

APPENDIX F

PRAIRIE ISLAND ISFSI RISK ASSESSMENT

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0.0 SUMMARY

The Prairie Island Nuclear Generating Plant operates an Independent Spent Fuel Storage Installation (ISFSI) located on the plant site. Plant personnel receive an average annual dose of 4.6 mrem from the ISFSI; members of the public located at the nearest residence receive an annual dose less than 1.0 mrem from operation of the ISFSI. These doses are so low that they are well within the variation of natural background levels across the State of Minnesota. Annual doses from the ISFSI to plant workers are less than 2% of natural background radiation levels; annual doses to the general public are less than 1% of natural background. Average worker doses are 1000 times lower than federal occupational exposure limits. Doses to the public are 100 times lower than applicable public dose limits as established by the U.S. Nuclear Regulatory Commission.

Health risks (as measured by cancer mortality) from radiation exposure to workers and the public cannot be measured directly because doses are so low. Public health impacts must be determined theoretically. Assuming a worker population of 1000, less than one additional cancer death due to radiation exposure would be expected in the next 70 years as a result of ISFSI operations. In comparison, about 200 cancer deaths would be expected in this population from all causes of cancer. Similarly, no additional cancer deaths due to radiation exposure would be expected among members of the public living in the vicinity of the plant. Assuming a population of 400 persons, 80 individuals would be expected to die of cancer from all causes.

Based on current dose estimates, ISFSI operations do not pose a health threat to either workers or members of the general public.

1.0 INTRODUCTION

Prairie Island Nuclear Generating Plant (PINGP) is located in Goodhue County, Minnesota on the banks of the Mississippi River. The plant has two 575 MWe pressurized water reactors. Unit 1 began commercial operations at full power in 1973; Unit II did so in 1974. PINGP is owned by Xcel Energy Corporation and operated by Nuclear Management Company, LLC. The US Nuclear Regulatory Commission licensed an Independent Spent Fuel Storage Installation (ISFSI) to PINGP in 1993. The plant began storing spent fuel at the Installation in 1995. The ISFSI is located within the owner controlled area, in the southwestern sector of the plant site.

This report is a health risk assessment for the ISFSI at PINGP. It is part of Nuclear Management Company's petition to the State of Minnesota to increase storage capacity of spent nuclear fuel at the ISFSI. Dry cask storage of spent nuclear fuel can result in radiation exposure of workers and the public due to penetrating gamma and neutron radiation from the radioactive decay of spent nuclear fuel. Doses from inhalation of radionuclides or immersion in a radioactive plume as a result of leakage of canisters are assumed to be zero. Canisters are designed and tested to be leak tight. Thus, leakage is not considered to be a credible accident scenario.

For the purposes of radiological risk assessment and management it is assumed that any radiation dose, no matter how small may increase the risk of cancer.¹ This risk assessment is based on doses to workers and the public reported in the PINGP Safety Analysis Report and updated public doses provided by.²

1.1 Purpose of risk assessment

The purpose of risk assessment is to provide pertinent information on populations at risk, exposure patterns, radiation doses, types of health effects and probabilities of health effects to risk managers, policy makers and regulators so that the best possible decisions can be made regarding management of the risk. Risk assessment does not measure the *real* health effects that exposure to a hazardous agent may have on a population. Risk assessments may be conducted without considering what the actual exposures may be to a population considered at risk. Risk assessment particularly involving very small exposures to hazardous agents have a high degree of uncertainty but conservative safety margins are built into an assessment analysis to ensure protection of the public.

Exposure to ionizing radiation has been well characterized. Ionizing radiation can be easily measured and sources of natural background radiation are well known. The major source of ionizing radiation to human populations is inhalation of radon gas accounting for about half of the total exposure (Table 1).³ The table excludes contributions from medical exposures. When the risk assessment exercise involves very small doses of ionizing radiation, as in the present risk assessment, the contribution of the natural background becomes important in assessing overall risk and putting the additional radiation doses into appropriate perspective. Humans are exposed primarily from natural sources; non-medical anthropogenic exposures

1. Only cancer mortality risks are considered in this study. National Council on Radiation Protection and Measurements, *Risk Estimates for Radiation Protection*. NCRP Report No. 115. Bethesda, MD: NCRP; 1993.

2. Prairie Island Independent Spent Fuel Installation Safety Analysis Report, Section 7; Memo on public dose rates from Oley Nelson, PINGP to Kenneth Mossman May 30, 2007.

including exposure from the nuclear fuel cycle (of which storage of spent nuclear fuel is an end stage) provide very little additional exposure.³

Regulations to limit environmental and occupational exposures to ionizing radiation are based on the assumption that any dose, no matter how small, might cause cancer and that the relation between dose and cancer induction is linear. The biological assumptions underlying the linear, no-threshold (LNT) theory are now seriously questioned. There is now clear evidence that other biologically plausible theories are more appropriate for some tumors and carcinogens. Many scientists now believe that LNT-derived risks overestimate true risks in the low dose range.⁴

Risks are determined in a relatively straightforward manner by multiplying the dose by the LNT-derived risk coefficient. This is a conservative approach to risk assessment since direct observations of adverse health effects have not been observed in the dose range of interest in this report. As the final step in the risk assessment process, risk characterization must include careful consideration of uncertainties in risk. To do otherwise would imply that risks are known with a degree of certainty that is not borne out by the data.

