow sheet for a typical 1000 MWe light water reactor nuclear power plant (Ref. 8)
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Figure 5	Projected discharges of spent fuel for calendar year ending (Ref. 10)
Figure 6	Free air dose rate profile from cosmic-ray charged particles, 1969-70 (Ref. 21)
Table 1	Radioactivity Found in Environment During Radiological Surveillance Studies (Ref. 9)
Table 2	Long Half-Life Radionuclides From Light-Water Nuclear Reactors
Table 3	Radionuclide Content of Light Water Reactor (LWR) Fuel Decayed 150 Days and Mixed Core-Blanket Liquid Metal Fast Breeder Reactor (LMFBR) Fuel Decayed 30 Days, (Burnup Is 33,000 Megawatt-Days per Tonne, with Specific Power of 30 (LWR) and 58 (LMFBR) Megawatts per Tonne), from Reference 10.
Table 4	Projected High-Level and Alpha Wastes (Ref. 3, Culler, Blomeke and Belter, p. 3.2-4)
Table 5	Estimated Annual Cosmic Ray and External Gamma Whole-Body Doses from Natural Terrestrial Radioactivity (Ref. 17) Average Annual Doses (mrem)
Table 6	Estimated Average Annual Internal Radiation Doses From Natural Radioactivity in the United States (Ref. 17)

TABLE 1. *Radioactivity Found in Environment During Radiological Surveillance Studies (Ref. 9)*

Study Location	Environmental Sample	Radionuclides
BWR	external radiation from gaseous effluent	
	air	^{133}Xe, ^{135}Xe, ^{138}Cs
	cattle thyroids	^{131}I (?)
	snow	^{89}Sr (?)
	field corn	^{137}Cs (?)
	effluent water	^{58}Co, ^{60}Co, ^{89}Sr, ^{90}Sr, ^{131}I, ^{134}Cs, ^{137}Cs, ^{140}Ba
	sediment	^{58}Co, ^{60}Co, ^{90}Sr, ^{134}Cs, ^{137}Cs, ^{140}Ba
PWR	external radiation from waste storage tanks	
	effluent water	^{3}H
	water moss	^{54}Mn, ^{58}Co, ^{60}Co
	dead leaves	^{60}Co (?)
	sediment	^{54}Mn, ^{60}Co, ^{125}Sb, ^{137}Cs
Fuel Reprocessing	air	^{3}H, ^{85}Kr
	effluent water	^{3}H, ^{60}Co, ^{90}Sr, ^{106}Ru, ^{125}Sb, ^{137}Cs
	sediment	^{60}Co, ^{90}Sr, ^{106}Ru, ^{134}Cs, ^{137}Cs, ^{238}Pu, ^{239}Pu
	deer meat	^{3}H, ^{90}Sr, ^{134}Cs, ^{137}Cs
	deer thyroid	^{129}I
	fish flesh	^{3}H, ^{60}Co, ^{90}Sr, ^{137}Cs

TABLE 2. *Long Half-Life Radionuclides From Light-Water Nuclear Reactors*

Isotope	Curies/Year Per 1000 MWe*	Half-Life	Principal Decay Mode (keV)
^{3}H	$23.8 \cdot 10^{3}$	12.4 years	18.6 max β
^{54}Mn		303 days	835 γ
^{58}Co		71 days	474 max β+ 810 γ
^{60}Co		5.25 years	1173 γ 1332 γ
^{85}Kr	$386 \cdot 10^{3}$	10.76 years	670 max β
^{89}Sr	$3300 \cdot 10^{3}$	52.7 days	1463 max β
^{90}Sr	$2640 \cdot 10^{3}$	28.0 years	546 max β
$^{106}Ru/^{106}Rh$	$14,100 \cdot 10^{3}$	367 days	39/3540 max β
^{125}Sb	$280 \cdot 10^{3}$	2.7 years	610 max β
^{129}I	1.3	$17 \cdot 10^{6}$ years	150 max β
^{131}I	75	8.05 days	364 γ
^{131m}Xe		11.8 days	164 γ
^{133m}Xe		2.26 days	233 γ
^{133}Xe		5.27 days	346 max β
^{135}Xe		9.1 hours	920 max β 250 γ
^{134}Cs	$7350 \cdot 10^{3}$	2.046 years	605 γ 796 γ
^{137}Cs	$3660 \cdot 10^{3}$	30.0 years	661 γ
^{140}Ba	$14.8 \cdot 10^{3}$	12.8 days	1020 max β
^{238}Pu	$97 \cdot 10^{3}$	86.4 years	5500 α, 72% 5460 α, 28%
^{239}Pu	$11.4 \cdot 10^{3}$	24,400 years	5160 α, 88% 5110 α, 12%

