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PATHWAY MODELING AND SURVEILLANCE

Andrew P. Hull
Health Physics and Safety Division
Brookhaven National Laboratory
Upton, New York 11973

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ENVIRONMENTAL RADIATION DOSE CRITERIA AND ASSESSMENT -- PATHWAY MODELING AND SURVEILLANCE*

Andrew P. Hull
Health Physics and Safety Division
Brookhaven National Laboratory
Upton, New York 11973

ABSTRACT

The controversy in recent years over the extent of the risk to the public from environmental radioactivity attributable to nuclear facilities (in particular nuclear power plants and fuel reprocessing facilities) has resulted in a lowering of previously "acceptable" environmental radiation levels. The proposal by the AEC to limit effluents from light-water-cooled nuclear reactors so that the exposure of any individual in the public would not exceed 5 mR/yr, and the pronouncement by the BEIR Committee that the current environmental radiation protection guides are unnecessarily high, are illustrative.

In turn the AEC has issued a Safety Guide calling for considerable refinement in the measuring and reporting of effluents from nuclear power plants, and has only recently issued a counterpart dealing with the measuring and reporting of radioactivity in the environs of nuclear power plants. The EPA has also recently issued a guide for the surveillance of environmental radioactivity. Currently, power reactor operators are being required by the AEC Regulatory Staff to conduct detailed, sensitive environmental surveillance, at levels consistent with the proposed concentration limits of Appendix I.

Much of this appears to be based on extremely conservative assumptions throughout, including dose-effect relationships, exposure situations, pathway models, reconcentration factors and intakes, which cannot be substantiated when examined in the light of current experience in the vicinity of existing power reactors. The expenditures occasioned by the required additional in-plant features necessary to meet the currently proposed effluent release criteria appear difficult to justify on a reasonable basis. Those for environmental monitoring at the proposed concentration limits appear even more excessive in terms of dollars per man-rem of potential dose commitment.

INTRODUCTION

Nuclear reactors have been utilized in the United States for military and research purposes since World War II.^{1,2} The first U. S. peacetime nuclear power plant at Shippingport went into operation in 1957, and by the end of the following decade ten more such plants were operational.² The first commercial fuel reprocessing facility became operational in 1966.³ During these two decades, from the mid-1940's to the mid-1960's, relatively little concern was expressed about environmental radiation dose criteria or about the risk to the public from the environmental radioactivity attributable to the operation of these facilities.

In the mid-1950's, the International Commission on Radiological Protection (ICRP) recommended⁴ environmental radiation dose limits of 0.5 rem/year for gonad or whole body exposure, and 1.5 rem/year for most other organs. These were generally a factor of 1/10 of the established occupational exposure limits. The ICRP also recommended⁵ that a corresponding factor be

applied to occupational maximum permissible concentrations in air and in water (or food), to establish concentration limits for the exposure of the public.

Even before this, responsible health physicists at individual facilities had applied a similar margin of safety to the involuntary exposure of the public from plant effluents. For example, an "off-site" exposure criterion of 3.5 mR/week was applied⁶ in 1948 at Brookhaven National Laboratory as a limit for the exposure of the public from the radioactive ⁴¹Ar in cooling air of the Brookhaven Graphite Research Reactor (BGRR).

The necessity of paying attention to indirect pathways and reconcentration mechanisms was recognized^{7,8} early in the development of the atomic energy program. In particular, that the presence of ¹³¹I in milk from cows grazing on a contaminated pasture might lead to thyroid doses considerably in excess of its direct inhalation was widely recognized from the experience following the release of about 20,000 curies of ¹³¹I from the air-cooled Windscale reactor⁹ in 1957. The early experience at Hanford⁸ and at Windscale¹⁰ in the release of multicurie amounts of activity to the aquatic and marine environments pointed to the possible existence of sub-populations at special risk due to bio-accumulations and/or unusual dietary practices.

From these and other similar experiences the ICRP evolved the concept of a selective approach to environmental situations. In its 1965 publication¹¹ on the principles of environmental monitoring, the ICRP said in part: "In most situations in which radioactive materials are introduced into man's environment there will be numerous and complex pathways by which each of the released nuclides may ultimately cause the radiation exposure of man ..." Simplified versions of these pathways, as depicted by the ICRP, are shown for releases to air in Figure 1, and for releases to ground or surface waters in Figure 2. The ICRP further indicated that: "A comprehensive and detailed study of all such pathways will not be needed, even for installations which involve potential radiation hazards of the greatest magnitude by reactors, reactor fuel reprocessing plants and stores of fuel reprocessing wastes. Experience has shown that a study of the situation will indicate that certain nuclides and certain exposure pathways are much more important than others. These nuclides and pathways are designated 'critical'." (emphasis the author's)

In the context of the development of the application of nuclear energy for scientific and industrial purposes, in 1961 a seminar¹² on the mechanisms of transfer of radionuclides from the environment through food, air and water to man, was conducted under the auspices of the United Nations, the World Health Organization and the International Atomic Energy Agency. It is evident that by this time an extensive basis for pathway modeling was available. Several papers presented at a 1968 symposium on environmental surveillance in the vicinity of nuclear facilities¹³ indicated a continuing refinement in the art of pathway modeling and dose assessment.