Table 1. Sources of human exposure to ionizing radiation

Average worldwide exposure to radiation (excluding medical exposure)		
Source	Annual effective dose (mSv)	
	Average	Typical range
Cosmic rays	0.39	0.3-1.0
External terrestrial	0.48	0.3-0.6
Inhalation (mainly radon)	1.15	0.2-10
Ingestion	0.29	0.2-0.8
Man-made	Very small	
Total	2.4	1-10

3. United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources and Effects of Ionizing Radiation*. Volume I: Sources. UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes. New York: United Nations; 2000

4. Mossman, KL. *Radiation Risks in Perspective*. Boca Raton, FL: Taylor and Francis Publishers; 2006.

2.0 DOSES TO WORKERS AND THE PUBLIC FROM DRY CASK STORAGE

Dose assessment is important for several reasons. Dose measurements are necessary in order to make decisions on siting of the ISFSI arrays within PINGP. The arrays must be sited such that the annual dose equivalents to individuals located beyond the controlled area does not exceed 25 mrem. Dose estimation is also important in the risk assessment process. The dose estimates used in this report are based on the assumption that there is no canister leakage that would contribute to dose and that ISFSI doses are due to gamma rays and neutrons from stored spent nuclear fuel.⁵

2.1 Radionuclides contributing to dose Spent nuclear fuel contains a number of biologically important radionuclides (Table 2). Radionuclides emitting gamma rays are particularly important because the radiation is highly penetrating and depending on the amount of shielding some fraction can escape containment and expose workers and the general public. Gamma ray dose decreases exponentially with increased shielding thickness. Radionuclides that emit alpha (α) and beta (β) radiation do not pose an external hazard because the radiation cannot penetrate the canister or ISFSI shielding. However, these radionuclides are a potential health hazard if contacted directly through inhalation, ingestion or skin contact. Neutrons can also be generated due to the interaction of high energy alpha radiation with surrounding material. For instance a mixture of Am-241 alpha rays and beryllium emits neutrons. Like gamma rays, neutrons can be highly penetrating and may expose individuals at a distance from the spent nuclear fuel elements.

The highest energy gamma radiation is emitted by Cs-137. It has a short half-life relative to other biologically important radionuclides (Table 2). In consideration of permanent disposal the concern is with the radiation emissions from the very long-lived transuranics (Table 2). These radionuclides emit relatively low energy gamma radiation. Thus the radiological hazard associated with gamma radiation emission would decrease significantly over several decades due to the decay of Cs-137. Radionuclides that emit gamma radiation do not constitute that portion of spent fuel which is of greatest concern with respect to storage of spent fuel over a long duration of time.

5. *Supra* note 2.

Table 2. Biologically Significant Long-Lived Radioisotopes in Commercial Spent Fuel

RADIONUCLIDE	HALF –LIFE	PRINCIPAL RADIATION EMISSIONS
Strontium-90/Yttrium-90	28.5 y	β^- , γ
Technetium-99	213,000 y	β^-
Cesium-137	30.2 y	β^- , γ
Neptunium-237	2,140,000 y	α , γ
Plutonium-238	87.7 y	α , γ
Plutonium-239	24,131 y	α
Plutonium-241	14.4 y	β^-
Americium-241	432 y	α , γ

2.2 Dose estimates

The following dose estimates were derived from the Prairie Island Independent Spent Fuel Installation Safety Analysis Report, Section 7 and from public dose rate data provided in a memo from Oley Nelson (Dry Cask Project Engineer, PINGP) to Kenneth Mossman dated May 30, 2007. Doses in mrem are due to gamma ray and neutron exposure from radionuclide decay of spent nuclear fuel, and refer to exposure of the whole body (and maximally exposed organ). Dose estimates are conservative and assume a 2500 hour-year for full-time employees; a 540 hour-year for outage employees, a 400 hour-year for summer help and a 8760 hour- year for calculation of annual public doses.

The annual dose to workers shown in Table 3 represents the weighted average dose to all full-time, outage and summer employees in 13 plant building locations. The highest doses were to workers in the Construction Warehouse and the NPD Annex Building. The dose rate to a member of the public living at the nearest residence is assumed to be 1 mrem per year from decay of radioactive material in spent nuclear fuel. The nearest residence is estimated to be 700 meters (0.45 miles) from the ISFSI arrays in the northwest direction. This is a very conservative estimate of dose rate; direct estimates of dose rate at 700 meters from the ISFSI (in the direction of the nearest residence) is 0.36 ± 0.18 mrem/year; at 600 meters the dose rate is 0.77 ± 0.11 mrem/year.⁶

6. *Supra* note 2.