*The amount of activity for a 1000 MWe light-water reactor, 32% thermal efficiency, fuel specific energy 33,000 MWt day/tonne, 100% load factor, using 34.5 tonnes of total fuel (fresh uranium) per year is calculated from:

$$\frac{\text{curies}}{\text{year}} = \left(\frac{\text{curies}}{\text{tonne}} \right)_{\text{after 150 days of cooling}} \left(34.5 \ \frac{\text{tonnes}}{\text{year}} \right)$$

The number of curies per year available at any typical new reactor (150 days after the fuel is removed from the core) provides an indication of the amount of activity of the various nuclides which will be transported through the environment. (See Fuel Reprocessing Plants, Section V, Part C, Table 1.)

Table 3. Radionuclide Content of Light Water Reactor (LWR) Fuel Decayed 150 Days and Mixed Core-Blanket Liquid Metal Fast Breeder Reactor (LMFBR) Fuel Decayed 30 Days (Burnup Is 33,000 Megawatt-Days per Tonne, with Specific Power of 30 (LWR) and 58 (LMFBR) Megawatts per Tonne), from Reference 10.

Nuclide	Concentration (curies/metric tonne) In LWR Fuel	In LMFBR Fuel	Nuclide	Concentration (curies/metric tonne) In LWR Fuel	In LMFBR Fuel
^{3}H	692	932	^{131}I	2.17	139,000
^{85}Kr	11,200	10,200	^{132}I	-	4,300
^{89}Sr	96,000	637,000	^{133}Xe	-	74,400
^{90}Sr	76,600	43,400	^{134}Cs	213,000	29,000
^{90}Y	76,600	43,500	^{136}Cs	20.8	28,800
^{91}Y	159,000	921,000	^{137}Cs	106,000	109,000
^{95}Zr	276,000	2,100,000	^{140}Ba	430	523,000
^{95}Nb	518,000	2,660,000	^{140}La	495	601,000
^{99}Mo	-	1,810	^{141}Ce	56,700	1,480,000
^{99m}Tc	-	1,730	^{144}Ce	770,000	1,280,000
^{99}Tc	14.2	14.9	^{143}Pr	694	644,000
^{103}Ru	89,100	1,760,000	^{147}Nd	51.0	185,000
^{106}Ru	410,000	1,290,000	^{147}Pm	99,400	353,000
^{103m}Rh	89,100	1,760,000	^{149}Pm	-	61.5
^{111}Ag	-	12,600	^{151}Sm	1,150	4,690
^{115m}Cd	44.3	269	^{152}Eu	11.5	10.5
^{124}Sb	86.3	76.7	^{155}Eu	6,370	79,400
^{125}Sn	20.0	6,720	^{160}Tb	300	9,460
^{125}Sb	8,130	19,600	^{239}Np	17.4	7,220
^{125m}Te	3,280	6,860	^{238}Pu	2,810	11,200
^{127m}Te	6,180	61,100	^{239}Pu	330	3,530
^{127}Te	6,110	61,800	^{240}Pu	478	4,260
^{129m}Te	6,690	181,000	^{241}Pu	115,000	600,000
^{129}Te	4,290	116,000	^{241}Am	200	1,570
^{132}Te	-	4,170	^{242}Cm	15,000	65,500
^{129}I	0.038	0.053	^{244}Cm	2,490	1,240

TABLE 4. *Projected High-Level and Alpha Wastes*

(Ref. 3, Culler, Blomeke and Belter, p. 3.2-4)