Work carried out at Brookhaven National Laboratory under contract with the U.S. Atomic Energy Commission.

While this development of pathway modeling was useful in the design of nuclear facilities, up to recently it was not primarily influential toward the installation of radioactive waste emission control facilities that would not otherwise have been employed in the absence of such modeling. In the author's judgment, this lack of influence was an outcome of the application, primarily the instigation of health physicists, of the "as low as practicable" concept in nuclear facility design, long before it became an official doctrine¹⁴ of the AEC in 1970. The application of this philosophy resulted in the radwaste control facilities and procedures that curtailed effluent releases to small fractions of those allowable under a boundary dose constraint of 500 mR/year.

This experience was summarized by Kahn et al.¹⁵ at the 4th Peaceful Uses Conference in 1971. From extensive surveillance programs at representative facilities, maximum doses of only a few millirems per year to small populations were apparent from the various identified pathways. The overall nearby population doses were generally found to be less than 1 mR/year, in the several studies referred to in this paper.

Despite this experience, late in the 1960's Gofman and Tamplin, Sternglass and others mounted a vociferous criticism of the then applicable environmental radiation protection standards and MPC's. In the context of the actual or anticipated nuclear power reactor (and fuel reprocessing plant) effluents, they adduced large numbers of additional cancers or infant deaths should the entire population of the United States or some large fraction thereof be exposed to the upper limit specified by the standards (variously interpreted as 170 or 500 mR/year), or if power reactor radionuclide levels were to remain continuously at the MPC's.

10CFR50 APPENDIX I

In what seemed in large part a response to these beside-the-fact arguments, rather than to scientific evidence, in June 1971 the AEC proposed additional amendments¹⁶ to 10CFR50, setting forth "numerical guidance to keep radioactivity in light-water-cooled nuclear power effluents as low as practicable". The essential details appear in Table I.

Table I
Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion "As Low as Practicable" for Radioactive Material in Light-Water-Cooled Nuclear Power Reactor Effluents*

Liquid Effluents	Annual Quantity	Annual Average Concentration
Except H-3	≤ 5 Ci	≤ 20 pCi/l
H-3*		≤ 5,000 pCi/l

*Prior to dilution in a natural body of water.

Gaseous Effluents	Annual Avg. Boundary Exposure Rate	Annual Avg. Boundary or Off-Site Concentration
Noble gases	≤ 10 mrem	
Iodines or particulates with $T_{1/2} > 8$ days	**	≤ $\frac{10\text{CFR20}}{100,000}$

**Calculated so that exposure of individuals off-site ≤ 5 mrem/year.

† From Appendix I, Section 50.36a, 10CFR50.

The announced intent was to limit effluents so as to keep radiation exposure of persons from a combination of whole body exposure due to noble gases and internal dose from radioiodines and airborne particulates, or from internal dose from radioactivity in liquid effluents as low as practicable. The reduction of 100,000 in the 10CFR20 concentration for iodines with $T_{1/2} < 8$ days appeared to be the most severe requirement. As of October 1973 the Rule Making Hearing on the proposed Appendix I, which the AEC had instigated early in 1972, appeared to be moving toward a conclusion after the submission of a Final Environmental Statement¹⁷ by the AEC Regulatory Staff a few months previously.

With regard to radioiodine, some easing of the proposed Appendix I limit seems likely. In June of 1973, the AEC Directorate of Regulatory Standards issued Regulatory Guide 1.42, "Interim Licensing Policy on As Low as Practicable for Gaseous Radioiodine Releases from Light-Water-Cooled Nuclear Power Reactors". It indicated that a design objective of 15 mrem/year is in the range of "as low as practicable" considering the "state of the art" of measuring concentrations and doses of radioiodine in effluents to the environs.

Reinforcement for the lowering of environmental radiation protection guides was given in 1972 by the NAS-NRC Advisory Committee on the Biological Effects of Ionizing Radiation.¹⁸ The BEIR Committee viewed the current radiation protection guide (170 mR/year) as "unnecessarily high" since it found that the "needs of society can be met with far lower average exposures and genetic and somatic risks than permitted by current Radiation Protection Guides."