Table 3. Estimated doses to workers and the general public from ISFSI arrays

GROUP	ANNUAL DOSE	ANNUAL NATURAL BACKGROUND LEVEL
Workers: Plant Personnel	4.6 mrem	240 mrem (100-1000)
Public: Nearest Residence	1.0 mrem	

Both occupational and public dose estimates are well within applicable federal regulatory limits. The annual dose limit for workers is 5000 mrem; the annual public dose limit from all sources of exposure excluding medical applications is 100 mrem. The nearest real resident cannot receive a dose in excess of 25 mrem per year (as a single source of exposure) and assumes that individuals may be exposed to other sources of radiation that, when summed, do not exceed the 100 mrem limit.⁷

2.3 Dose comparison with natural background radiation levels

Worker and public dose estimates are well within world-wide annual average natural background radiation levels of 200-300 mrem (Table 2; 1 mSv = 100 mrem). Natural background levels around the world range from about 100 mrem per year to about 1000 mrem per year. In fact the estimated doses from the ISFSI array are so small that they are well within local variations in natural background levels. Differences in natural background radiation levels in Minnesota exceed the dose estimates in Table 3 for the ISFSI array.⁸

The average American receives about 300 millirem annually from natural sources including the sun's rays, rocks, soil, building materials and other background sources. According to the National Council on Radiation Protection and Measurements,⁹ an independent scientific body, the major sources of natural radiation exposure to the public are:

Radon in Indoor Air. Small amounts of radon-222, a radioactive gas, seep from uranium that is widely distributed in the Earth's crust. On average, radon trapped in

7. Dose limits for radiation workers may be found at 10 CFR 20; dose limits for members of the general public may be found at 10 CFR 72.104.

8. Natural background radiation levels vary across the State of Minnesota. The major source of variability is radon concentration. See <http://www.epa.gov/radon/zonemap/minnesota.htm>

9. National Council on Radiation Protection and Measurements. *Ionizing Radiation Exposure of the Population of the United States*. NCRP Report No. 93. Bethesda, MD: NCRP; 1987.

homes accounts for 55 percent of the radiation to which Americans are exposed -- approximately 200 millirem every year.

The Human Body. About 11 percent of the average person's total exposure -- an average of 39 millirem per year -- comes from the human body itself. Potassium-40 and other radionuclides found in air, water and soil are incorporated into the food we eat, then into our bodies' own tissues.

Rocks and Soil. Rocks and soil account for about 8 percent of the public's exposure to radiation from all sources, or 28 millirem per year. The exposure comes from the Earth's crust and from building materials derived from soil and rocks. Brick and cinder-block homes expose the public to more radiation than do wooden homes. Granite used to build large structures, such as Grand Central Station in New York City, also exposes the public to small amounts of radiation.

Cosmic Rays. The average person receives about 8 percent of his total exposure -- 28 millirem per year -- from cosmic radiation from outer space. Actual exposures vary, since cosmic radiation increases with altitude, roughly doubling every 6,000 feet. A resident of Denver (one mile high) receives an average dose of about 50 millirem per year from cosmic radiation; those in Leadville, Colorado., at an altitude of two miles, get a cosmic ray dose of about 125 millirem per year; while a resident of Florida (at sea level) receives about 26 millirem per year from this source. Similarly, a passenger in a jet airliner at 37,000 feet (seven miles) may receive 60 times as much cosmic radiation in a given time as does someone at sea level.

The estimate doses from the ISFSI arrays are only a tiny fraction of the dose attributable to any single component of the natural background.

3.0 HEALTH EFFECTS FROM SMALL DOSES OF IONIZING RADIATION

The principal health effect of concern following exposure to small doses of ionizing radiation is cancer induction. Ionizing radiation at high dose (above about 10,000 mrem) is a known human carcinogen. Numerous population studies involving military, medical, and occupational uses of radiation clearly show that leukemia and a variety of solid tumors may be induced by radiation. However at low doses of radiation (e.g., the dose estimates under consideration in this risk assessment) the evidence for cancer causation is much less compelling. Most low dose epidemiological studies show no consistent health effects. Only a few studies suggest a significant association between radiation and cancer. However, even in these

investigations, the causal nature of such associations and the levels of risk remain highly uncertain.¹⁰

Radiation risks for cancer have been based primarily on studies of Japanese survivors of the atomic bombings.¹¹ Excess cancers have been observed in the Japanese cohort that received doses above 20,000 mrem. Below this dose, radiogenic cancers are proportionally lower in number and have been very difficult to detect. Extrapolation of data derived from the “high” dose cohort, using the LNT theory, has been the basis for predicting cancer risk at low doses.

