HEALTH PHYSICS SOCIETY

Specialists in Radiation Safety

Testimony of

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Hearing on
Oversight of the Status of the Yucca Mountain Project

Before the
Senate Committee on Environment and Public Works

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INTRODUCTION

Mr. Chairman, Ranking Member Jeffords, and distinguished members of the Committee, my name is Dade W. Moeller. I am Chairman of the Board of Dade Moeller & Associates and am appearing today as a representative of the Health Physics Society (HPS), an independent nonprofit scientific organization of professionals who specialize in radiation safety. Thank you for providing this opportunity for the Society and me to serve as a resource as you examine the status of the Yucca Mountain project. I received a Masters in Environmental Engineering from the Georgia Institute of Technology in 1948, and a Doctorate in Nuclear Engineering from North Carolina State University in 1957. I served in the U.S. Navy for 2 years during World War II and as a commissioned officer in the U.S. Public Health Service from 1948 to 1966. Subsequently, I was appointed to the Faculty of the School of Public Health, Harvard University and remained there from 1966 to 1993. Initially, I served as Chairman of the Department of Environmental Health Sciences, and later as Associate Dean for Continuing Education. I am a past-President of the Health Physics Society, and the recipient of the Meritorious Achievement Award from the U.S. Nuclear Regulatory Commission. I was elected to the National Academy of Engineering in 1978 and to the Georgia Tech Engineering Hall of Fame in 1999. I received the Distinguished Engineering Alumnus Award from N.C. State University in 2001, the Robley D. Evans Commemorative Medal from the Health Physics Society in 2003, and the William McAdams Outstanding Service Award from the American Academy of Health Physics in 2005.

I am the author of more than 200 papers published on various aspects of environmental health, with emphasis on radiation protection, waste management, and environmental monitoring. The bulk of these during the last 5 to 10 years have related to independent assessments of potential radionuclide releases from the proposed Yucca Mountain high-level radioactive waste repository. I am the author of a widely used textbook on Environmental Health, the third edition of which was published in 2005.

THE HEALTH PHYSICS SOCIETY

The HPS includes approximately 6,000 members in over 40 countries who are currently engaged in the practice, science, and/or technology of radiation safety. Its mission is to assure excellence in radiation safety. Society activities include encouraging research in radiation science, developing standards, and disseminating radiation-safety information. As a nonprofit scientific organization, it is not affiliated with any governmental, industrial, or private entity. The Society is affiliated with the International Radiation Protection Association, the American Academy of Health Physics, the American Board of Health Physics, the National Council on Radiation Protection and Measurements, and other scientific and professional societies and institutions.

In my testimony I will try to be clear as to whether statements are those of the Health Physics Society or are my own professional opinion.

BACKGROUND

At present, progress on the development of the proposed Yucca Mountain high-level radioactive waste repository is at a standstill. So long as controversies over the dose rate limit and the health effects of low doses of radiation exist, there will continue to be delays in completing this project. In the meantime, spent fuel and high level radioactive waste is being stored at more than 100 commercial nuclear power plants, and at multiple facilities of the U.S. Department of Energy. It will remain at these sites until this log-jam is broken. Although I will make some comments on the Environmental Protection Agency's environmental performance standards that are at the heart of the controversy contributing to this log-jam, my central message is to make a proposal for a path forward.

PROPOSAL

The key elements of the approach I propose are as follows:

1. Rather than seeking to "dispose" of the waste at this time, the suggested policy would be that, as an interim step, the waste be "stored" in the proposed facility for perhaps 100 years, during which time it would be subject to retrieval, if necessary.

2. One of the immediate benefits in adopting this approach would be to enable the U.S. Congress to meet the obligation it assumed in passing the Nuclear Waste Policy Act of 1982, that is, for the Federal government to accept responsibility for the management of high-level radioactive waste, an obligation that it has not been able, to date, to fulfill.

3. To ensure that the waste is not contaminating the environment, the Yucca Mountain facility would need to be equipped with monitoring devices that would provide, throughout the proposed 100-year period, immediate warnings of the deterioration of any waste packages and ensuing potential leakage. In anticipation of the potential occurrence of such events, provisions should be developed, and implemented if necessary, to retrieve and stabilize the affected waste packages. The monitoring program should include the status of engineered systems and components (such as borehole and shaft seals, backfill, and drip shields), as well as the thermal interaction effects of the waste packages, backfill, drip shields, rock, and unsaturated zone and saturated zone water. The program should also provide continuous online information on the condition of the waste packages, supported by laboratory experiments that focus on their internal condition (USNRC, 2001).

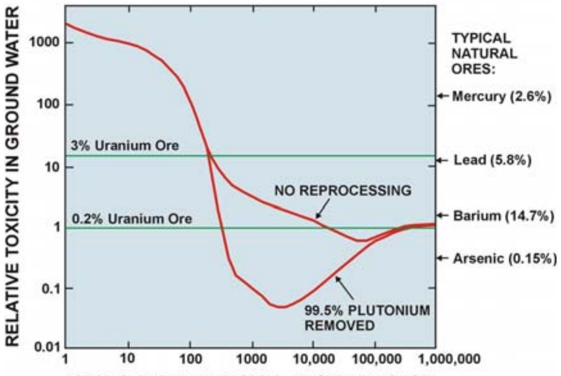
4. Another step that could be taken to enhance the comfort of the population groups that could be affected by radionuclide releases would be to limit, through regulations, the development of other nuclear related facilities within the region during the proposed 100-year period. Under these conditions, the applicable dose rate limit, based on the long-term dose rate limits recommended by the

International Commission on Radiological Protection (ICRP, 1991, paragraph 191), the National Council on Radiation Protection and Measurements (NCRP, 1993, Section 15, page 46), the U.S. Nuclear Regulatory Commission (USNRC, 1991, 10 CFR Part 20.1301), and the Health Physics Society (HPS, 2003, recommendation 4), would be 1 mSv per year. The HPS recommendation also supports the ICRP "special circumstances" provision that states, "in special circumstances, a higher value… could be allowed in a single year, provided the average (dose rate) over 5 years does not exceed 1 mSv per year." (ICRP, 1991, paragraph 192). This means that, in case of an inadvertent release, the public dose rate limit for the year in which it occurred could be as high as 5 mSv.

5. Even though intruders who might seek to remove some of the waste would receive very high radiation doses (and obtaining the equipment required to remove any of the waste would be far beyond their capabilities), the facility would nonetheless need to be equipped with adequate security devices to provide surveillance 24 hours per day.

6. During the proposed 100-year storage period, many significant technological developments will occur, some of which could completely change current concepts on the best approach for the final disposition of high-level radioactive waste. Based on the information in the figure below (Boulton, 1978), one of the most promising changes would be to resume the reprocessing of spent nuclear fuel. As the graphs indicate, after about 200 to 350 years, the toxicity of the remaining waste (assuming 99.5% effectiveness in removing the plutonium) would be comparable to that of the original uranium ore that was mined to fuel the reactor from which the spent fuel was removed. This would, in essence, remove the need for a dose rate limit in terms of periods of time on the order of thousands of years. Congress has recently shown an interest in moving towards a reprocessing capability as demonstrated, for example, in the *Integrated spent fuel recycling* provisions of the fiscal year 2006 appropriations to the Department of Energy (House of Representatives, 2005, pages 156-157).

RELATIVE TOXICITY (IN GROUND WATER)
OF USED NUCLEAR FUEL AND NATURAL ORES



Source: J. Boulton, Ed., "Management of Radioactive Fuel Wastes: The Canadian Disposal Program", AECL-6314, 1978.

7. Another technological advance that leading cancer specialists predict will be developed within the next 50 years, at most, is a method for the prevention, or cure, of many of the cancers that are common today. Adding support to this optimism is a recent item published in Science (von Eschenbach, 2005) in which the then current Director of the National Cancer Institute stated that NCI "could meet its target of eliminating suffering and death from cancer by 2010 if its nearly $5 billion annual budget were increased by $4.2 billion over 5 years." In this regard, the NCRP (1995) has offered the following comments:

   "One of the most important factors likely to affect the significance of radiation dose in the centuries and millennia to come is the effect of progress in medical technology. Medical progress achieved during the past several decades has reduced the risk of premature death and increased the average age of the population, leading to a relative increase in diseases prevalent in the elderly, *e.g.*, cancer." … "At some future time, it is possible that a greater proportion of somatic diseases (diseases such as cancer) caused by radiation will be treated successfully. If, in fact, an increased proportion of the adverse health effects of radiation prove to be either preventable or curable by advances in medical science, the estimate of long-term detriments may need to be revised as the consequences (risks) to future populations could be very different." (NCRP, 1995, Report No. 121, Section 4.2.2.3).

8. The temporary storage of the spent fuel for the suggested 100-year period would provide time for the United States to take advantage of these and similar developments. Since the hereditary effects of radiation have been shown to be minimal, absent the fear of cancer, the potential health problems associated with the disposal of the waste would be significantly reduced.

BENEFITS OF THE PROPOSED POLICY

The proposed approach offers multiple benefits. These include:

1. Centralized storage of waste is provided for security and controllability in a manner that is reversible, allowing for new technologies to be applied to the waste before being interned for perpetuity.

2. If reprocessing the spent fuel from nuclear reactors is judged to be warranted, the toxicity of the waste will be of concern for only 250 to 300 years (as noted above) such that the designation of an appropriate long-term dose rate limit would no longer be needed. Similar considerations will apply to the time-period for which it must be documented that the disposal facility, including the waste containers, etc., has been designed to maintain their integrity.

3. A benefit to reprocessing, if initiated, is that the extracted plutonium can be used as nuclear fuel, thus enhancing our capacity to generate electricity through a process that generates no airborne releases that will contribute to global warming.

4. Another benefit to reprocessing is that it will reduce the amount of waste requiring disposal in Yucca Mountain.

5. Also of note is that the proposed policy is based on sound science as illustrated by citations to the recommendations of the NCRP and the ICRP. The roles of these two organizations are important as sources of radiation protection standards since, in chartering the NCRP in 1964, Congress stipulated that it was to:

   > “collect, analyze, develop and disseminate in the public interest information and recommendations about (a) protection against radiation and (b) radiation measurements, quantities and units, particularly those concerned with radiation protection.”

   Concurrently, Congress stipulated that the NCRP was to “cooperate with the International Commission on Radiological Protection.” In accord with this directive, members of the NCRP are active participants in developing the documents that are published by the ICRP.

6. The proposed policy would also remove the implication that any human being, or government body, has the insight or knowledge to make recommendations beyond a few hundred years into the future. On reflection, most people would agree that the establishment of dose rate limits 10,000 to one million years into the future is ludicrous. Archeological discoveries have documented the presence of humans on earth only slightly more than 10,000 years ago, and written records documenting the presence of humans date only some 5,500 years ago (Whitehouse, 1999).

Undoubtedly, other approaches will be proposed. All should be given careful consideration, including detailed reviews and evaluations, prior to making a final selection.

EPA PERFORMANCE STANDARDS

The adoption of my proposed policy for monitored retrievable storage in the near future (i.e., 100 years) negates the need to evaluate the Environmental Protection Agency’s (EPA) performance standards for Yucca Mountain as a permanent high-level waste repository until a decision on the final disposition of spent fuel and other high-level waste is made after incorporating the development of improved technology and scientific knowledge. However, it seems appropriate to make some comments on these standards since they are the currently proposed standards, and are of interest for this hearing.

These comments are offered with the understanding that my central message calling for a re-design of the purpose for the Yucca Mountain project will make these issues moot.