		Calendar Year Ending			
		1980	1990	2000	Unit
Installed nuclear electric capacity		150,000	450,000	940,000	MW
Fuel reprocessed		3,000	9,000	19,000	m tons/yr
Solidified high level waste[a]					
Annual volume		9.7	33	58	10^3 ft^3
Accumulated volume		44	290	770	10^3 ft^3
Total accumulated activity		19,000	110,000	270,000	MCi
Total thermal power		90	410	1,040	MW
Significant isotopes accumulated,	half-life				
^{90}Sr	28.9 years	960	5,700	12,000	MCi
^{137}Cs	30 years	1,300	8,000	20,000	MCi
^{129}I	17,000,000 years	480	3,300	9,700	Ci
^{85}Kr	10.8 years	120	690	1,500	MCi
^{3}H	12.3 years	7.3	44	110	MCi
^{238}Pu,[b]	87.4 years	1.2	10	40	MCi
^{239}Pu,[b]	24,400 years	0.02	0.3	1.7	MCi
^{240}Pu,[b]	6,600 years	0.04	0.5	2.4	MCi
^{241}Pu,[b]	14.3 years	6.6	58	240	MCi
^{241}Am	433 years	2.3	28	150	MCi
^{244}Cm	18.1 years	30	170	330	MCi
Number of shipments to repositories[c]		23	240	590	
Alpha wastes					
Annual volume		0.36	0.92	2.5	10^6 ft^3
Accumulated volume		4.6	10.4	27.0	10^6 ft^3
Total activity		31	150	420	MCi
Total thermal power		0.03	0.17	0.66	MW
Significant isotopes accumulated,	half-life				
^{238}Pu	87.4 years	0.51	2.6	8.4	MCi
^{239}Pu	24,400 years	0.11	0.58	2.0	MCi
^{240}Pu	6,600 years	0.16	0.83	2.8	MCi
^{241}Pu	14.3 years	30	146	400	MCi
^{241}Am	433 years	0.14	1.0	6.6	MCi
Number of shipments to repositories[d]		930	1,200	3,030	

[a] Assumes 1 ft^3 of solidified waste per 10,000 MWd(th).
[b] Assumes 0.5% of plutonium in fuel is lost to waste.
[c] Each shipment consists of 57.6 ft^3 of waste in thirty-six 6-in.diam. cylinders. Half of the waste is aged 5 years and half is aged 10 years at the time of its shipment.
[d] Each shipment contains 832 ft^3 of waste.

TABLE 5

Estimated Annual Cosmic Ray and External Gamma Whole-Body Doses from Natural Terrestrial Radioactivity (Ref. 17)

Average Annual Doses (mrem)