The four major cancer types identified in the Japanese survivors are: leukemia, lung cancer, female breast cancer and cancer of the thyroid gland. The first cancer reported was leukemia which began to appear in the exposed Japanese population a few years after the bombing. However, not all leukemia types were equally affected. Acute leukemia and chronic granulocytic leukemia were substantially increased in the exposed populations but chronic lymphocytic leukemia incidence remained unchanged in survivors. Radiation-induced solid cancers became apparent 5 to 10 years (at a minimum) after leukemia induction. Only after 1974 did the cumulative excess of solid cancers since 1950 exceed the leukemia excess. Cancers of the esophagus, stomach, urinary tract and lymphomas have also been observed in excess in the Japanese survivor studies.¹²

The Hiroshima and Nagasaki experience has formed the basis for an extensive human data base which has been used in the development of radiation risk estimates and radiation protection standards. Supplementing the atomic bomb survivor data are a large number of smaller epidemiological studies involving medical uses of radiation.¹³

4.0 RISK ESTIMATION

10. United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources and Effects of Ionizing Radiation*. Volume II: Effects. UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes. New York: United Nations; 2000

11. The largest single source of radiogenic cancer risk data is the survivors of the atomic bombings of Hiroshima and Nagasaki in August, 1945. In the Life Span Study (one of several cohort-based epidemiological studies), conducted by the Radiation Effects Research Foundation, approximately 86,000 atomic bomb survivors are being studied with mortality and causes of death continuously updated. Individuals received doses ranging from less than 10,000 mrem to more than 500,000 mrem. The average dose to survivors was approximately 20,000 mrem. Over 6,000 cancer deaths have been observed; only about 400 of these cancers might attributable to radiation exposure. See Preston, D.L. et al., Studies of mortality of atomic bomb survivors, Report 13: Solid cancer and non-cancer mortality 1950-1997. *Radiation Research* **160**: 381-407 (2003).

12. National Research Council, *Health Effects of Exposure to Low Levels of Ionizing Radiation*. BEIR V Report. Washington, DC: National Academy Press; 1990; National Research Council, *Health Risks from Exposure to Low Levels of Ionizing Radiation*. BEIR VII Report. Washington, DC: The National Academies Press; 2005.

13. *Ibid.*

Based on the dose estimates presented in Section 2.0, radiogenic cancer risks to workers and the public can be determined. The calculation is straightforward and is simply the product of the dose and risk coefficient (i.e., lifetime risk of cancer per unit radiation

dose). Several authoritative bodies have estimated cancer risks for use in radiation

protection.¹⁴ For the purposes of this risk assessment the following nominal lifetime excess cancer risk coefficients have been assumed:

5.0×10^{-7} lifetime fatal cancers per mrem for members of the public

The nominal risk to the general public is 25% higher than the worker risk because the general population includes males and females of all ages (children are more sensitive than adults). Worker populations are predominantly male between the ages of 20 and 70. Thus, worker populations exclude women and children that contribute to the collective sensitivity of the population. For purposes of this report worker risks are considered equivalent to public risks. This assumption results in a conservative estimate of harm in the worker population.

As discussed more completely in section 5.0 (Risk Assumptions and Uncertainties), risk estimates should be viewed as subject to many uncertainties including epidemiological limitations, risk extrapolation from high dose to low dose and extrapolating risks from high dose rate to low dose rate. Although risk coefficients appear to be highly quantitative and better defined than risks for most other carcinogens, there is a need to carefully interpret risk assessments based on these risk coefficients.

This risk assessment examines cancer mortality risks in the following populations:¹⁵

1. plant personnel: N = 923
2. members of the public residing at the nearest residence: N = 414

4.1 Health risks to plant personnel

14. The International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurements have general agreement on the magnitude of radiogenic cancer risks (see National Council on Radiation Protection and Measurements. *Limitation of Exposure to Ionizing Radiation*. NCRP Report No. 115. Bethesda, MD: NCRP; 1993. The U.S. National Research Council BEIR Committees also analyses scientific data and publishes risk estimates that are in general agreement with the ICRP and NCRP estimates. The risk estimates used in this report are taken from NCRP Report No. 115.

15. *Supra* note 2.