SCIENTIFIC BASIS FOR EPA STANDARDS FOR YUCCA MOUNTAIN – BEGINNING OPERATION TO 10,000 YEARS

The EPA standards for the period from when Yucca Mountain begins operation as a permanent waste repository to 10,000 years have been a long time in development and have gone through an extensive review during the rulemaking process. However, the HPS wants to take this opportunity to point out that the existence of a ground water protection standard that is separate from an individual protection standard is not founded in science. The HPS understands the courts have upheld the EPA's right to establish a ground water standard separate from an "all pathways" individual protection standard. However, the HPS believes it is appropriate to continue to reaffirm its position that "[Public radiation-safety standards] should be expressed as an effective dose resulting from all exposure pathways" (HPS, June 2003). Since the EPA's right to establish a separate ground water protection standard is founded in their legislative authority and enabling legislation, alteration of this EPA approach, which is not consistent with current scientific knowledge, would require congressional action.

SCIENTIFIC BASIS FOR EPA STANDARDS FOR YUCCA MOUNTAIN – 10,000 TO 1 MILLION YEARS AFTER BEGINNING OPERATION

Basis for Proposed Standard

It should be noted that the International Commission on Radiological Protection (ICRP, 1991) has for some time stated that one of the approaches for judging the acceptability of dose rate limits for members of the public "is to base the judgment on the variations in the existing level of dose from natural sources. This natural background may not be harmless, but it makes only a small contribution to the health detriment which society experiences. It may not be welcome but the variations from place to place (excluding the large variations in the dose from radon in dwellings) can hardly be called unacceptable."

Also to be noted is that there are large uncertainties in the dose rates from each of the components of natural background. In terms of radon, alone, there are large uncertainties in the measured value of the radon concentration (the presence of thoron; the status of the equilibrium of the radon decay products; the fraction that is unattached versus attached; etc.).

For these and other reasons, any such dose rate limit should be accompanied by an expression of the range of uncertainty it encompasses. The HPS has taken the position that "Estimation of health risk associated with radiation doses that are of similar magnitude as those received from natural sources should be strictly qualitative and encompass a range of hypothetical health outcomes, *including the possibility of no adverse health effects at such low levels*" (emphasis added) (HPS, 2004).

The EPA proposed rule has a detailed discussion about the "Effects of Uncertainty" (USEPA, 2005, pages 49025 to 49027). However, the uncertainty addressed by the

EPA relates to uncertainty of projecting geological and human activity into the future. It does not discuss the uncertainty of today's knowledge of hypothetical health outcomes from low doses of radiation, which forms the basis for the dose rate limit in the proposed standards, including the possibility of no adverse health effects at these low levels.

Validity of the USEPA Analyses

Although the variation in the dose rates from natural background radiation can be a valid basis for making judgments for radiation protection purposes, a series of extensive studies that my colleagues and I have performed have shown that the variations estimated by the EPA (USEPA, 2005) could be improved through the incorporation of the following adjustments.

- One would be to base the dose estimates to the maximum extent on site-specific values;
- Another would be to apply the latest estimated value of the coefficient for converting radon exposures into dose;
- A third would be to estimate the doses from both outdoor and indoor exposures;
- The last would be to discuss the uncertainties that accompany the dose rate estimates.

With respect to the last comment, our review and evaluation showed that the primary sources of the uncertainties, associated with the dose rate estimates for radon, are the measured values of the radon concentration, and the previously cited dose coefficient. For these and other reasons, any such dose rate limit should be accompanied by an expression of the range of uncertainty it encompasses. The significance of our assessments is that the estimated magnitude of the overall uncertainty in the current estimates of the combined (total) dose rate from all sources of natural background is about 150%. As a result, the differences in the estimated dose rates in one area of the country, compared to another, can only be realistically evaluated in light of these uncertainties. This leads to the realization that, even though the procedures used by the USEPA (2005) in developing their recommended dose rate of 3.5 mSv per year could have been improved, their estimate was nonetheless well within the range of the associated uncertainties and is therefore acceptable.

The peer reviewed studies that support the above statements and other analyses of the EPA standards are contained in five scientific articles, two of which have been published and three of which are in publication. The first two articles, *Sensitivity Analyses Of The Standards For The Proposed Yucca Mountain Repository—A Review, Evaluation, And Commentary* (HPJ, May 2005), and *Impacts Of Stable Element Intake On 14C And 129I Dose Estimates* (HPJ, October 2005) are attached. The remaining three articles will be forwarded to the Committee when they are published in the next several months.

PERSPECTIVE ON 3.5 mSv/year

The discussions that follow are designed to provide perspective on the impacts of a dose rate of 3.5 mSv per year. One way of gaining perspective on this impact involves calculating an estimated risk of cancer from the exposure and comparing it to other risks, such as the “natural” risk of cancer. I must note that the HPS position is that

> “Estimation of health risk associated with radiation doses that are of similar magnitude as those received from natural sources should be strictly qualitative and encompass a range of hypothetical health outcomes, including the possibility of no adverse health effects at such low levels.”

However, the HPS does recognize that

> “. . . risk assessment at low doses . . . can be used to inform decision making with respect to cleanup of sites contaminated with radioactive material, disposition of slightly radioactive material, transport of radioactive material, etc.”

In the following discussions I am using quantitative risk calculations to inform decision making but I am not stating that it is known for a fact that there will be actual cancer induction or death from radiation exposure at these levels. Also, the 3.5 mSv per year results in a lifetime dose that is greater than the lifetime dose of 100 mSv below which the HPS recommends not doing quantitative assessments.

Estimated Risk of a Cancer Fatality per Unit of Dose

According to the International Commission on Radiological Protection (ICRP, 1991, Table 4, page 24), the risk of death due to the exposure of a member of the public to ionizing radiation is 5×10^{-2}/Sv (5×10^{-5}/mSv) of effective dose. Expressed in another manner, the coefficient (5×10^{-5}/mSv) means that the chances of dying from a cancer caused by exposure to radiation are 5 in 100,000 per mSv of effective dose. At the same time, however, it is important to recognize that this coefficient incorporates the linear-no-threshold hypothesis (LNT), a concept that the ICRP has repeatedly stated leads to risk estimates that are conservative, that is, too high (ICRP, 1966, page 60; ICRP, 1977, paragraph 30). More importantly, keep in mind this is for a population with today’s medical treatment and care, which does not account for the likely medical advances that will exist in 10,000 years when this dose rate limit will be applicable. Keeping this caveat in mind, if it is assumed that a population group receives an average dose rate of 3.5 mSv per year, they will receive a total dose during a lifetime of 70 years of:

$$(3.5 \text{ mSv per year}) \times (70 \text{ years}) = 245 \text{ mSv}.$$

Applying the ICRP risk coefficient, the estimated percentage of the people who would die of fatal cancer due to being exposed to a lifetime dose of this magnitude would be:

$$(5 \times 10^{-5} \text{ per mSv}) \times (245 \text{ mSv}) = (1225 \times 10^{-5}) = 1.225 \times 10^{-2} = 1.2\%.$$

Prior to applying this risk estimate in evaluating the impacts of potential radionuclide releases from the proposed Yucca Mountain repository, it is important to recognize that the exposed people are assumed (a) to be adults, as required by the USNRC regulations (2001), and (b) to take in a sufficient amount of radioactive material each year that, during the 50 years that follow, they will ultimately receive a *committed* dose of no more than 245 mSv. This latter assumption leads to additional conservatism in the dose rate estimates, the reason being that many of the exposed people will not live long enough to receive the full 50-year dose commitment. In fact, the NCRP has estimated that the average adult, who is exposed under these conditions, will receive less than half of the estimated committed dose (NCRP, 1993, Section 6.1, page 25).

This is in contrast to the case on which the ICRP risk coefficient was based, namely, that the estimated doses are received in full by the exposed population group. Accounting for these considerations, and the fact that a relatively large fraction of the radionuclides that will potentially be released from the proposed Yucca Mountain repository have long effective half-lives, the actual increase in the cancer fatality rate could readily be half of that estimated above, namely, about 0.6%.

On this basis, the relative increase in cancer *fatalities* within the exposed Amargosa Valley population can be estimated as follows. The spontaneous rate of cancer deaths in the United States currently is about 1800 per 10,000 persons, that is to say, 18% of our population die from cancer due to other causes (NRC, 1995, page 72). Based on an added radiation dose rate of 3.5 mSv per year, the chances of dying from cancer, for the average resident of the Amargosa Valley, would have been increased from 18% to about 18.6%. On a relative basis, this represents an increase of:

$$(0.6\%) \div (18.6\%) = \sim 3\%.$$

Estimated Risk of Cancer Incidence per Unit of Dose

According to the NRC (2005, BEIR VII Report), "… approximately one individual in 100 persons would be expected to develop cancer from a lifetime (70 year) exposure to low-LET natural 'background' radiation (excludes radon and other high LET radiations)." According to the NCRP (1987, Table 9.6, page 148),and the ICRP (1991, paragraph 191), the total dose rate from natural background, excluding exposures to radon and its decay products, namely, (a) cosmic radiation, (b) terrestrial radiation, and (c) ingested naturally radioactive materials, is "about 1 mSv per year."

Since a dose rate of 1 mSv per year, over a lifetime of 70 years, will yield a total of 70 mSv, the probability of developing cancer would be 1 chance in 100 (1%) per 70 mSv of effective dose. The probability, based on a dose rate of 3.5 mSv per year would be 3.5 times as high, namely, about 3.5%. Once again, this estimate of the increase in the cancer incidence rate was based on the assumption that the estimated doses are received in full by the exposed population group. Accounting for this and other considerations, the actual increase in the cancer fatality rate could readily be half of that estimated above, namely, about 1.8%.

On this basis, the relative increase in cancer fatalities, within the exposed Amargosa Valley population, can be estimated as follows. The spontaneous rate of cancer incidence in the United States is about 42 persons per 100, that is, about 42% of our population, at some point in their lives, will develop cancer due to other causes (NRC, BEIR VII Report, 2005). Based on an added radiation dose rate of 3.5 mSv per year, the chances of suffering cancer, for the average person in the Amargosa Valley, would have been increased from 42% to about 43.8%.

This accompanying relative increase in cancer incidence would be:

$$(1.8\%) \div (43.8\%) = \sim 4\%.$$

Although based on two different sources of information and risk estimation methodologies, this shows good agreement with the estimate for the increase in average risk of cancer fatalities (about 3%) presented above. Also to be kept in mind is that the estimated percentage increases in the number of cancer fatalities among residents of the Amargosa Valley would be 0.6%, and the comparable estimate of the increase in cancer incidence would be 1.8%.

Confirming the Cancer Risks due to a Dose Rate of 3.5 mSv per Year

The estimated risks of cancer incidence and death, due to exposures to ionizing radiation, are based on epidemiological studies, the most notable being the extensive studies of the survivors of the World War II atomic bombings in Japan. Just how difficult it is to quantify the health impacts of a dose rate of 3.5 mSv per year is illustrated by the fact that the National Research Council (NRC, 1995, Table 7-2, page 73) estimates that it would require careful data collection and study throughout the lifetime (i.e., 70 years) of a population group of at least 3,000 people to detect an increase in the total cancer mortality due to an annual exposure of 3.5 mSv for a total of 70 years. One of the reasons for this is that "… even at a continued exposure of 5 mSv per year, the change in the age specific mortality rate is very small." (ICRP, 1991, paragraph 191).