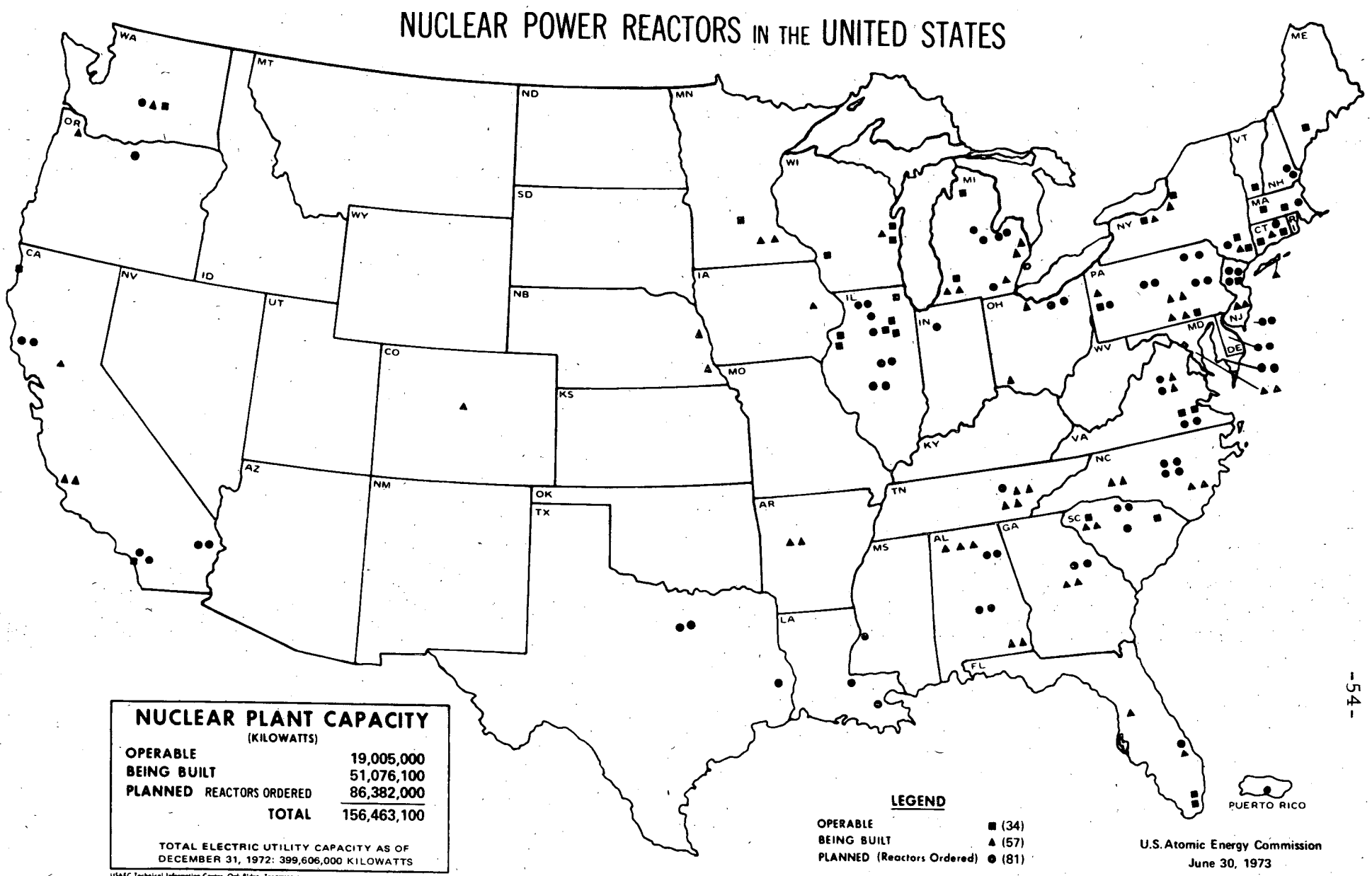
Political Unit	Cosmic Radiation	External Whole Body	Political Unit	Cosmic Radiation	External Whole Body
Alabama	40	70	New Jersey	40	60
Alaska	45	---	New Mexico	105	70
Arizona	60	---	New York	45	65
Arkansas	40	75	North Carolina	45	75
California	40	50	North Dakota	60	---
Colorado	120	105	Ohio	50	65
Connecticut	40	60	Oklahoma	50	60
Delaware	40	---	Oregon	50	---
Florida	35	---	Pennsylvania	45	55
Georgia	40	---	Rhode Island	40	65
Hawaii	30	---	South Carolina	40	70
Idaho	85	---	South Dakota	70	115
Illinois	45	65	Tennessee	45	70
Indiana	45	55	Texas	45	30
Iowa	50	60	Utah	115	40
Kansas	50	---	Vermont	50	45
Kentucky	45	---	Virginia	45	55
Louisiana	35	40	Washington	50	---
Maine	50	75	West Virginia	50	---
Maryland	40	55	Wisconsin	50	55
Massachusetts	40	75	Wyoming	130	90
Michigan	50	---			
Minnesota	55	70	Canal Zone	30	---
Mississippi	40	65	Guam	35	---
Missouri	45	---	Puerto Rico	30	---
Montana	90	---	Samoa	30	---
Nebraska	75	55	Virgin Islands	30	---
Nevada	85	40	District of Columbia	40	55
New Hampshire	45	65	Average for U.S.	45	60

TABLE 6

Estimated Average Annual Internal Radiation Doses From Natural Radioactivity in the United States (Ref. 17)

Radionuclide*	Annual Doses (mrem)		
	Whole-Body	Endosteal Cells	Bone Marrow
^{3}H	0.004	0.004	0.004
^{14}C	1.0	1.6	1.6
^{40}K	17	8	15
^{87}Rb	0.6	0.4	0.6
^{210}Po	3.0	21	3.0
^{222}Rn	3.0	3.0	3.0
^{226}Ra	-	6.1	0.3
^{228}Ra	-	7	0.3
Total	~25	~47	~24