A nuclear worker on the plant site may be exposed to ionizing radiation from the ISFSI arrays. Table 4 provides estimates of risk assuming that all workers receive a weighted average dose of 4.6 mrem per year. Some workers will receive more or less depending on their employment status (full-time, outage, summer employment) and their work location. Table 4 provides estimates of risk in terms of probabilities and cancer mortality rates per 10,000 population over exposure periods ranging from 1 to 70 years. The highest risks are for workers exposed for a 70 year period (an unrealistic time frame if one assumes that work begins at age 20). Nevertheless no excess cancer deaths would be expected even for 70 years of employment given that there are fewer than 1000 persons employed at the plant. By comparison 20 percent of the worker population would be expected to die from cancer from all cancer causes.¹⁶

4.2 Health risks to members of the public at nearest residence

A member of the public located in a house about 0.45 miles northwest of the plant may be exposed to ionizing radiation from the ISFSI arrays. For the purposes of this risk assessment it is assumed that residents receive 1.0 mrem year with no air or building shielding. Table 4 provides estimates of risks (in terms of probabilities) and mortality rates (in terms of cancer deaths per 10,000 population) and are calculated for different exposure periods (1-70 years). No excess cancer deaths would be expected even if exposure were for a 70 year period since there are fewer than 500 persons residing in the immediate vicinity of the plant. By comparison about 100 persons in this population would be expected to die of cancer from all causes of cancer.¹⁷

4.3 Brief risk analysis

Numbers in Table 4 have been rounded to facilitate analysis and presentation. Because the doses are so small, the associated risks for cancer are also small and impossible to measure directly. The probabilities and the respective mortality rates (cancer deaths per 10,000) are equivalent expressions of risk. But the mortality rate may be easier to comprehend. For comparative purposes and to put the radiological risks into perspective, the probability of death from cancer and the resulting number of cancer deaths in a population of 10,000 persons are shown. The reference population size of 10,000 is arbitrary and is used to facilitate comparisons of estimated health effects over various time periods (Table 4). In fact, the actual population that lives in the immediate vicinity of the plant is estimated to be closer to 400. Clearly, if no health effects (even for a 70-year exposure) are expected among 10,000 persons, there will be no health effects in a population that is 25 times smaller.

16. American Cancer Society, *Cancer Facts & Figures 2007*. Atlanta GA: American Cancer Society Inc. 2007.

17. *Ibid.*

The number of radiogenic cancers from a 70-year exposure is minuscule compared to the total mortality cancer burden in the population from all causes of cancer that are expected in the absence of radiation exposure from the ISFSI. In a population of 10,000 persons, 2,000 would be expected to die of cancer from all causes (e.g., smoking) excluding ISFSI radiation. Likewise, in a population of 400 persons, 80 would be expected to die of cancer. Similar comparisons can be made regarding the worker population (about 900 full-time employees, outage workers and summer help).

Table 4. Cancer mortality risks to workers and members of the public

INTEGRATED RISK	Workers: Lifetime Cancer Mortality Risk	Workers: Excess cancer deaths per 10,000	Public: Lifetime Cancer Mortality Risk at nearest residence	Public: Excess cancer deaths per 10,000 at nearest residence
1 year	1/430,000	0.0 (0-0)	1/2,000,000	0.0 (0-0)
10 years	1/43,000	0.2 (0-0.4)	1/200,000	0.1 (0-0.1)
20 years	1/21,000	0.5 (0-1)	1/100,000	0.1 (0-0.2)
50 years	1/8,000	1.2 (0-2)	1/40,000	0.3 (0-0.5)
70 years	1/6,000	1.6 (0-3)	1/28,000	0.4 (0-0.7)
cancer deaths/ no radiation	1/5	2,000	1/5	2,000

Calculations of risks for 10, 20, 50 and 70 year periods simply assumed that the total dose was delivered all at once. This assumption introduces significant conservatism in the risk calculation because no accounting is made for repair of radiation damage when the dose is actually delivered at a uniform rate over the time period of interest. An instantaneous dose of 70,000 mrem would be more biologically effective than the same dose delivered uniformly over a 70 year period.

Mortality rates are also expressed as a range of possible values (numbers shown in parentheses in Table 4) based on an uncertainty analysis of lifetime cancer mortality risk estimates.¹⁸ Because of the uncertainties in risk at doses approximating natural

18. National Council on Radiation Protection and Measurements. *Uncertainties in Fatal Cancer Risk Estimates Used in Radiation Protection*. NCRP Report No. 126. Bethesda, MD: NCRP; 1997.

background radiation levels, the lower value of the range is zero.¹⁹ The most probable outcome is no increase in cancer deaths as a result of radiation exposure. It should be emphasized that the possibility of health effects at small doses cannot be totally discounted. However, if there is a risk it is so small that it cannot be measured reliably.

A (theoretical) person who lived continuously at the nearest residence for 70 years would have about a 1 in 28,000 chance of dying of cancer because of radiation exposure from the spent nuclear fuel stored at the ISFSI array. However, this same person's chance of dying of cancer without PINGP radiation exposure is about 1 in 5 (i.e., a risk that is 5600 times higher than the radiation risk). The additional risk from radiation exposure from PINGP cannot be detected because of the large number of cancer deaths that will occur because of other causes unrelated to radiation exposure.