ICRP Recommended Dose Rate Limit for Members of the Public

The long-term annual dose rate limit for members of the public, as recommended by the ICRP (1991, paragraph 192), and the NCRP (1993, page 46) is 1 mSv per year. Compliance with this recommendation is to be based on what is called the "Critical Group," which was introduced by the ICRP in 1977, and defined as follows:

"It is often possible to identify population groups with characteristics causing them to be exposed at a higher level than the rest of the exposed population from a given practice… These groups … (are) known as critical groups..." (ICRP, 1977, paragraph 216).

In elaborating on the Critical Group, the ICRP stated:

> “The actual doses received by individuals (within the Critical Group) will vary depending on factors such as differences in their age, size, metabolism and customs, as well as variations in their environment. … With exposure of members of the public it is usually feasible to take account of these sources of variability by the selection of appropriate critical groups within the population provided the critical group is small enough to be relatively homogeneous with respect to age, diet and those aspects of behaviour that affect the doses received. Such a group should be representative of those individuals in the population expected to receive the highest dose equivalent, and the Commission believes that it will be reasonable to apply the appropriate dose-equivalent limit for individual members of the public to the weighted mean dose equivalent to this group. Because of the innate variability within an apparently homogeneous group some members of the critical group will in fact receive dose equivalents somewhat higher than the mean. However, because of the maximizing assumptions used, the dose equivalent actually received will usually be lower than the estimated dose equivalent.” (ICRP, 1977, paragraph 85).

In a later report, the ICRP (1985a, paragraph 69) offered the following commentary on additional characteristics of the Critical Group:

> “It is obvious from the definition that some individuals will receive dose equivalents in excess of the calculated mean dose equivalent. Decisions on the acceptability of the exposure of the critical group will depend not only on the proximity of the calculated mean dose equivalent to the dose-equivalent limit but also the expected spread of the distribution of actual dose equivalents. It is also necessary to consider that other sources may contribute to the exposure of any one critical group. It is suggested that, in general, to satisfy the homogeneity requirement the ratio of maximum to minimum values should not exceed an order of magnitude. For many distributions, therefore, the mean will be a factor of two to three lower than the maximum postulated. The necessary degree of homogeneity in the critical group depends on the magnitude of the mean dose equivalent in the group as a fraction of the relevant source upper bound. If that fraction is less than about one tenth, a critical group should be regarded as homogeneous if the distribution of individual dose equivalents lies substantially within a total range of a factor of 10, i.e., a factor of about 3 on either side of the mean. At higher fractions, the total range should be less, preferably no more than a factor of 3.”

The important fact to note is that, based on the criteria described above, some members of the Critical Group (as applied in determining the regulatory compliance of the proposed Yucca Mountain repository) would receive dose rates three times the limit. If the applicable long-term dose rate limit for members of the public were 1 mSv per year (as recommended by the ICRP and the NCRP), these individuals would be expected to receive dose rates up to 3 mSv per year.

Additional Perspective

On the basis of epidemiological studies, it is estimated that 30% of the cancer deaths in the United States are due to the use of tobacco products, and an additional 35% are due to improper diets, obesity, and the lack of exercise (Moeller, 2005, Table 1.2, page 5). In short, 65% of the fatal cancers that occur in the U.S. population are due to deficiencies in our personal habits, factors that are under our control. In contrast, only 2% of the cancer deaths in this country are estimated to be due to environmental pollution. In the overall scheme of life, the risk of fatal cancer due to an annual dose of 3.5 mSv throughout one's lifetime is certainly acceptable. As the ICRP has so eloquently stated:

"The Commission … wishes to emphasize its view that ionising radiation needs to be treated with care rather than fear and that its risks should be kept in perspective with other risks." (ICRP, 1991, paragraph 14).

CONCLUSION

Thank you Mr. Chairman and Members of the Committee for the opportunity to testify before you today as you oversee the status of the Yucca Mountain project. I would be happy to answer any questions you may have.

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Attachment to Testimony by Dade W. Moeller to the Senate Committee on Environment and Public Works on the Status of Yucca Mountain, 1 March 2006

Paper

SENSITIVITY ANALYSES OF THE STANDARDS FOR THE PROPOSED YUCCA MOUNTAIN REPOSITORY—A REVIEW, EVALUATION, AND COMMENTARY

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Abstract—**The standards and regulations for the proposed Yucca Mountain high level radioactive waste repository, which were developed and promulgated by the U.S. Environmental Protection Agency and the U.S. Nuclear Regulatory Commission, respectively, are complex and challenging. A major reason is that they are divided into three parts, an Individual Protection Standard, a Human Intrusion Standard, and multiple Ground Water Protection Standards. Because the individual parts are not fully integrated, the one that controls under a specific set of circumstances depends on the radionuclide being evaluated, its mechanisms of transport, its avenues of intake, and differences in the specified limits. Although the coefficients in Federal Guidance Report (FGR) No. 11 are being used to estimate the doses, other sources (for example, Title 10, CFR, Part 20, and/or FGR No. 13) may deserve consideration. Since the regulations specify that the reasonably maximally exposed individual is an adult, this leaves unanswered the estimated doses to other age groups, such as infants and adolescents. Summarized in this paper are comparisons of the dose coefficients for different age groups, as well as evaluations of the sensitivity of effective and organ dose estimates for adults, depending on the source of the coefficients. All the latter analyses were based only on the consumption of ground water. While the dose estimates are different, depending on the sources of the coefficients, this was not unexpected. What these evaluations demonstrate is the caution that must be exercised to ensure that a full range of considerations is taken into account in interpreting the outcome of the dose assessments being made with respect to the proposed repository.**

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INTRODUCTION

UNDER FEDERAL law, the U.S. Environmental Protection Agency (U.S. EPA) is assigned the responsibility for establishing standards for the proposed Yucca Mountain high-level radioactive waste repository, and the U.S. Nuclear Regulatory Commission (U.S. NRC) is to develop regulations that will ensure that the proposed repository complies with the standards. As a result, the regulations promulgated by the U.S. NRC (2001) incorporate the essential features of the EPA standards (U.S. EPA 2001). A third Federal agency, the U.S. Department of Energy (U.S. DOE), is assigned the responsibility for preparing and submitting a License Application to the U.S. NRC for permission to construct and operate the proposed facility.

In July 2004, the United States Court of Appeals for the District of Columbia Circuit (U.S. Court 2004) vacated Title 40, Code of Federal Regulations, Part 197 (U.S. EPA 2001) to the extent that it incorporates a 10,000-y compliance period. The reason for this action, as explained by the Court, was that such a compliance period is contrary to section 801(a) of the Energy Policy Act of 1992 (PL 102-486), in that it is not "based upon and consistent with" the recommendations of the National Academy of Sciences/National Research Council (NAS/NRC 1995). For similar reasons, the Court vacated the U.S. NRC regulations (U.S. NRC 2001) insofar as they incorporate EPA's 10,000-y compliance period. With respect to the length of the compliance period, the NRC Committee found "no scientific basis for limiting the time period of the individual risk standard to 10,000 y or any other value." As such, this decision could have impacts on how the regulations are applied. One could be to expand the list of radionuclides that must be considered, particularly on a long-term basis. Nonetheless, the accompanying review in this paper of other key factors related to the standards and the accompanying dose assessments continue to be germane and informative. This is particularly true with respect to the manner in which the regulations specify the person to be protected and many of his/her characteristics; differences in the dose estimates as a function of the coefficients that are applied; and the conditions and circumstances under

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which the concentrations and doses due to the release of certain radionuclides will be controlled by specific parts of the regulations.

STANDARDS FOR YUCCA MOUNTAIN

The Yucca Mountain regulations, in essence, include three parts, each of which is described below.

Individual Protection Standard (IPS)

The first part (U.S. NRC 2001; §63.311) specifies the IPS. As noted in Table 1, its characteristics and requirements are based on the conventional approach of specifying, for each year of intake, a limit on the committed *effective* dose for members of the public. Throughout this paper, the term "dose" will be used with this meaning, the one exception being that, in the case of the Ground Water Protection Standards, discussed immediately below, the term "dose" will be expanded to include the committed *organ* dose. In accordance with the IPS, the dose limit applies to all sources and all pathways of exposure and naturally occurring radionuclide sources are exempted from consideration. The numerical value for this limit is 0.15 mSv, which is generally in accord with the limit for radioactive waste disposal that has been recommended by the International Commission on Radiological Protection (ICRP 1997).

Of particular interest is that the IPS states that the reasonably maximally exposed individual (RMEI) is a hypothetical person who has "a diet and living style representative of the people who now reside in the Town of Amargosa Valley, Nevada." Furthermore, it states that DOE "must use projections based upon surveys" of the designated population group "to determine their current diets and living styles and use the mean values of these factors in the assessments. . ." of their doses. The regulations further specify that the RMEI "is an adult with metabolic and physiological considerations consistent with present knowledge of adults," and that he/she shall be assumed to drink "2 liters of water per day from wells drilled into the ground water" at a point "above the highest concentration of radionuclides in the plume of contamination." As a result, many significant factors for use in documenting compliance with this and other parts of the regulations are specified.

Human-Intrusion Standard (HIS)

The second part (U.S. NRC 2001; §63.321), the HIS, is designed to ensure that there is a reasonable expectation that, should human intrusion take place at or before 10,000 y after disposal of the waste, the RMEI will not, through "all potential environmental pathways of radionuclide transport and exposure," receive "an annual dose" of more than 0.15 mSv. In addition, the regulations specify that DOE, in analyzing such an event, must assume that:

1. The intrusion is a single event resulting from exploratory drilling for ground water;
2. The borehole penetrates directly through a degraded waste package into the uppermost aquifer underlying the proposed repository;
3. The drillers use the common techniques and practices that are currently being employed in exploratory drilling for ground water in the region surrounding Yucca Mountain;
4. The drillers neglect to seal the borehole carefully; no particulate waste material falls into the borehole; and the exposure scenario includes only those radionuclides transported to the saturated zone by water (e.g., water enters the waste package, releases radionuclides, and transports them by way of the borehole to the saturated zone); and
5. No radionuclide releases are included which are caused by unlikely natural processes and events.

Ground Water Protection Standards (GWPSs)

The third part (U.S. NRC 2001; §63.331) specifies the GWPSs. As noted in Table 2, these standards, which are identical to those promulgated by the U.S. EPA in

Table 1. Individual protection standard (IPS).

Committed effective dose limit (per year of intake)	Receptor	Exposure pathways to be considered	Conditions for radionuclide releases	Conditions for compliance
0.15 mSv (150 μSv)	Adult who has a diet and living style representative of people now living in the Town of Amargosa Valley, NV, and drinks 2 L of water each day drawn from a well drilled into the ground water at a location above the highest concentration of radionuclides in the contaminated plume	All potential pathways of radionuclide transport and exposure	Includes all radionuclide releases from normal (undisturbed) operations, plus any releases due to natural events (i.e., volcanoes and earthquakes) estimated to have at least a chance of one in 10^4 or greater of occurring within 10^4 years of disposal	Reasonable expectation that for 10,000 y following disposal, the dose to the RMEI[a] will not exceed the limit

[a] Reasonably maximally exposed individual.

Table 2. Ground water protection standards (GWPSs).