* Other natural radionuclides would contribute to doses but such a small fraction that they would not affect the totals within the accuracy of these estimates. As an example, doses from ^{3}H are shown here.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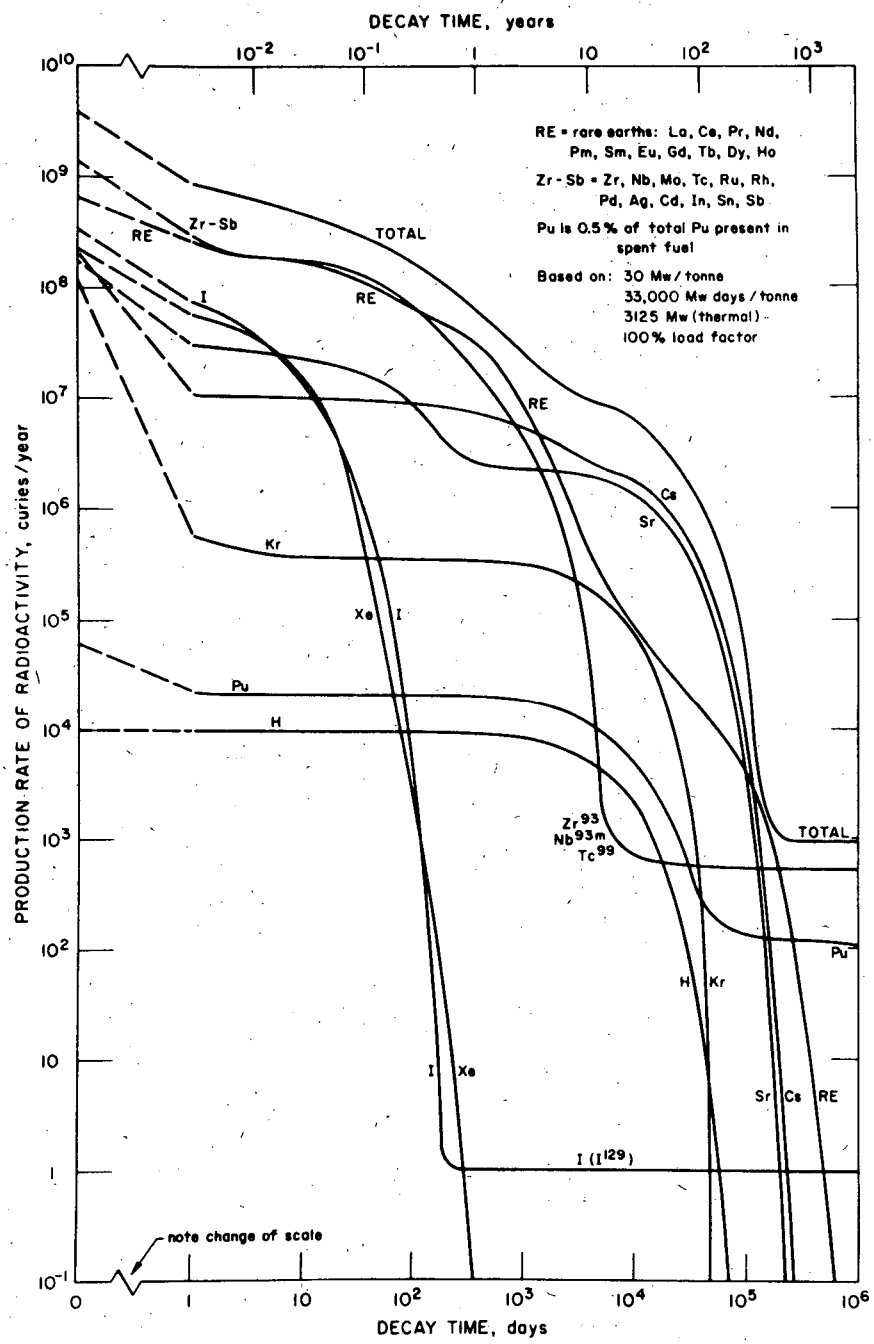
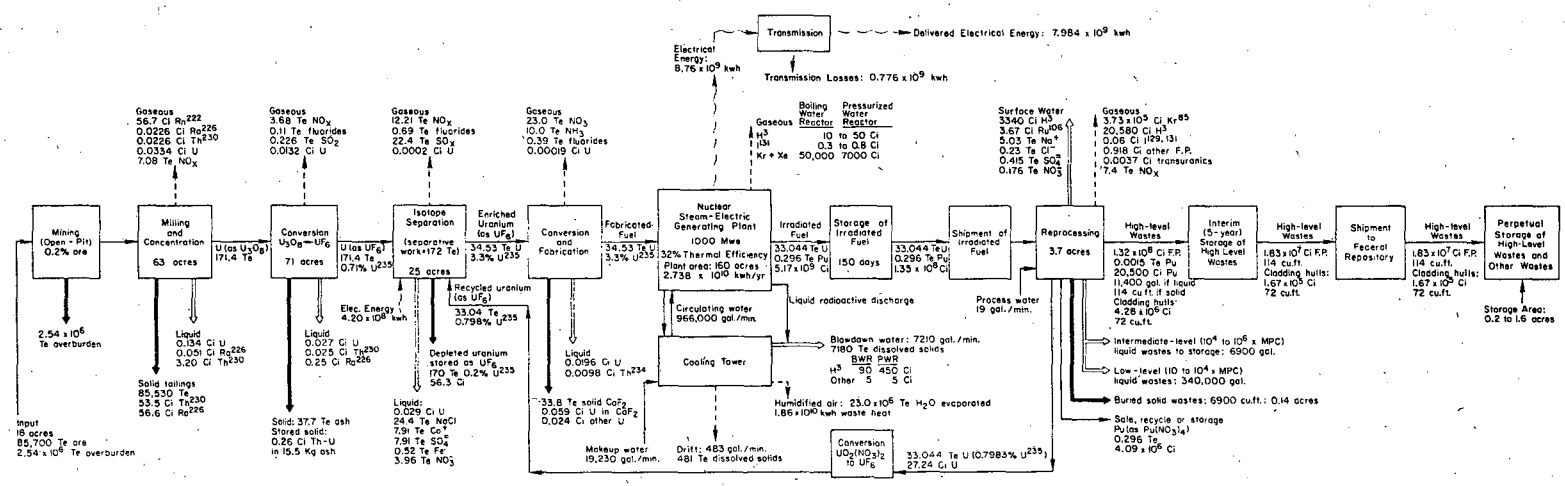
WV
PA
NY
VT
NH
ME
MA
CT
RI
NJ
MD
DE
PUERTO RICO
NUCLEAR PLANT CAPACITY
(KILOWATTS)
OPERABLE 19,005,000
BEING BUILT 51,076,100
PLANNED REACTORS ORDERED 86,382,000
TOTAL 156,463,100
TOTAL ELECTRIC UTILITY CAPACITY AS OF DECEMBER 31, 1972: 399,606,000 KILOWATTS
USAEC Technical Information Center, Oak Ridge, Tennessee
LEGEND
OPERABLE (34)
BEING BUILT (57)
PLANNED (Reactors Ordered) (81)
U.S. Atomic Energy Commission
June 30, 1973