Subsequent to the issuance of the proposed Appendix I in December 1971, the AEC Directorate of Regulatory Standards issued Safety Guide 21, "Measuring and Reporting of Effluents from Nuclear Power Plants". It called for considerable refinement in the identification and measurement of radionuclides in both airborne and liquid effluents, as shown in Table II.

Table II
Minimum Sensitivity for Individual Nuclides Specified by AEC Safety Guide 21

Plant Stream	Intermittent Release	Continuous Release
Air-Noble Gas	10^{-4} $\mu\text{Ci}/\text{cm}^3$	300 Ci/yr
Air-Tritium	10^{-6} " "	0.3 " "
Air-Radioiodines	10^{-10} " "	3 mCi/yr
Liquid-Gross $\beta\gamma$	10^{-7} " "	-
Liquid-Tritium	10^{-5} " "	-
Liquid- ^{89}Sr & ^{90}Sr	10^{-8} " "	-

Early in 1973, the Directorate of Regulatory Standards issued Regulatory Guide 4.1, "Measuring and Reporting of Radioactivity in the Environs of Nuclear Power Plants". It is rather general in nature and relies heavily on the ICRP "critical pathway" concept. It calls for "every reasonable effort to achieve detection capabilities which will detect radiation levels or radioactivity concentrations in critical pathways that could result in radiation doses corresponding to a few percent of the Federal Radiation Council's radiation protection guides, e.g., a few percent of 170 mrem/year for whole body dose to a suitable sample of the exposed population."

Somewhat more detailed recommendations for a minimum level of environmental radiation surveillance outside a nuclear power plant boundary are contained in a guide¹⁹ published in mid-1972 by the Environmental Protection Agency. It also utilizes the ICRP "critical path" concept, but additionally sets forth a detailed list of types and frequency of samples. It also contains recommendations for sample size, method of analysis, and minimum detectable levels, i.e., for ¹³¹I in air, a 300 m³ sample, analysis by gamma spectrometry, and a detectable concentration of 0.04 pCi/m³ (corresponding to an annual dose of 1.0 mrem/year), or for ¹³¹I in milk, a 3.5 liter sample, analysis by the same method, and a minimum detectable concentration of 10 pCi/l (corresponding to a dose of 50 mrem).

It is evident that the EPA guide methods are not entirely adequate to achieve the detection of concentrations of radioiodine called for or implied in the Appendix 1 dose limits. In its recent Regulatory Guide 4.3, "Measurements of Radionuclides in the Environment, Analysis of I-131 in Milk", issued in September 1973, the AEC Directorate of Regulatory Standards has indicated as "acceptable" a method for analysis of I-131 down to concentrations of 0.25 pCi/l (by ion exchange, elution, reduction to I², extraction with CCl₄, precipitation as palladous iodide, and counting for 1,000 minutes in a low background beta counter).

IMPLICATIONS

In its introduction to the proposed Appendix 1, the AEC stated, "These levels of exposure would be indistinguishable from exposures due to variation in natural background, would not be measurable with existing techniques, and would be estimated from effluent data from nuclear power plants by calculational techniques."

The recently issued three volume Final Environmental Statement¹⁷ (FES) concerning the proposed Appendix 1, contains details of the calculational techniques underlying the concentration limits shown in Table I. An elaborate model which contains many assumptions with regard to source term, release routes, exposure situation, and which considers multiple environmental pathways has been utilized in computer calculations of the environmental doses from gaseous effluents, from airborne halogens and particulates, and from liquid effluents for boiling water reactors and pressurized water reactors containing a range of radwaste options. The FES calculations are probably the most ambitious and thorough effort at pathway modeling toward environmental radiation dose assessment attempted to date. A consideration of even the simplified pathways shown in Figures 1 and 2 is suggestive of the inherent complexities of pathway modeling. It necessitates the assumption at the many intermediate steps, of residence times, transfer functions, concentration factors, etc. Obviously the pertinence of the outcome is strongly dependent on the relevance of the underlying assumptions to reality. Many of the comments to the earlier Draft Environmental Statement (contained in Volume 3 of the FES) suggest that the AEC Staff has utilized extremely conservative assumptions throughout, including dose-effect relationships, exposure situations, pathway models, reconcentration factors and intakes.