Radionuclide or type of radiation emitted	Regulatory limit[a]	Is natural background included?
Combined ^{226}Ra and ^{228}Ra	5 pCi L^{-1b}	Yes
Gross alpha activity (including ^{226}Ra, but excluding radon and uranium)	15 pCi L^{-1b}	Yes
Combined beta and photon emitting radionuclides	0.04 mSv (4 mrem) y^{-1c}	No

[a] Applies to total contribution or dose from all radionuclides in the given category.
[b] For purposes of clarity traditional units have been used instead of SI units. This way direct comparisons to the standards can be made.
[c] The dose rate limit applies to the whole body or any organ, and is based on the consumption of 2 L d^{-1} of ground water from the highest concentration level in the plume of contamination in the accessible environment.

accordance with the requirements of the 1996 Safe Drinking Water Act Amendments and promulgated in 40 CFR 141, are separated into three sub-categories (U.S. EPA 2000). The first applies to combined ^{226}Ra and ^{228}Ra; the second to gross alpha activity; and the third to combined beta and photon emitting radionuclides. Each of these has its interesting aspects. The regulatory limits for the first two sub-categories are expressed in terms of Maximum Contaminant Levels (MCLs) and include contributions from naturally occurring radionuclides. In contrast, the limit for combined beta and photon emitting radionuclides is expressed in terms of a dose rate that applies to "the whole body or any organ." In addition, natural background sources are not included even though several of the radionuclides in this subcategory (i.e., ^{14}C and ^{129}I) are naturally occurring (NCRP 1983, 1985). Also of interest, and extremely important, is that the GWPSs and the IPS are severable; that is, the requirements of each must be met independently.

The discussions in this paper will be focused on the IPS and the GWPSs and will be directed exclusively to doses occurring through the ingestion of ground water, the goal being to assess the influence of various conversion factors on the dose estimates. While dose contributions from other pathways, such as the ingestion of food, will be considered, such as in the discussion of which Standard controls which radionuclide and under what circumstances, no specific estimates of the dose contributions from radionuclide intakes through the ingestion of food will be made. In this regard, the following statements in §63.342 of the U.S. NRC regulations (2001) have special significance:

"DOE's performance assessments should not include consideration of *very unlikely* features, events, or processes, i.e., those that are estimated to have less than one chance in 10,000 of occurring within 10,000 years of disposal. *Unlikely* features, events, and processes, or sequences of events and processes shall be excluded from the assessments for the human intrusion and ground water protection standards upon prior Commission approval for the probability limit used for unlikely features, events, and processes (emphasis added). In addition, DOE's performance assessments need not evaluate the impacts resulting from any features, events, and processes or sequences of events and processes with a higher chance of occurrence if the results of the performance assessments would not change the results significantly."

For this reason, the radionuclide concentrations in the ground water that must be evaluated for compliance with the IPS and the GWPSs may be different than those inferred by the dose limit for the IPS (Table 1) and the MCLs stipulated by the GWPSs (Table 2). In fact, the permissible concentrations may be higher in the former (IPS) case due to the necessity of including the impacts of potentially higher frequency disruptive events, such as volcanic eruptions that release radionuclides into the atmosphere and subsequently to the soil surface, but not to the ground water. This, as well as the fact that estimates of the actual doses will depend on local food use, water consumption from non-ground water sources, and many other factors, could lead to a situation in which some of the comparisons in this paper may not be valid. The authors nonetheless believe that the comparisons that have been made are useful and informative.

RADIONUCLIDES OF IMPORTANCE

The proposed repository is a deep geological disposal system, and ground water is the primary vehicle for the postulated *chronic* release of radioactive material. Taking into consideration the qualifications listed above, all comparisons of dose coefficients and dose estimates that follow are based on the ingestion of radionuclides under assumed chronic release, uptake, and exposure conditions. The radionuclides selected for analyses are those that (Garrick 2003):

1. Are present in relatively large quantities in spent fuel and high-level radioactive waste;
2. Have sufficiently long radioactive half-lives to persist over periods of thousands of years or more, or are the radioactive decay products of radionuclides having this characteristic;

3. Are soluble and/or readily transportable through the environment (in solution or as a colloid); and
4. Are readily absorbed into the body, and have long biological half-lives.

Based on analyses and evaluations of the information in the IPS and the GWPSs, there are eight radionuclides that possess these characteristics and would appear to be important during the first 10,000 y after closure of the proposed repository. Their identities, radioactive properties, and the organs that will receive the highest doses if they are ingested by an adult, are summarized in Table 3.

SOURCE OF DOSE COEFFICIENTS

The regulations provide detailed guidance for many aspects of the dose assessment processes. They do not, however, specify the source of the dose coefficients that are to be used. Based on this review, there are three primary sources that might be considered:

1. "Standards for Protection Against Radiation" (Title 10, CFR, Part 20), which were promulgated by the U.S. NRC for application to its licensees (U.S. NRC 1991). If the application for a license to construct and operate the proposed repository is approved, DOE will be such a licensee. Although these regulations do not provide dose coefficients, they can readily be calculated based on the concentration limits for the release of the individual radionuclides into unrestricted areas;
2. Federal Guidance Report (FGR) No. 11, which is based on recommendations developed by EPA for radiation workers and was approved by the President in 1987 (Eckerman et al. 1988). This guidance is thus compatible with the stipulation that the RMEI is an adult. Following this approach, the dose estimates would be based on a 50-y commitment, that is, the dose that the ingested radionuclides would produce over a time span of 50 y following intake; and
3. FGR No. 13, which was developed by EPA for application to members of the public (Eckerman et al. 2002). As such, it includes age-specific dose and risk coefficients. One of its primary features is that it incorporates the latest scientific information on the uptake, metabolism, and related factors that influence radionuclide dose estimates. While, as was the case for FGR No. 11, the dose coefficients in FGR No. 13 for adults are based on a 50-y commitment, those for children are based on a commitment of 70 y minus the age in which the intake occurs (ICRP 1991).

INTER-RELATIONSHIPS AND OBSERVATIONS

The GWPSs are far more stringent than the IPS. This is due to the fact that (a) the dose rate limit (0.04 mSv y^{-1}) for combined beta and photon emitting radionuclides is comparatively low; (b) it applies to any organ as well as the whole body; and (c) it is impossible for the committed effective dose to the whole body to exceed that to any of its organs. Also of note is that the ICRP replaced the critical organ concept more than 25 y ago with one involving the use of tissue weighting factors and the concept of effective dose equivalent. The concept was introduced in 1977 and formalized in 1978 (ICRP 1977, 1978).

In justifying the stringency of this limit, the U.S. EPA stated that, "because of its many potential uses," ground water is one of the Nation's "most precious resources," noting, for example, that it serves as a potable water supply for more than 50% of the U.S. population. The U.S. EPA also pointed out that ground water, once

Table 3. Characteristics of key radionuclides having a potential for release from the proposed Yucca Mountain high level radioactive waste repository.

Radionuclide	Principal emissions[a]	Radioactive half-life (y)	Effective half-life	Organ receiving maximum dose[b]
^{14}C	β	5.73×10^3	12 to 40 d[c]	Whole body Stomach wall[d]
^{99}Tc	β	2.11×10^5	0.5 to 22 d[c]	Thyroid LLI wall[d,e]
^{129}I	β, γ	1.57×10^7	120 d	Thyroid
^{226}Ra	α, β, γ	1.60×10^3	43.7 y	Bone surface
^{228}Ra	β	5.75	5.10 y	Bone surface
^{237}Np	α, β, γ	2.14×10^6	100 y	Bone surface
^{239}Pu	α, β	2.41×10^4	100 y	Bone surface
^{241}Am	α, β, γ	4.32×10^2	81.2 y	Bone surface

[a] Includes emissions from decay products.
[b] Except as noted, information is based on FGR No. 11.
[c] Depends on chemical compound in which radionuclide is incorporated and the body organ(s) in which it concentrates.
[d] Based on information in FGR No. 13.
[e] Lower large intestine wall.

contaminated, is extremely difficult to decontaminate and that, for this and other reasons, it is "prudent and responsible to protect ground water resources from contamination through pollution prevention rather than to rely on cleanup" after the pollution has occurred (U.S. EPA 2001, 32106–32107). Nonetheless, as discussed below, this approach and philosophy have yielded a set of GWPSs that are inconsistent both internally and in comparison to the IPS.

Comparisons of the *effective* doses based on the GWPSs using various coefficients

As a first step, the dose estimates for each of the eight key radionuclides have been compared both individually and collectively. In the cases for ^{226}Ra, ^{228}Ra, and the alpha emitting radionuclides, the doses are based the conditions provided in Table 2. For the combined beta and photon emitting radionuclides, the dose estimates were based on the MCLs (Table 4) developed by EPA to facilitate the determination of compliance with the 0.04 mSv y^{-1} limit (Table 2). Even in this case, however, it is important to keep in mind that the 0.04 mSv y^{-1} limit applies to the combined committed thyroid dose from ^{14}C, ^{99}Tc, and ^{129}I. As noted in Table 3, the thyroid is the major recipient of the dose resulting from the ingestion of the last two of these radionuclides, the one exception being in the case of FGR No. 13. For purposes of comparison, dose estimates were made for each radionuclide using the coefficients in FGR No. 11 and FGR No. 13, and those derived from Title 10, CFR, Part 20. In all cases, it was assumed that the RMEI was an adult. The dose estimates for Title 10, CFR, Part 20, and FGR No. 13 are compared to those based on the coefficients in FGR No. 11.

Table 4. Comparison of committed *organ* doses to adults due to intakes of ground water containing each of three beta and photon emitting radionuclides.

	Organ dose (μSv)		
Source of values for dose coefficients	^{14}C (2,000 pCi L^{-1})[a,b]	^{99}Tc (900 pCi L^{-1})[a,b]	^{129}I (1 pCi L^{-1})[a,b]
Title 10, CFR, Part 20	33 (whole body)[c]	250[d] (thyroid)	83[d] (thyroid)
FGR No. 11	30 (whole body)	39 (thyroid)	67 (thyroid)
FGR No. 13	34 (stomach wall)	96 (LLI wall)[e]	57 (thyroid)

[a] Derived level developed by EPA for judging compliance with the Drinking Water Standards.

[b] For purposes of clarity traditional units have been used instead of SI units. This way direct comparisons to the standards can be made.

[c] Indicates organ on which the dose estimates were based.

[d] Calculated by dividing the effective dose estimate by the tissue weighting factor for the thyroid (0.03).

[e] Lower large intestine wall.

In the case for FGR No. 11 and No. 13, estimating the doses was straightforward. In the case for Title 10, CFR, Part 20, however, the procedure was as follows. Table 2, column 2, Appendix B, of these regulations provides the concentration of each radionuclide in water which, if consumed at a rate of 2 L d^{-1} for a year, will yield a committed *effective* dose to an adult of 0.5 mSv. The committed *effective* doses for the radionuclides in Table 5 were calculated simply by dividing the concentration listed in the Table 2 in the U.S. NRC regulations by the applicable MCL, and multiplying the quotient by 0.50 mSv.