Fig. 1.



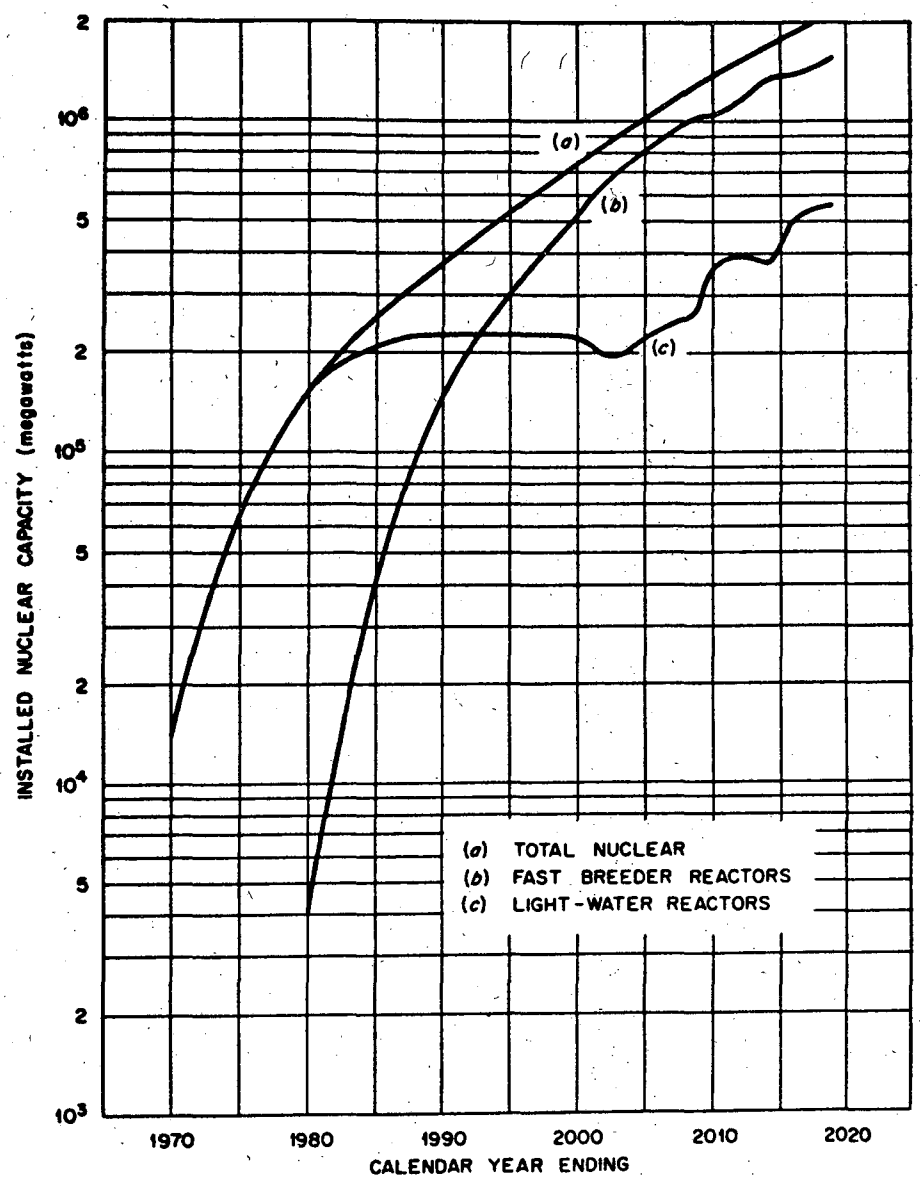
XBL 741-19

Fig. 2.



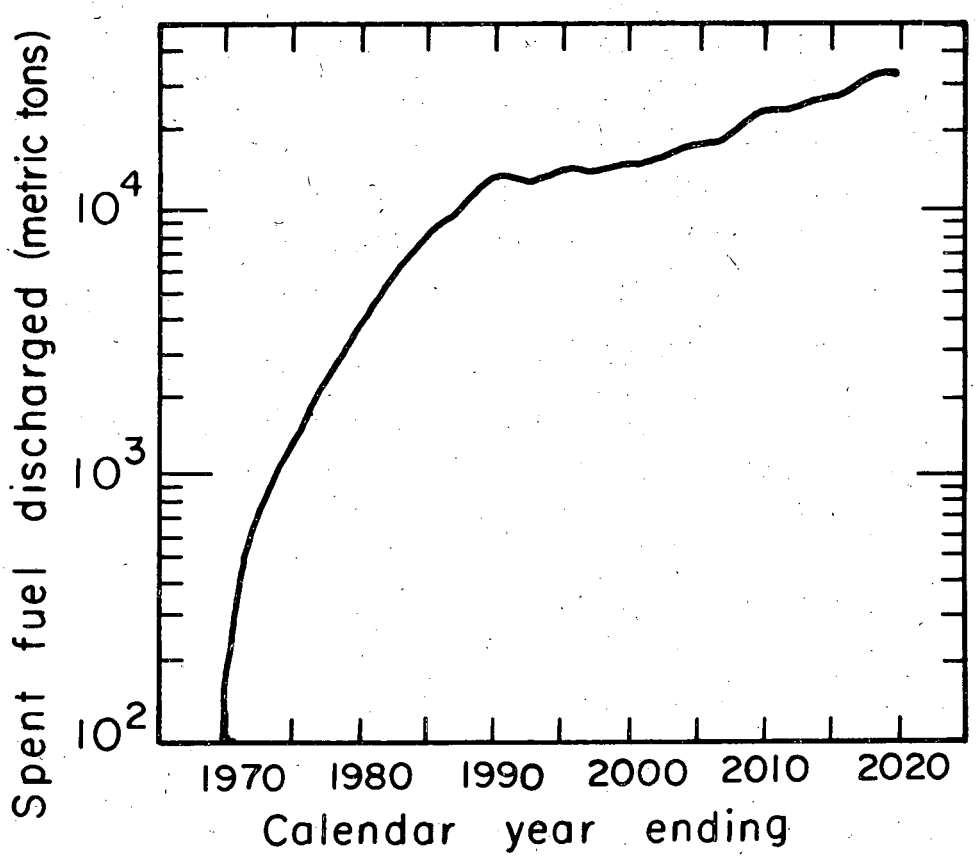
XBL 741-12

Fig. 3.