Insofar as this is so, the risk reduction benefits of the Appendix 1 proposals seem largely hypothetical. From the AEC Staff cost-benefit analysis, also contained in the FES, it appears that the application of the proposed limits (as indicated in

Table I) may occasion expenditures approaching \$10⁶ per year per reactor. Much of it would be for the control of ¹³¹I emissions on the basis of doses indicated by the staff model, doses which have not yet been substantiated by in depth surveys around existing nuclear facilities such as those indicated in Ref. 16. The reasonableness of these expenditures has been considered elsewhere.²⁰

An additional cost not considered in the FES is that of environmental surveillance at the proposed concentration limits. For example, the dose commitment per 0.25 pCi in one liter of milk ingested by an infant is about 5×10^{-3} mrad. Appendix 1 considers a hypothetical infant at the site boundary. If the cost per analysis is \$100., and the milk in question is ingested by this one infant, then the analysis cost per thyroid-rem would be $\$2 \times 10^7$. Recently published estimates²¹ of the value of a man-rem (which presumably carries a higher risk or value than a thyroid-rem) are in the order of \$10 to \$250. Thus it can be appreciated that one has to postulate that the analysis is of a composite representative of many liters of milk ingested by many infants, in order to arrive at a reasonable cost-benefit ratio for this limit of detection.

Another apparent thrust of the Appendix proposals (and the seemingly conservative pathway models adopted by the AEC Staff) is the trend toward the utilization of a variety of techniques such as the above to perform routine environmental surveillance at ultra low levels or concentrations previously considered appropriate and/or necessary only for research programs. As indicated by McLaughlin and Beck²² at the 1972 IEEE Nuclear Science Symposium, these include the employment of pressurized ion chambers coupled to sensitive electrometers, the widespread use of CaF thermoluminescent dosimeters capable of measuring dose increments as small as 1 mR, and the analysis of most environmental samples using high resolution Ge-Li detectors and computer spectrum interpretation of every discernible photopeak.

Much of this will obviously be to the benefit of those involved in promoting this kind of effort in the name of protecting the public from the risks of radiation. Before we get carried away with the virtue of the enterprise, a comparison of the calculated risk of five millirems per year with other risks, as shown in Table III, may be useful. It should be observed that the risk from radiation is postulated on the application of the linear hypothesis from data obtained mostly from instantaneous doses in the order of 100 rems. It may be suggested that in a world of finite resources, the Appendix 1 stimulated attention low-level radiation is currently receiving seems grossly out of proportion to that being accorded other more evident risks.

Table III
Annual Probability of Fatal Injury
From Radiation and Other Causes

Cause	Individual Probability of Fatal Injury or Effect per Year of Exposure	Reference
Radiation (5 mrem/yr)	5×10^{-7} (Note 1)	23,24
Natural Disasters	2×10^{-6}	25
Fossil Fuel Plants	4×10^{-6}	25
Electricity	2×10^{-5}	25
Firearms	2×10^{-5}	25
Air Pollution	1×10^{-4} (Note 2)	26
Smoking	5×10^{-4} (Note 3)	25
Automobiles	1×10^{-2} (Note 4)	25

(Explanation of notes on following page)

Notes for Table III:

1. Estimated from ICRP data^{23,24} which assumes effect rates observed at high doses (~ 100 rem) are linear with decreasing dose.
2. Assumes entire population exposed 100% of the time.
3. Assumes smoker at continuous risk.
4. Assumes exposure is limited to 216 hours per calendar year.

CONCLUSIONS

Considerable effort has been devoted to the development of environmental radiation dose criteria and assessment through both pathway modeling and environmental surveillance, ever since the first utilization of nuclear reactors in the United States in the 1940's, and particularly since the advent of civilian nuclear power reactors. Conservative effluent release practices, generally consistent with the as low as practicable philosophy, have been followed.

Within the past few years, extensive surveillance at representative nuclear facilities has indicated maximum doses of only a few millirems per year through a few pathways and to small nearby populations. They have been well below the environmental dose limits of 500 mrem/year specified by the ICRP for individuals in the general population, and also generally less than the basic Appendix I limit of 5 mrem/year, proposed by the AEC.

However, the Appendix I implementation of this basic limit, in terms of the proposed release and concentration limits, is based on unrealistically conservative assumptions, which exaggerate its supposed risk-reduction benefits. It appears to be widely assumed by governmental regulators (and even by some persons within the health physics profession) without much conscious deliberation, that it is appropriate and/or desirable to make a corresponding level of effort to accurately document environmental radiation doses from all conceivable pathways within the proposed 5 mrem/year limit, as it was to document those doses with regard to the 500 mrem/year limit. The benefits of devoting significant resources of manpower and equipment to such an effort toward the ever improvement in the sensitivity of modeling and surveillance of a minimal risk seem most questionable.

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FIG. 1
SIMPLIFIED PATHWAYS BY WHICH RADIOACTIVE MATERIALS RELEASED TO THE ATMOSPHERE MAY CAUSE HUMAN EXPOSURE *

FIG. 2
SIMPLIFIED PATHWAYS BY WHICH RADIOACTIVE MATERIALS RELEASED GROUND OR SURFACE WATERS (INCLUDING OCEANS) MAY CAUSE HUMAN EXPOSURE *