In evaluating the results of these computations, it is important to recognize that the dose estimates for ^{226}Ra, ^{228}Ra, and the alpha emitting radionuclides are primarily of importance in terms of their potential contributions to the Individual Protection Standard. Whether compliance with this Standard is being achieved will depend on the concentrations of radionuclides present in the ground water, and resulting estimates of the *effective* dose per year of intake through the consumption of ground water, locally produced food, and other pathways. Whether the estimates comply with the GWPSs will depend on the collective concentrations and the applicable MCL for each group of radionuclides. A comparison of the committed *effective* dose estimates (Table 5), based on the GWPSs, shows the following:

1. The upper bound doses for ^{99}Tc and ^{129}I are extremely low, reflecting the stringency of the regulatory limits for combined beta and photon emitting radionuclides. This is vividly demonstrated by all three of the estimates for ^{129}I, and two of those for ^{99}Tc; namely, the ones based on Title 10, CFR, Part 20, and on FGR No. 11. In every case, the estimates are at or below the dose (10 μSv) that the National Council on Radiation Protection and Measurements (NCRP 1993) has defined as a Negligible Individual Dose (NID) per source or practice. In so doing, the Council stated that the NID represents a level of average annual excess risk of fatal health effects attributable to radiation below which efforts to reduce radiation exposure to the individual are "unwarranted;"
2. In terms of specifics, the dose estimates for ^{14}C are generally 10 to 15 times those for ^{129}I. Individually, however, the estimates for each of these two radionuclides are comparable regardless of the source of the coefficients. In contrast, the dose estimates for ^{99}Tc differ, depending on the source of the coefficients, ranging from a factor of 0.7 lower than that for FGR No. 11, in the case of Title 10, CFR, Part 20, to 1.7 times higher in the case of FGR No. 13. This is due,

Table 5. Comparison of committed *effective* doses due to intakes by adults of the eight key radionuclides based on the applicable MCLs and the coefficients derived from Title 10, CFR, Part 20, and provided in FGR No. 11 and FGR No. 13.

	Radionuclide (dose in μSv)							
Source of values for dose coefficients	^{14}C[a]	^{99}Tc[a]	^{129}I[a]	^{226}Ra[b]	^{228}Ra[b]	^{237}Np[b]	^{239}Pu[b]	^{241}Am[b]
Title 10, CFR, Part 20	33	7.5	2.5	42	42	375	375	375
FGR No. 11	30	9.6	2.0	48	53	486	388[c]	399
FGR No. 13	31	15.6	2.9	38	94	43	102	83

[a] For these radionuclides, the doses were calculated using the derived limits (MCLs) provided by the EPA (Table 5).

[b] For these radionuclides, the doses were calculated using the MCLs provided in the GWPSs (Table 2).

[c] Assuming the ^{239}Pu is in a soluble form; if it is insoluble, the dose would be 6 μSv.

in part, to a change in the identity of the organ receiving the highest dose (Table 3);

3. Based on the dose coefficients in FGR No. 11 and those derived from Title 10, CFR, Part 20, the dose estimates for ^{226}Ra and ^{228}Ra are significantly lower than those for ^{237}Np, ^{239}Pu, and ^{241}Am. This is attributable, in part, to differences in the deposition of these two radionuclides in the bone and their shorter effective half-lives, once deposited (Stannard 1988), combined with the fact that their MCL (5 pCi L^{-1}) is one third that (15 pCi L^{-1}) for the other three radionuclides (Table 2); and
4. The dose estimates for ^{237}Np, ^{239}Pu, and ^{241}Am are, in the case of FGR No. 13, substantially lower than the previously cited high values for FGR No. 11 and Title 10, CFR, Part 20. This is due primarily to two changes that occurred between the issuance of FGR No. 11 and FGR No. 13. First, the value for their estimated absorption through the human gastrointestinal tract was reduced by a factor of two; second, the tissue weighting factor for the bone surface, the body organ receiving the highest dose (Table 3), was reduced by a factor of three.

Comparisons of organ doses based on the GWPSs using various coefficients

The complexities in applying the GWPSs can be illustrated in another way. Applying the MCLs developed by EPA, estimates were made for the *organ* doses that ^{14}C, ^{99}Tc, and ^{129}I would produce in an adult, based on the dose coefficients derived from Title 10, CFR, Part 20, and those provided in FGR No. 11 and FGR No. 13. Comparable organ dose estimates were not developed for ^{226}Ra and ^{228}Ra, or the alpha emitting radionuclides, since their limits in the GWPSs are prescribed by the MCLs and their limits relative to the IPS are based on the *effective* dose. This exercise resulted in three different dose estimates each for ^{14}C, ^{99}Tc, and ^{129}I (Table 4).

As in estimating the committed effective doses (Table 5), the *organ* doses for Title 10, CFR, Part 20, in the case for ^{99}Tc and ^{129}I, were calculated by estimating the *effective* doses, based on Table 2, column 2, Appendix B, of these regulations, and dividing them by 0.03, the tissue weighting factor for the thyroid. Comparisons of these estimates to the *organ* dose rate limit (0.04 mSv y^{-1}) yielded the following observations:

1. Five of the nine dose estimates exceeded the organ dose rate limit; none of the four underestimates was less than 25% of the limit;
2. All three of the estimates for ^{14}C were less than the limit; the other underestimate was for ^{99}Tc, based on the dose coefficient from FGR No. 11;
3. The estimate for ^{99}Tc was, in the case for Title 10, CFR, Part 20, more than six times the limit; for FGR No. 13, it was more than twice the limit; for FGR No. 11, however, the difference was not significant; and
4. For ^{129}I, the estimate based on Title 10, CFR, Part 20, was more than twice the limit; for FGR No. 11, it was almost 1.7 times the limit; for FGR No. 13, it was 1.4 times the limit.

Of the above, the one obvious outlier is the estimate for ^{99}Tc based on the dose coefficient derived from Title 10, CFR, Part 20. This particular dose estimate should not be considered important for several reasons: (1) it is based on an assumed thyroid tissue weighting factor of 0.03 which may not apply; (2) as noted in FGR No. 13, the thyroid is no longer considered the body organ that receives the highest dose from this radionuclide; and (3) it is highly unlikely that dose coefficients derived from Title 10, CFR, Part 20, will be considered for application in estimating effective doses due to postulated radionuclide releases from the proposed repository.

Comparison of GWPSs doses to the IPS using various coefficients

To gain additional insights, the estimated doses for each of the eight key radionuclides, based on the GWPSs (Table 5), were compared to the IPS limit of 150 μSv. For the *combined beta and photon emitting radionuclides*, it can be noted that:

1. Even for ^{14}C, where in the case for Title 10, CFR, Part 20, and FGR No. 11, the whole body receives the same dose as the maximally exposed organs, the dose, based on the GWPSs, is a factor of about 4.5 times lower in the former case and five times lower in the latter case, than the IPS; for FGR No. 13, wherein the stomach wall is the organ receiving the highest dose, it is again a factor of almost five times lower than the IPS;
2. For ^{99}Tc, the dose estimates, based on Title 10, CFR, Part 20, and FGR No. 11, are factors ranging from more than 15 to 20 lower than the IPS; for FGR No. 13, it is a factor of more than 9 lower; and
3. For ^{129}I, the difference is even more dramatic; for the three sources of dose coefficients the effective dose estimates range from factors of 50 to more than 70 lower than the IPS.

For ^{226}Ra and ^{228}Ra and the *alpha emitting radionuclides*, the analyses reveal that:

1. The dose estimates for all cases, except for ^{228}Ra based on the dose coefficient from FGR No. 13, are a factor of about three lower than the IPS. For FGR No. 13, the estimate for ^{228}Ra is a factor of about 1.6 lower;
2. For the alpha emitting radionuclides (^{237}Np, ^{239}Pu, and ^{241}Am), the dose estimates, using the coefficients derived from Title 10, CFR, Part 20, and those provided in FGR No. 11 (and assuming that the ^{239}Pu is soluble), are factors ranging from 2.5 to more than three times the IPS. If the ^{239}Pu is assumed to be insoluble, its dose (6 μSv, Table 5, footnote c) would be a factor of 25 lower than the IPS. In cases where the ^{239}Pu is transported in an insoluble form as a colloid, the doses should probably be estimated assuming that it is insoluble; and
3. As previously discussed, the estimated doses for ^{237}Np, ^{239}Pu, and ^{241}Am, using the coefficients from FGR No. 13, are much less, ranging from factors of about 1.5 to about 3.5 lower than that permitted by the IPS. In contrast to the examples cited immediately above, these estimates are more in line with the ground water protection philosophy that EPA has indicated served as a basis for the development of the GWPSs.

Identification of controlling regulation

Since, as noted previously, the IPS and GWPSs are severable, it is illustrative to seek to identify which of these two parts of the regulations would likely be controlling, and under what types of circumstances. Based on the preceding analyses (Table 5), it would appear that:

1. For ^{14}C, the GWPSs dose estimates for FGR No. 11 and FGR No. 13 range from 20% to 23% of the IPS. If the intake from food doubled the estimated dose from this radionuclide,[‡] its contribution would approach half of the IPS. When potential contributions from other radionuclides are considered, it appears that the IPS will be controlling in the case of ^{14}C. Another factor to consider in evaluating this radionuclide is that, within 5,730 y, it will have decayed to 50% of its original amount; at 10,000 years, it will have decayed to about 30% of its original amount. On a longer-range basis, this radionuclide will be less important;
2. For ^{99}Tc and ^{129}I, the IPS has essentially no relevance, the reason being that the doses based on the GWPSs are so low. Even if present in the ground water at their limit, the contributions of these two radionuclides to the dose limit for the RMEI would be almost insignificant. As a result, for these two radionuclides, the GWPSs will be controlling under essentially all conditions;
3. For ^{226}Ra and ^{228}Ra, the estimated GWPSs doses range from about from 25% to 35% of the IPS. The one exception, as noted previously, is the dose estimate for ^{228}Ra, using the coefficient from FGR No. 13. In this case, the estimated dose is about 60% of the IPS. Even so, the GWPSs will most likely be controlling for both of these radionuclides, the primary reason being that naturally occurring sources (which are anticipated to be the major contributors of intake) are exempt from consideration under terms of the IPS (Table 2). Further substantiating this conclusion, for ^{228}Ra, is that the waste destined for placement in the proposed repository is not expected to contain significant quantities of ^{232}Th, its precursor; and
4. For ^{237}Np, ^{239}Pu, and ^{241}Am, the doses, based on the GWPSs and the application of the dose coefficients in Title 10, CFR, Part 20, and FGR #11, as previously indicated, range from 2.5 to more than 3 times the IPS. If the additional potential intake through food is considered, the dose contributions from these radionuclides would be even higher. For these reasons, the

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[‡] Personal communication, T. J. McCartin, U.S. Nuclear Regulatory Commission, Division of Waste Management, Washington, DC, 25 August 2004.

IPS would most likely be the controlling standard in these cases. Although the dose estimates for FGR No. 13 are much lower, the IPS would likely control, once the additional contributions from food and other sources of intake were taken into consideration.

OTHER CONSIDERATIONS

The preceding reviews, evaluations, and dose estimate comparisons relate primarily to those necessary for documenting compliance with the regulations. There are, however, other considerations that need to be addressed, particularly in terms of enhancing communications and building public confidence. Two of these are discussed in the sections that follow.

Dose estimates for other age groups

During the review of the license application, inquiries may arise concerning the dose to groups other than adults, three examples being infants, the fetus, and adolescents. While the magnitude of the dose coefficients is one contributing factor, the actual doses incurred are dependent on both the coefficients and the quantities of radioactive materials taken into the body. The latter will depend on the age-specific patterns of diet, particularly for infants and teenagers (U.S. EPA 2002). Recognizing these limitations, the dose coefficients for each of these age groups are compared in the sections that follow.

Since dose coefficients for younger age groups (infants and 15-y-olds) were not available in FGR No. 11, ICRP Publication 56 (ICRP 1989) served as a surrogate source in both of these cases. Since both ICRP Publication 56 and FGR No. 11 were based on ICRP Publication 30 methodology, this was deemed acceptable. To ensure internal consistency, ICRP Publication 56 also served as a source of the dose coefficients for an adult.