5.0 RISK ASSUMPTIONS AND UNCERTAINTIES

A number of key principles have emerged in the study of cancer in exposed human populations that bear on interpretation of risk assessment data:

- Cancer is a very common collection of diseases. Incidence and mortality rates vary significantly among cancer types but when all cancer are considered collectively roughly one in three individuals will get cancer and about one in five will die of cancer (in the U.S.).
- Radiation induced cancers are indistinguishable from the spontaneous or naturally occurring cancers. Breast cancer induced by ionizing radiation is indistinguishable from breast cancer that appears spontaneously.
- Cancer has a long latent period that extends from years to a few decades. Lung cancer is thought to appear about 20 years after the beginning of smoking.
- Various host factors influence cancer risk including gender and age. Children are considered at higher risk because they are young enough to live beyond the cancer latent period. Individuals exposed at age 70 have a minimal risk because they are not likely to live beyond the latency period to express disease.

¹⁹. *Supra* note 12. BEIR V Report.

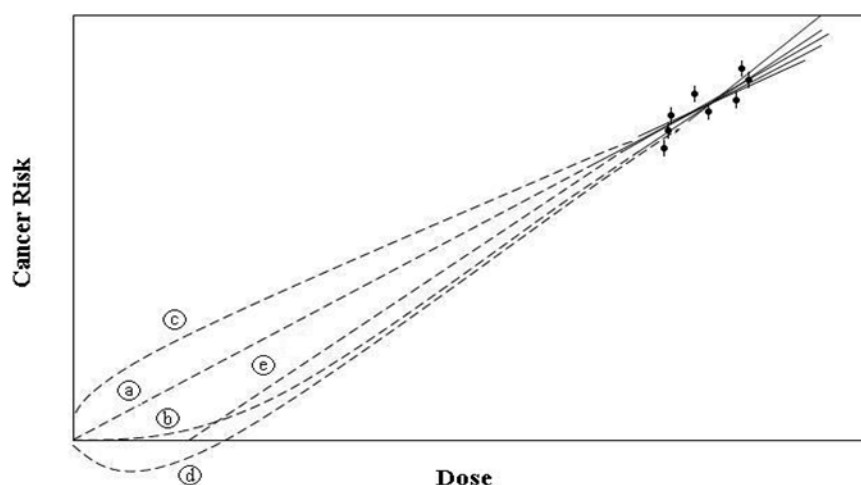
These principles make detection of small cancer risks extremely difficult to measure and to interpret. The multi-year latency period requires long term study of populations for which follow-up may be difficult. The high spontaneous rates of cancer may make it nearly impossible to detect radiation induced cancers (the signal) from the large number of spontaneous cancers that occur in the absence of radiation (the noise).

Risks at very small doses of ionizing radiation are theoretically determined and are highly uncertain. Risk estimates should be interpreted with great caution. Understanding and communicating very small risks must consider sources of uncertainty. Two major sources of uncertainty are considered below:

5.1 Estimating risks using the LNT predictive theory

Risks are uncertain in part because of lingering questions about the appropriateness of the LNT theory to predict risks at small doses.. This theory argues that any exposure to radiation is harmful, and one can calculate the probability of cancer from a linear extrapolation of observed cancer at high radiation exposures. This philosophy has led to the widespread belief that there is no safe dose of radiation and that regulations should establish exposure limits as low as possible if not zero.

Figure 1. Possible shapes of dose-response curves in risk assessment:



There are several biologically plausible theories that could be used in risk assessment. Figure 1 compares (a) linear, no threshold, (b) sub-linear, (c) supra-linear, (d) hormesis or U-shape, and (e) threshold dose-response theories. As shown, the different curves fit the data equally well at high doses but predict very different risks at low doses. The data points (with error bars) and the solid lines represent the region of direct observations; the dotted lines represent theoretical risk projections. Other theories predict risks that may be higher or lower than LNT derived risks. In fact, the range of risk prediction at low doses is quite wide and includes the prediction of beneficial effects (hormesis prediction). Selecting a particular theory to the exclusion of alternatives is problematic because observations in the low dose range are inadequate to support a clear choice. There is now considerable evidence to suggest that the LNT theory overestimates risk in the low dose range. If the LNT theory overestimates risk, then estimates of population health effects would be too high and actual detriment would be lower than predicted. In a 2001 report, the National Council of Radiation Protection and Measurements admitted that there is substantial evidence against LNT but nevertheless continues to endorse LNT by concluding that no other theory was more plausible than LNT. In 2005, the National Research Council's BEIR VII Committee drew similar conclusions.²⁰

5.2 Dose extrapolation and detection limits in epidemiology

20. *Supra* note 12. BEIR VII Report; National Council on Radiation Protection and Measurements. *Evaluation of the Linear Nonthreshold Dose-Response Model for Ionizing Radiation*. NCRP Report No. 136. Bethesda, MD: NCRP; 2001.