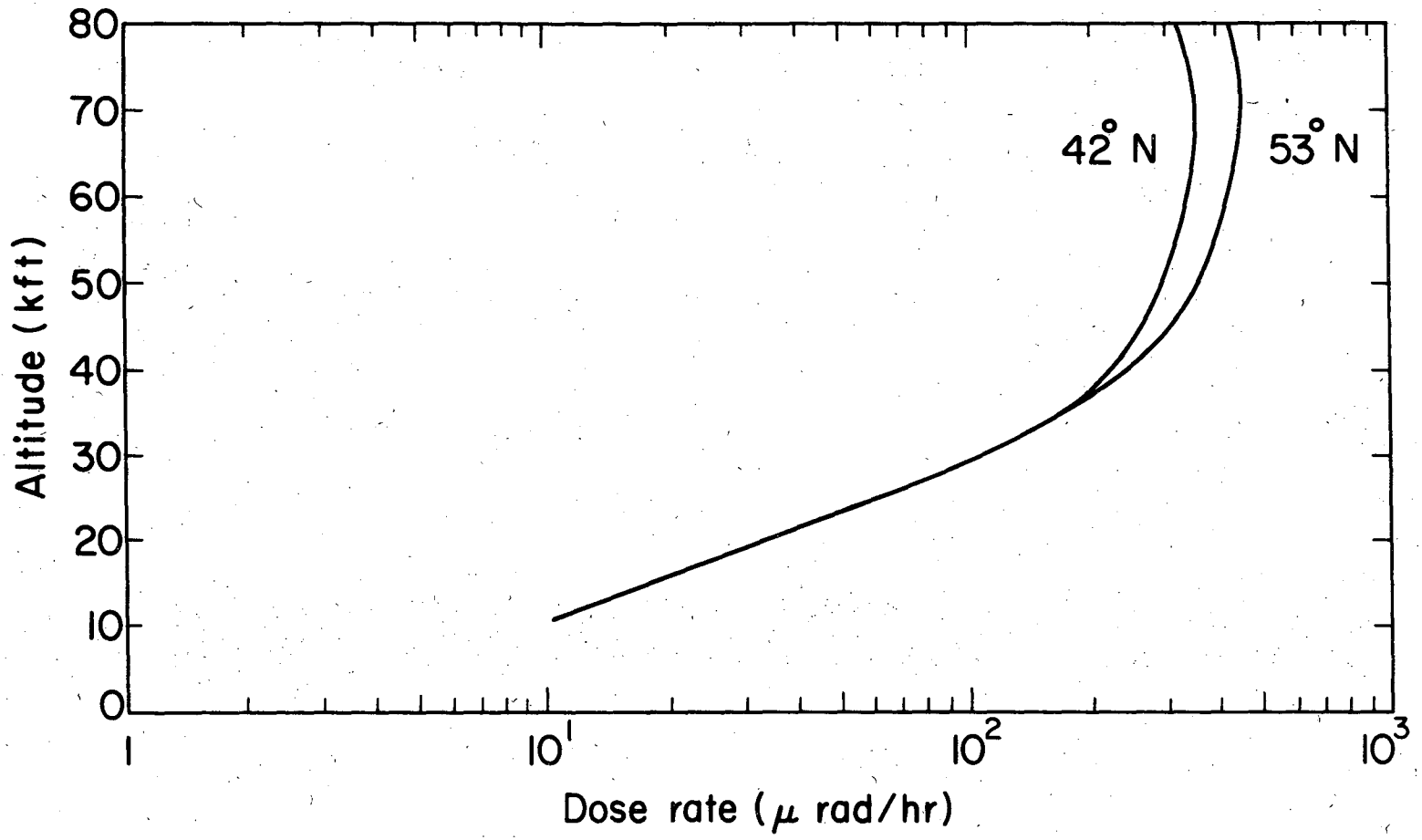
XBL 741-16

Fig. 4.



XBL 741-2171

Fig. 5.



XBL7210-4192

Fig. 6.

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