Infants. In accord with the caveats described above, comparisons of the ratios of the dose coefficients for an infant to those for an adult for each of the eight key radionuclides are summarized in Table 6. A review of the results of these comparisons reveals the following:

1. For ^{14}C and ^{129}I, the ratios of the dose coefficients for an infant compared to an adult, based on the information from ICRP Publication 56, were essentially the same as those in FGR No. 13. To be specific, those for ^{14}C for an infant were higher by a factor of 2.3 for Publication 56 and 2.5 for FGR No. 13; for ^{129}I, they were higher by a factor of 1.7 in both cases;
2. For ^{99}Tc, the ratio for FGR No. 13 was comparable to those for ^{237}Np, ^{239}Pu, and ^{241}Am. The relatively high value of this ratio (16.0), as contrasted to those for ^{14}C and ^{129}I, may be due to the designation of the lower large intestine wall as the organ that receives the highest dose when ^{99}Tc is ingested. Comparable information for ^{99}Tc was not available in ICRP Publication 56;
3. For ^{226}Ra, the ratio for FGR No. 13 was comparable to those for ^{237}Np, ^{239}Pu, and ^{241}Am; for ^{228}Ra, the ratio was a factor of about 2.2 to 2.5 times those for ^{237}Np, ^{239}Pu, and ^{241}Am. Similar information was not available in ICRP Publication 56 for either of these two radionuclides;
4. For ^{237}Np, ^{239}Pu, and ^{241}Am, the ratios for an infant in ICRP Publication 56 ranged from a factor of 12.2 to 14.4 higher than those for an adult. For FGR No. 13, the ratios for an infant ranged from a factor of 16.7 to 18.7 times higher; and
5. For ^{237}Np, ^{239}Pu, and ^{241}Am, the ratios for an infant, based on Publication 56 and FGR No. 13, ranged from

Table 6. Comparison of committed *effective* dose ingestion coefficients for a three-month-old infant and an adult based on ICRP Publication 56 and FGR 13.

	ICRP Publication 56[a]			FGR No. 13		
	Dose coefficient (Sv/Bq)			Dose coefficient (Sv/Bq)		
Radionuclide	Infant	Adult	Ratio[b]	Infant	Adult	Ratio[b]
^{14}C	1.3×10^{-9}	5.6×10^{-10}	2.3	1.44×10^{-9}	5.81×10^{-10}	2.5
^{99}Tc[c]				1.03×10^{-8}	6.42×10^{-10}	16.0
^{129}I	1.1×10^{-7}	6.4×10^{-8}	1.7	1.84×10^{-7}	1.06×10^{-7}	1.7
^{226}Ra[c]				4.65×10^{-6}	2.80×10^{-7}	16.6
^{228}Ra[c]				2.94×10^{-5}	6.97×10^{-7}	42.2
^{237}Np	5.5×10^{-6}	4.5×10^{-7}	12.2	2.00×10^{-6}	1.07×10^{-7}	18.7
^{239}Pu	1.4×10^{-5}	9.7×10^{-7}	14.4	4.19×10^{-6}	2.51×10^{-7}	16.7
^{241}Am	1.2×10^{-5}	8.9×10^{-7}	13.5	3.73×10^{-6}	2.04×10^{-7}	18.3

[a] The dose coefficients in ICRP Publication 56 were used for an infant since they were not available in FGR No. 11. To ensure consistency, the dose coefficients from ICRP Publication 56 were also used for an adult, even though they were also available in FGR No. 11.

[b] Ratio of dose coefficient for an infant (3-mo-old) to that for an adult.

[c] The necessary coefficients were not available in ICRP Publication 56.

a factor of about 5 to 8 times higher than those for ^{14}C. In a similar manner, the ratios for an infant for these same three radionuclides ranged from about 7 to 11 times higher than those for ^{129}I.

While the differences described above are important, it must be recognized that the dose coefficients, alone, are not necessarily representative of the doses that infants would receive. Other factors that must be considered include whether the infant is nursed by its mother. If so, the doses will depend on the type and source of the mother's diet, the radionuclides it contains, and the extent of their uptake and subsequent secretion into her milk. If the infant consumes milk from cows, the dose will depend on whether it is produced locally or outside the area, whether the cows are on open pasture or housed and fed indoors, and other factors.

Fetus. A second consideration is the fetus. While this may initially be appear to be a source for concern, a comparison shows that the dose coefficients for the fetus, based on the radionuclides being taken in by the mother-to-be, are dramatically lower than those for an infant, ranging from factors of 2 to 20 lower for ^{14}C, ^{99}Tc, and ^{129}I; a factor of more than 10 lower for ^{226}Ra; a factor of about 100 lower for ^{228}Ra; about 5×10^2 lower for ^{237}Np and ^{239}Pu; and more than 10^3 lower for ^{241}Am.

Fifteen-year-olds. Again, based on the caveats described above, the ratios of the dose coefficients for 15-y-olds to those for adults, based on ICRP Publication 56, were compared to those in FGR No. 13. A summary of these comparisons is presented in Table 7. As the data illustrate:

1. Based on information from ICRP Publication 56, with the exception of ^{129}I, and the absence of information on ^{99}Tc, ^{226}Ra, and ^{228}Ra, there is essentially no difference in the dose coefficients for the two age groups. Even in the case of ^{129}I, which had the maximum difference, the dose coefficient for a 15-y-old proved to be only 1.3 times that for an adult; and
2. Based on information from FGR No. 13, the ratios of the coefficients for ^{14}C, ^{99}Tc, and ^{129}I, as well as ^{237}Np, ^{239}Pu, and ^{241}Am, were essentially the same as those for FGR No. 11. The only significant differences were those observed for the two isotopes of radium. For ^{226}Ra, the ratio for a 15-y-old is more than 5 times that for an adult; for ^{228}Ra, it is more than 7 times higher. In the main, this reflects the higher uptake in the skeleton of the 15-y-old due to bone growth.

COMMENTARY AND CONCLUSIONS

While the details of the various sensitivity studies conducted as part of this review and evaluation are interesting, the knowledge and insights that have been gained are far more important. These may be summarized as follows:

1. The science of internal dosimetry has undergone significant progress and dramatic change during the years spanning the issuance of ICRP 2 (1960), the basis for the MCL's; this is exemplified by ICRP Publication 26 (ICRP 1977); Title 10, CFR Part 20; FGR No. 11; and, most recently, FGR No. 13. It is essential, therefore, that the analysts and regulators acknowledge that these changes have occurred, that the dose estimates will differ depending on the basis on which they are made, and that caution must be

Table 7. Comparison of committed *effective* dose ingestion coefficients for a 15-y-old and an adult based on ICRP Publication 56 and FGR 13.

	ICRP Publication 56[a]			FGR No. 13		
	Dose coefficient (Sv/Bq)			Dose coefficient (Sv/Bq)		
Radionuclide	15-y-old	Adult	Ratio[b]	15-y-old	Adult	Ratio[b]
^{14}C	5.5×10^{-10}	5.6×10^{-10}	1.0	8.00×10^{-10}	5.81×10^{-10}	1.4
^{99}Tc[c]				8.24×10^{-10}	6.42×10^{-10}	1.3
^{129}I	8.4×10^{-8}	6.4×10^{-8}	1.3	1.40×10^{-7}	1.06×10^{-7}	1.3
^{226}Ra[c]				1.52×10^{-6}	2.80×10^{-7}	5.4
^{228}Ra[c]				5.14×10^{-6}	6.97×10^{-7}	7.4
^{237}Np	4.7×10^{-7}	4.5×10^{-7}	1.0	1.08×10^{-7}	1.07×10^{-7}	1.0
^{239}Pu	9.8×10^{-7}	9.7×10^{-7}	1.0	2.46×10^{-7}	2.51×10^{-7}	1.0
^{241}Am	9.1×10^{-7}	8.9×10^{-7}	1.0	2.04×10^{-7}	2.04×10^{-7}	1.0

[a] The dose coefficients from ICRP Publication 56 were used for a 15-y-old since they were not available in FGR No. 11. To ensure internal consistency, the coefficients from ICRP Publication 56 were also used for an adult even though they were available in FGR No. 11.

[b] Ratio of dose coefficient for a 15-y-old to that for an adult.

[c] The necessary coefficients were not available in ICRP Publication 56.

exercised to ensure that these factors are taken into consideration in interpreting the outcomes;

2. These calculations provide insights on the influence dose conversion factors have on the estimates of dose. While this is not the only source of such influences, it is one of major importance. Differences in dose coefficients can result in changes in dose estimates by an order of magnitude depending on the source from which they were obtained; and
3. While the regulations specify certain measurements and assessments to be made, it will be incumbent on both the analysts and regulators to recognize that, if they are to meet the needs of the stakeholders and interested members of the public, as well as the professional radiation safety community, they must expand their efforts beyond the regulatory requirements. This includes estimating doses based on several possible sources of dose coefficients and for age groups other than adults.

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■■

Paper

IMPACTS OF STABLE ELEMENT INTAKE ON ^{14}C AND ^{129}I DOSE ESTIMATES

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***Abstract*—The purpose of this study was to evaluate and provide insights related to the influence of the intake of stable isotopes of carbon and iodine on the *committed* doses due to the ingestion of ^{14}C and ^{129}I. This was accomplished through the application of two different computational approaches. The first was based on the assumption that ground (drinking) water was the only source of intake of ^{14}C and ^{129}I, as well as stable carbon and stable iodine. In the second, the intake of ^{14}C and ^{129}I was still assumed to be restricted to that in the ground (drinking) water, but the intake of stable carbon and stable iodine was expanded to include that in other components of the diet. The doses were estimated using either a conversion formula or the applicable dose coefficients in Federal Guidance Reports No. 11 and No. 13. Serving as input for the analyses was the estimated maximum concentrations of ^{14}C or ^{129}I that would be present in the ground water due to potential releases from the proposed Yucca Mountain high-level radioactive waste repository during the first 10,000 y after closure. The estimated contributions of stable carbon and iodine through the consumption of ground water were based on analyses of samples collected in the Amargosa Valley, NV. The contributions through dietary intake were based on surveys conducted in the United States. Based on the accompanying analyses, it was noted that stable isotope intake has a significant effect on the estimated doses due to the intake of radioactive isotopes of the same element. While this is a well-known fact, this observation has international implications in terms of dose estimates for key radionuclides, such as ^{14}C and ^{129}I, a primary reason being the wide variations in the intakes of stable carbon and iodine in various countries. For this reason, analysts planning to apply the dose coefficients developed by the International Commission on Radiological Protection (ICRP) should either confirm that the average total intake in their country of stable isotope(s) of the radioactive isotope being evaluated is in reasonable agreement with the value assumed by the ICRP or suitably modify the ICRP dose coefficients to account for any differences. If such a procedure is to be implemented, there is a need for periodic updates of the dietary intakes of various stable elements in countries throughout the world. The importance of this is documented by recent surveys in Asia that revealed that their average total daily intake of stable iodine was less than half of the ICRP value for Reference Man. In this case, application of the ICRP dose coefficients, without modification, would underestimate the dose due to ingested ^{129}I by a factor of more than two. A related situation exists in the United States where the latest surveys indicate that the daily intake of stable iodine is 75% of the ICRP value.**

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Key words: ^{14}C; ^{129}I; waste disposal; dose assessment

INTRODUCTION

THE PURPOSE of this study was to evaluate the influence of the intake of stable isotopes of carbon and iodine on dose estimates due to the ingestion of ^{14}C and ^{129}I. Serving as an example for achieving this objective were data based on analyses and measurements related to the proposed high-level radioactive waste repository at Yucca Mountain, Nevada. Since the regulations (U.S. NRC 2001) that apply to this facility specify that the reasonably maximally exposed individual (RMEI) is a hypothetical person who has "a diet and living style representative of the people who now reside in the Town of Amargosa Valley, Nevada," and that he/she "is an adult" who "drinks 2 liters of water per day from wells drilled into the ground water. . . ," these are the conditions that were applied in the dose estimates that follow.