Dose extrapolation is also a serious source of uncertainty. For most carcinogens (including ionizing radiation) very large doses of the agent are needed in order to observe a statistically significant increase in cancer. This is because small doses typically encountered in environmental and occupational settings are associated with very low risks of cancer and, in the absence of any exposure, cancer occurs at a very high rate naturally (about 1 in 3 Americans will get cancer).

Predicting radiogenic health effects at environmental and occupational exposure levels requires that directly observable dose response data be extrapolated 2-3 orders of magnitude (i.e., 100-1000 times).²¹ This degree of dose extrapolation strains the credibility of risk assessment at low dose and is comparable to the dose extrapolations used to "demonstrate" the human cancer-causing effects of commonly occurring chemicals including cyclamates, saccharin, Alar, and ethylene dibromide (EDB) based on laboratory animal data. Accordingly, numbers of cancer deaths due to low doses of carcinogens must be considered speculative; risk estimates at low dose have great uncertainties because they are theoretically derived. For ionizing radiation the possibility that there may be no health risks from doses comparable to natural background radiation levels cannot be ruled out; at low doses and dose rates, the lower limit of the range of statistical uncertainty includes zero.²²

Dose estimates (Table 3) suggest that radiogenic risks are so small that they cannot be measured reliably. Figure 2 identifies the size of the population necessary to detect a significant risk at a given radiation dose (1 mSv = 100 mrem). The solid line is the boundary that defines the population size-dose space. Population sizes to the right of the boundary will be large enough to detect a significant risk for a given dose. Populations to the left of the boundary are too small to detect a radiogenic risk. To illustrate, examples of large populations exposed to small doses of radiation are plotted as points on the graph.²³ Except for the Japanese survivors that include those that received relatively high doses, no population group shown is large enough to detect significant risk.²⁴ An epidemiological study designed to detect an increased

21. Cancer risks are statistically significant at radiation doses of 20,000 mrem and higher based on analysis of Japanese atomic bomb survivor data. The doses used to calculate risks in Table 3 of this report range from about 80 to 330 mrem when integrated over 70 years.

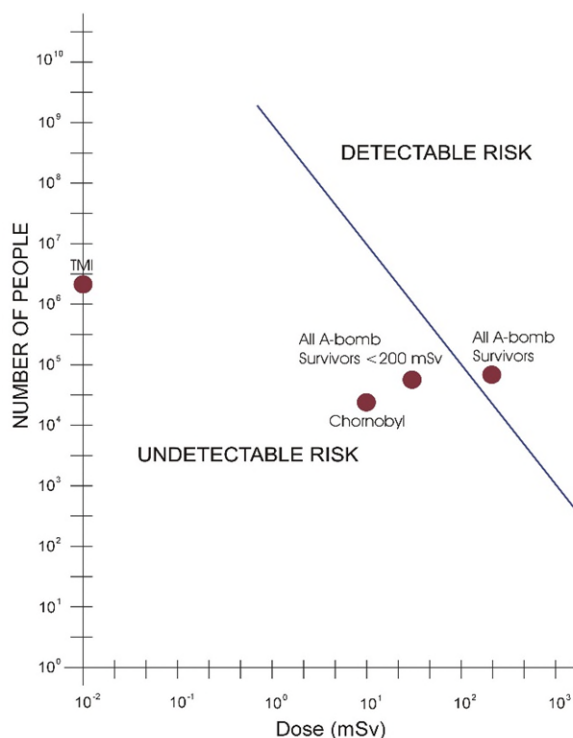
22. *Supra* note 12. BEIR V Report.

23. The point identified as "all A-bomb survivors" represents about 86,000 Japanese survivors who received an average dose of 20,000 mrem in 1945. The point identified as "all A-bomb survivors <200 mSv" refers to the 65,000 A-bomb survivors who received doses less than 20,000 mrem. The point identified as "Chornobyl" refers to the 30,000 workers who received an average dose of about 10,000 mrem as a consequence of the Chornobyl nuclear plant accident in 1986. The point identified as "TMI" refers to the 2 million members of the general public who received about 1 mrem as a consequence of the nuclear power plant accident at TMI in 1979.

24. Significant increased cancer mortality in Japanese survivors receiving more than 20,000 mrem has been reported. The majority of reports of health studies of Pennsylvania residents near TMI report no elevated risks of cancer that could be attributed to radiation exposure. There have been reports of elevated thyroid cancer in children near

health risk in a population exposed to 4.6 mrem per year for 70 years (see Tables 3 and 4) would require a population of about 500 million persons or almost twice the size of the current U.S. population (Figure 2). Obviously it is not possible to detect such small risks.

Figure 2. Large populations are needed to detect very small radiogenic risks.