ASSUMPTIONS AND ANALYTICAL APPROACHES

For purposes of the analyses, the following computational approaches and assumptions were applied:

- In all cases, the assumed intake of either ^{14}C or ^{129}I was limited to that arising through the ingestion of 2 L d^{-1} of ground (drinking) water. Any ^{14}C or ^{129}I present in other components of the diet was ignored;
- In contrast, the intake of *stable* carbon (^{12}C + ^{13}C) and *stable* iodine (^{127}I) was, for purposes of an initial dose estimate (#1a), assumed to be only that in the ground

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(drinking) water; for purposes of a second dose estimate (#1b), it was assumed to be that in the *total* diet, namely, that in the ground water plus other components of the diet;

- As a first computational approach (#1a and #1b), the doses were estimated using a conversion formula that incorporates the ratio of the intake of ^{14}C or ^{129}I to that for stable carbon or stable iodine;
- As a second approach (#2a and #2b), the doses were estimated using the coefficients provided in Federal Guidance Report (FGR) No. 11 (Eckerman et al. 1988) and FGR No. 13 (Eckerman et al. 2002), respectively;
- The assumed concentration of ^{14}C or ^{129}I in the ground water was the maximum estimated to result from postulated releases of ^{14}C and ^{129}I during the first 10,000 years after repository closure; and
- The assumed concentrations of stable carbon and stable iodine in the ground water were based on analyses of samples collected in the Amargosa Valley, NV.

A summary of the two computational approaches is presented in Table 1. In the case of approaches #2a and #2b, the impacts of the mass ratio of stable carbon or iodine in the total intake to that for ^{14}C or ^{129}I had already been implicitly incorporated into the dose coefficients by the International Commission on Radiological Protection (ICRP), whose publications served as guidance in developing the dose coefficients presented in FGR No. 11 and FGR No. 13. This was accomplished through the assignment of a biological half-time based on the turnover rate of carbon or iodine in the human body (Eckerman et al. 1999; Eckerman 2004**). Because, in applying this approach, there is no readily available method to avoid taking into account the amount of stable carbon or stable iodine in other components of the diet, only one dose estimate was made in each of these two cases.

In addition to the items enumerated above, it is important to note the following differences in the assumptions underlying the dose estimates for ^{14}C and ^{129}I that were based on computational approaches #1a and #1b and involved the application of a dose conversion formula:

- For ^{14}C, the assumed daily intake of stable carbon was 300 g, the value for Reference Man provided by the International Commission on Radiological Protection (ICRP 1975). Reviews indicate that the estimated daily intake for adults living in the United States is the same (Till 1983; NCRP 1984, 1985); and
- For ^{129}I, the assumed daily intake of stable iodine in the United States was 150 μg. This value was based on the National Health and Nutrition Examination Survey (NHANES) IV (NRC 2004), and NHANES I and NHANES III conducted from 1971–1974 and 1988–1994, respectively (Hollowell et al. 1998). This estimate is 75% of the value (200 μg) provided for Reference Man (ICRP 1975).

Table 1. Summary of computational approaches and assumptions used for estimating annual doses for ^{14}C and ^{129}I.[a]

Computational approach	Stable element intake	Basis for dose estimate
#1a	Drinking water only	Conversion formula based on intake ratio of activity of radioisotope to mass of stable element[b]
#1b	Drinking water plus other components of diet	Conversion formula based on intake ratio of activity of radioisotope to mass of stable element[b]
#2a	Implicitly incorporated through value assigned to biological half-time	Dose coefficients from FGR No. 11
#2b	Implicitly incorporated through value assigned to biological half-time	Dose coefficients from FGR No. 13

[a] All dose estimates are based on the quantity of ^{14}C or ^{129}I ingested in the ground (drinking) water. The intake in other components of the diet was ignored.

[b] In some cases, the inverse ratio is applied.

DOSE ESTIMATES FOR ^{14}C

Based on data provided by the U.S. Department of Energy (U.S. DOE 2002), the maximum concentration of ^{14}C in the ground water during the first 10,000 y after repository closure is estimated to be 2×10^{-3} pCi L^{-1}. Assuming a consumption of 2 L d^{-1} of ground water, this would yield a daily intake of 4×10^{-3} pCi d^{-1} (1.48×10^{-4} Bq d^{-1}). Based on site-specific analyses, the average concentration of stable carbon in the ground water in the Amargosa Valley is 56 mg L^{-1} (Peters 2004††) which, in a similar manner, would yield an intake rate of 112 mg d^{-1}.

^{14}C—computational approach #1a

Applying the applicable dose conversion formula (Killough and Rohwer 1978) under the conditions specified in this approach, the total body dose equivalent rate (rem d^{-1}) due to the intake of ^{14}C would be:

$$0.57\left(\frac{\mu\text{Ci}\,^{14}\text{C}}{\text{g}\ ^{\text{stable}}\text{C}}\right). \qquad (1)$$

** Eckerman KF. Influence of stable carbon. E-mail transmission. Oak Ridge, TN: Oak Ridge National Laboratory; 13 September 2004.

†† Peters M. Request for information on ^{14}C. E-mail transmission. Washington, DC: U.S. Department of Energy; 18 August 2004.

The constant, 0.57, expressed in units of rem d^{-1} per μCi g^{-1} of stable carbon, applies specifically to the dose rate to the whole body due to the ingestion of ^{14}C. Under the conditions specified in approach #1a, the estimated dose rate would be:

$$\frac{(0.57 \text{ rem d}^{-1})(4 \times 10^{-9}\ \mu\text{Ci}\ ^{14}\text{C d}^{-1})}{(112 \text{ mg }^{\text{stable}}\text{C d}^{-1})(10^{-3}\text{ g mg}^{-1})} = 2.04 \times 10^{-8} \text{ rem d}^{-1}. \quad (2)$$

On this basis, the estimated dose rate, on an annual basis, would be:

$$(2.04 \times 10^{-8} \text{ rem d}^{-1})(365 \text{ d y}^{-1}) = 7.45 \times 10^{-6} \text{ rem y}^{-1} = (7.45 \times 10^{-6} \text{ rem y}^{-1}) \times (10^{4}\ \mu\text{Sv rem}^{-1}) = 7.45 \times 10^{-2}\ \mu\text{Sv y}^{-1}. \quad (3)$$

Although the conversion formula being applied is based on the older methodology, for the assumed conditions of chronic exposure and equilibrium the estimated dose rate to the body will be essentially the same as the committed effective dose equivalent (CEDE), per year of intake, derived through the application of more modern computational methods. One of the primary reasons that this is the case is the relatively rapid biological half-time (40 d) of carbon in the body (NCRP 1985).

^{14}C—computational approach #1b

Computational approach #1b, as noted in Table 1, is the same as #1a, except that the total daily intake of stable carbon is assumed to be 300 g (ICRP 1975). Although this is not a realistic exposure scenario (since it would not be possible to ingest the stable carbon in the remainder of the diet without ingesting the accompanying ^{14}C), the calculations were performed on the basis of this assumption so that the outcome could be reviewed, evaluated, and the accompanying insights revealed. Applying the dose conversion formula under the specified conditions, the estimated dose rate would be:

$$\frac{(0.57 \text{ rem d}^{-1})(4 \times 10^{-9}\ \mu\text{Ci}\ ^{14}\text{C d}^{-1})}{(300 \text{ g }^{\text{stable}}\text{C d}^{-1})} = 7.60 \times 10^{-12} \text{ rem d}^{-1}. \quad (4)$$

On this basis, the estimated dose rate, on an annual basis, would be:

$$(7.60 \times 10^{-12} \text{ rem d}^{-1})(365 \text{ d y}^{-1}) = 2.77 \times 10^{-9} \text{ rem y}^{-1} = 2.77 \times 10^{-5}\ \mu\text{Sv y}^{-1}. \quad (5)$$

^{14}C—computational approach #2a: FGR No. 11

The value of the CEDE coefficient for ingested ^{14}C in FGR No. 11 is 5.64×10^{-10} Sv Bq^{-1}. Applying this coefficient to the annual intake of ^{14}C, the estimated dose, per year of intake, would be:

$$(1.48 \times 10^{-4} \text{ Bq d}^{-1})(365 \text{ d})(5.64 \times 10^{-10} \text{ Sv Bq}^{-1}) = 3.05 \times 10^{-11} \text{ Sv} = 3.05 \times 10^{-5}\ \mu\text{Sv}. \quad (6)$$

Because, as noted earlier, the impact of the total intake of stable carbon is incorporated into the dose coefficient from FGR No. 11, the contributions of stable carbon from other components of the diet are automatically taken into account in this case.

^{14}C—computational approach #2b: FGR No. 13

The value of the effective dose coefficient for ^{14}C in FGR No. 13 is 5.81×10^{-10} Sv Bq^{-1}. In this case, the estimated dose, per year of intake, would be:

$$(1.48 \times 10^{-4} \text{ Bq d}^{-1})(365 \text{ d})(5.81 \times 10^{-10} \text{ Sv Bq}^{-1}) = 3.14 \times 10^{-11} \text{ Sv} = 3.14 \times 10^{-5}\ \mu\text{Sv}. \quad (7)$$

As in dose estimate #2a, this estimate automatically accounts for the total intake of stable carbon.

The results of these four sets of calculations are summarized in Table 2. As may be noted, the dose rate estimate ($7.45 \times 10^{-2}\ \mu$Sv y^{-1}), based on computational approach #1a, is clearly not in agreement with the estimates derived on the basis of the assumptions and computational approaches applied in the other three cases. The reason for this difference can be explained as follows. The specific activity of ^{14}C is 1.63×10^{11} Bq g^{-1}. Based on the assumed daily drinking water consumption rate, this would yield a daily mass intake of ^{14}C of:

$$\frac{1.48 \times 10^{-4} \text{ Bq d}^{-1}}{(1.63 \times 10^{11} \text{ Bq g}^{-1})(10^{-3}\text{ g mg}^{-1})} = 9.08 \times 10^{-13} \text{ mg d}^{-1}. \quad (8)$$

Table 2. Comparison of annual dose estimates due to ingestion of ^{14}C, based on the several computational approaches.

Approach	Assumed conditions	Estimated dose
#1a	Application of Killough & Rohwer (1978) dose conversion formula assuming a daily stable carbon (drinking water) intake of 112 mg	$7.45 \times 10^{-2}\ \mu$Sv
#1b	Application of Killough & Rohwer (1978) dose conversion formula assuming a daily stable (total) carbon intake of 300 g	$2.77 \times 10^{-5}\ \mu$Sv
#2a	Application of FRG No. 11 dose coefficient without explicit regard to the daily stable carbon intake	$3.05 \times 10^{-5}\ \mu$Sv
#2b	Application of FRG No. 13 dose coefficient without explicit regard to the daily stable carbon intake	$3.14 \times 10^{-5}\ \mu$Sv

This being the case, the ratio of the mass in the ground water of stable carbon to ^{14}C (which served as an input for computational approach #1a) would be:

$$\frac{112 \text{ mg d}^{-1}}{9.08 \times 10^{-13} \text{ mg d}^{-1}} = 1.23 \times 10^{14}. \tag{9}$$

If the corresponding ratio were calculated for computational approach #1b (based on the *total* intake of stable carbon), it would be equal to:

$$\frac{(300 \text{ g d}^{-1})(10^{3} \text{ mg g}^{-1})}{9.08 \times 10^{-13} \text{ mg d}^{-1}} = 3.30 \times 10^{17}. \tag{10}$$

On this basis, the ratio of the mass relationship for total intake, vs. that in the ground water, would be:

$$\frac{3.30 \times 10^{17}}{1.23 \times 10^{14}} = 2.68 \times 10^{3}. \tag{11}$$

The corresponding inverse ratio, that is, of the dose estimate for computational approach #1a, divided by that for approach #1b, is:

$$\frac{7.45 \times 10^{-2} \ \mu\text{Sv y}^{-1}}{2.77 \times 10^{-5} \ \mu\text{Sv y}^{-1}} = 2.69 \times 10^{3}. \tag{12}$$

As would be anticipated, the ratio in each case is essentially the same. This observation, coupled with the fact that the dose estimate based on computational approach #1b closely agreed with the estimates based on computational approaches #2a and #2b, confirms, as previously noted, that the dose coefficients in FGR No. 11 and No. 13 were prepared taking into account the daily intake contribution of stable carbon in other components of the daily diet. For this reason, the coefficients applied in dose assessment approaches #2a and #2b will, in all normal situations, yield the proper results regardless of the source of the ^{14}C intake or the contribution of stable carbon from that particular source *so long as the stable carbon intake of the exposed population is comparable to that for Reference Man*. In contrast, it is not possible for the dose estimate based on approach #1a to be correct unless the contributions of stable carbon from other components of the diet are considered. Application of the dose conversion formula under the artificial constraint that contributions of stable carbon from other components of the diet be ignored (computational approach #1a) did not permit this to be done.

DOSE ESTIMATES FOR ^{129}I

Based on information provided by the U.S. Department of Energy (U.S. DOE 2002), the maximum concentration of ^{129}I in the ground water during the first 10,000 y after repository closure is estimated to be 2×10^{-5} pCi L^{-1}. Assuming a ground water consumption rate of 2 L d^{-1}, this would yield a daily intake of 4×10^{-11} μCi d^{-1} (1.48×10^{-6} Bq d^{-1}). Based on site-specific analyses, the average concentration of stable iodine in the ground water in the Amargosa Valley, measured as the iodide, is 5.0 μg L^{-1} (Peterman 2003[‡‡]). Since, under the conditions expected in the Yucca Mountain ground water, all the iodine will be present as the iodide, the consumption of 2 L d^{-1} would yield a daily stable iodine intake of 10.0 μg.

^{129}I—computational approach #1a

As in the case for ^{14}C, any potential contribution of ^{129}I in other components of the diet will be ignored in the application of this approach. Although this, as noted earlier, is not a realistic scenario, once again the calculations were performed so that the outcome could be reviewed, evaluated, and relevant insights derived.

Applying the specific activity for ^{129}I (6.53×10^{6} Bq g^{-1}), the mass of ^{129}I in the daily ground water intake would be:

$$\frac{1.48 \times 10^{-6} \text{ Bq d}^{-1}}{6.53 \text{ Bq } \mu\text{g}^{-1}} = 2.27 \times 10^{-7} \ \mu\text{g d}^{-1}, \tag{13}$$

Accordingly, the ratio of the mass of stable iodine to that of ^{129}I in the assumed daily intake, at the time of the maximum estimated concentration of ^{129}I, would be:

$$\frac{10.0 \ \mu\text{g d}^{-1}}{2.27 \times 10^{-7} \ \mu\text{g d}^{-1}} = 4.41 \times 10^{7}. \tag{14}$$

Assuming that the average adult thyroid weighs 20 g and contains 10 mg of iodine (ICRP 1979), the mass of ^{129}I in the thyroid at equilibrium would be:

$$\frac{10 \text{ mg}}{4.41 \times 10^{7}} = 2.27 \times 10^{-7} \text{ mg}. \tag{15}$$

This would be equivalent to:

$$(2.27 \times 10^{-7} \text{ mg})(6.53 \times 10^{3} \text{ Bq mg}^{-1}) = 1.48 \times 10^{-3} \text{ Bq}. \tag{16}$$

Applying the dose conversion formula developed by Soldat et al. (1973), maintenance of a continuing burden of 1 pCi (3.70×10^{-2} Bq) of ^{129}I in the thyroid will impart a dose rate to that organ of 0.06 mrem y^{-1} (6×10^{-1} μSv y^{-1}). Under the conditions specified in computational approach #1a, the dose rate to the thyroid would be:

[‡‡] Peterman Z. Dissolved iodide in ground water. E-mail transmission. Las Vegas, NV: U.S. Department of Energy; Yucca Mountain Project; 19 June 2003.

$$(6.0 \times 10^{-1}\ \mu\text{Sv y}^{-1})\left(\frac{1.48 \times 10^{-3}\ \text{Bq}}{3.7 \times 10^{-2}\ \text{Bq}}\right) = 2.40 \times 10^{-2}\ \mu\text{Sv y}^{-1}. \quad (17)$$

^{129}I—computational approach #1b

Based on the previously cited *total* daily intake in the United States of 150 μg of stable iodine, and taking into account the mass of ^{129}I being consumed each day (calculated earlier), the ratio of the mass of stable iodine to that for ^{129}I in this case would be:

$$\frac{150\ \mu\text{g d}^{-1}}{2.27 \times 10^{-7}\ \mu\text{g d}^{-1}} = 6.61 \times 10^{8}. \quad (18)$$

Following this approach, the amount of ^{129}I in the thyroid at equilibrium would be:

$$\frac{10\ \text{mg}}{6.61 \times 10^{8}} = 1.51 \times 10^{-8}\ \text{mg}, \quad (19)$$

and the total ^{129}I activity in the thyroid, based on its specific activity, would be:

$$(1.51 \times 10^{-8}\ \text{mg})(6.53 \times 10^{3}\ \text{Bq mg}^{-1}) = 9.86 \times 10^{-5}\ \text{Bq}. \quad (20)$$

Applying the Soldat et al. formula, the dose rate to the thyroid would be:

$$(6.0 \times 10^{-1}\ \mu\text{Sv y}^{-1})\left(\frac{9.86 \times 10^{-5}\ \text{Bq}}{3.7 \times 10^{-2}\ \text{Bq}}\right) = 1.60 \times 10^{-3}\ \mu\text{Sv y}^{-1}. \quad (21)$$

^{129}I—computational approach #2a: FGR No. 11

For estimating the dose to the thyroid, the value of the dose coefficient for ^{129}I in FGR No. 11 is 2.48×10^{-6} Sv Bq^{-1}. Applying this to the intake of ^{129}I through consumption of ground water, the estimated committed thyroid dose, per year of intake, would be:

$$(2.48 \times 10^{-6}\ \text{Sv Bq}^{-1})(1.48 \times 10^{-6}\ \text{Bq d}^{-1})(365\ \text{d}) = 1.34 \times 10^{-9}\ \text{Sv y}^{-1} = 1.34 \times 10^{-3}\ \mu\text{Sv}. \quad (22)$$

^{129}I—computational approach #2a & b: FGR No. 13

Again, based on estimating the dose to the thyroid, the value of the dose coefficient for ^{129}I in FGR No. 13 is 2.11×10^{-6} Sv Bq^{-1}. In this case, the estimated committed thyroid dose, per year of intake, would be:

$$(2.11 \times 10^{-6}\ \text{Sv Bq}^{-1})(7.4 \times 10^{-7}\ \text{Bq L}^{-1})(2\ \text{L d}^{-1}) \times (365\ \text{d}) = 1.14 \times 10^{-9}\ \text{Sv y}^{-1} = 1.14 \times 10^{-3}\ \mu\text{Sv}. \quad (23)$$

COMMENTARY AND CONCLUSION

The data for ^{14}C in Table 2 show the dose estimate based on computational approach #1a is clearly not in agreement with those derived using the other three approaches. The same is true for ^{129}I (Table 3). In both instances, this is a direct result of the intentional omission from consideration of the contributions of stable carbon and iodine in other components of the diet. This was documented by the fact that the ratio of the mass intake of stable carbon to that of ^{14}C was essentially the same as the inverse ratios of the dose estimates. The same would be true for ^{129}I. The message that this portion of these computations reveals is clear. Dose estimates based on a conversion formula, in which the ratios of the activity of the radioisotope to the stable isotope intake are used as input, should not be made in isolation. All significant sources of both the radioactive and stable isotopes for an element must be considered.

Also of interest is that the dose estimates for ^{14}C, applying computational approaches #2a and #2b, which were based on the same average daily intake of stable carbon (300 g) as assumed in computational approach #1b, were nonetheless *higher* than those in approach #1b by 10% and 13%, respectively. This reflects, in part, the changes that have been incorporated into dose estimation methodologies in recent years. In contrast, the corresponding estimates for ^{129}I, based on computation approaches #2a and #2b, were not only *lower* but also by wider margins (19% and 40%). The latter case confirms, once again, the significant role that the assumed stable element intake plays in these types of dose assessments. As mentioned earlier, the assumed intake of stable iodine by Reference Man (ICRP 1975) is 200 μg, 25% higher than the 150 μg assumed in computational approach #1b. Application of the higher intake would have resulted in a lower dose estimate in the latter approach.

Table 3. Comparison of annual *thyroid* doses due to the ingestion of ^{129}I, based on several computational approaches.

Approach	Assumed conditions	Estimated dose
#1a	Application of Soldat et al. (1973) dose conversion formula assuming a daily stable iodine (drinking water) intake of 10 μg	2.40×10^{-2} μSv
#1b	Application of Soldat et al. (1973) dose conversion formula assuming a daily stable (total) carbon intake of 400 μg	1.60×10^{-3} μSv
#2a	Application of FRG No. 11 dose coefficient without explicit regard to the daily stable iodine intake	1.34×10^{-3} μSv
#2b	Application of FRG No. 13 dose coefficient without explicit regard to the daily stable iodine intake	1.14×10^{-3} μSv

The sharing of these observations is not to imply that the dose coefficients provided by the ICRP are, in any sense, incorrect. The point is that analysts in various parts of the world must recognize and account, where appropriate, for significant differences in key factors that may influence the doses being estimated. The importance of this, with respect to stable element intake, is documented by recent studies (Iyengar et al. 2004) of populations in nine Asian countries, representing more than half of the world's population, that indicate that their average total daily intake of stable iodine is only 90 μg, 45% of the ICRP value for Reference Man. In these cases, application of the ICRP dose coefficient for ingestion, without modification, would yield dose estimates that are less than half of the correct value. Nonetheless, if analysts are to have the data they need, it is essential that periodic assessments and updates be made of the dietary intakes of various stable elements in countries throughout the world. This is particularly the case in the United States where surveys, during the past three decades, indicate that there has been a decreasing trend in the daily average intake of stable iodine in this country. In fact, the estimated value has decreased from about 300 μg in the early 1970s to about 150 μg today (NRC 2004).

Moreover, the authors believe that a detailed and statistically rigorous analysis of expected values and ranges for the intake of stable elements in the normal diet can be a most important influence on the ultimate importance of the contribution to the dose of a specific radionuclide. This paper highlights this possibility for ^{14}C and ^{129}I. A better appreciation for the importance of this dilution factor would clearly be enhanced by more accurate information on dietary intakes and the associated implications. While the analyses in this paper apply solely to radioactive and stable isotopes of the same element, they also call attention to the fact that similar evaluations may be justified in terms of addressing situations in which the intake of a stable element, for example, calcium, significantly influences the uptake in the body of a radionuclide of another element, such as ^{90}Sr.

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