6.0 RISKS IN PERSPECTIVE

An integral part of the risk assessment and risk management exercise is framing and communicating risks. In some ways this represents the most challenging part of risk analysis. If expressed improperly, risk information can result in misunderstandings and incorrect messages that may lead to inappropriate risk management decisions.

Risk assessment is primarily carried out by scientists who may be quite detached from the real world activities that involve the risks they are studying. They often express risks in ways that are not understandable by the public. In addition to assessing risk, scientists have a responsibility to distill scientific and technical information into a

Chornobyl. However thyroid doses were quite high due to the concentration of radioactive iodine by the thyroid gland. Otherwise there have been no consistent reporting of health detriment in the Chornobyl populations.

package that can be readily comprehended by risk managers and the public. Risk managers similarly must be able to effectively communicate highly technical information in easily understandable terms for policy makers and the public. Unless workers and the public have a clear understanding of the risks and how the risks are managed they may be reluctant to buy into the technology and any particular risk reduction strategy.

6.1 Speculation Versus Reality

Using LNT theory to calculate health effects of exposure to very small doses of carcinogens is now so ingrained that real risks are no longer distinguishable from calculated, theoretical risks. Body bags are viewed the same whether they are real or calculated. Unwillingness to distinguish reality from speculation poses enormous problems in risk assessment and management. The idea that no dose is safe, and concerns for “trivial risks” has contributed to a system of increasingly restrictive regulations.

The idea that any dose is potentially harmful has led to unwarranted fears about radiation. In one survey of primary care physicians in Pennsylvania, 59% of the doctors identified fear of radiation as the primary reason for their patients’ refusal of mammography examinations. Women who refuse mammography may be denying themselves an important medical benefit by compromising early detection and the subsequent management of disease. Following the Chernobyl accident in 1986, the International Atomic Energy Agency estimated 100,000-200,000 Chernobyl-related induced abortions in Western Europe. In Greece, as in other parts of Europe, many obstetricians initially thought it prudent to interrupt otherwise wanted pregnancies or were unable to resist requests from worried pregnant women in spite of the fact that doses were much lower than necessary to produce *in utero* effects.²⁵

6.2 Communicating Risks

Risk communication is important because public perceptions of risk do not always match the actual risks. People fear the wrong things. We fret about activities that involve small risks and do not pay enough attention to risks that are significant and about which we can do something about. Consider automobile travel and airplane travel. Many people will not fly but have no hesitancy about getting into a car. In the 1990s Americans were, on a mile for mile basis, 37 times more likely to die in a car

25. Fear of radiation-induced cancer or other health effects is one of many factors that might be considered by individuals who decline medical x-ray procedures and by pregnant women who elect to have abortions. For instance, women also decline to have mammography procedures because of the cost of the procedure or pain and discomfort. See Albanes, D. et al. A survey of physicians’ breast cancer early detection practices. *Preventive Medicine* **17**: 643-652; 1988. Trichopoulos, D. et al. The victims of Chernobyl in Greece: Induced abortions after the accident. *British Medical Journal* **295**: 1100; 1987.

crash than on a commercial airliner. Commercial airline travel is so safe that the chances of dying in any flight are less than tossing heads twenty-two times in succession.²⁶ Although the risks are substantially higher for automobile travel, people do not seem to think the risks are anything to worry about. According to the National Highway Traffic Safety Administration, automobile traffic safety belts save about 9,500 lives per year. When used properly seat belts reduce fatal injury risk to front seat car passengers by 45%. More than 25% of Americans do not use seat belts.

Cigarette smokers who worry about radiation from mammograms or chest X-rays have perceptions of risk that are not congruent with what we actually know about these risks. There is no evidence that chest X-rays and mammograms kill anyone. However, cigarettes kill more than 400,000 people every year from cancer and heart disease. Certainly whether the risk is considered voluntary or controllable impacts how it is perceived. There is substantial literature on the subject of risk perception.²⁷

The Health Physics Society²⁸ has issued two relevant position statements. The first statement titled “Radiation Risk in Perspective” concludes that although there is substantial and convincing scientific evidence for health risks following high-dose exposures, below 5,000-10,000 mrem risks are either too small to be observed or are nonexistent. The Society recommends that below 5000 mrem in one year or a lifetime dose of 10,000 mrem above natural background risk estimates should not be used. Expressions of risk should only be qualitative, that is, a range based on the uncertainties in estimating risk emphasizing the inability to detect any increased health detriment (that is, zero health effects is a probable outcome).²⁹ In the second statement titled “Ionizing Radiation –Safety Standards for the General Public” the Health Physics Society supports the establishment of an acceptable dose of radiation of 1 mSv/y (100 mrem/y) above the annual natural radiation background. At this dose, risks of radiation-induced health effects are either nonexistent or too small to be observed.³⁰

26. Myers, D.G. Do we fear the right things? *Skeptical* **10** (1): 56-57; 2003.

27. Slovic, P. *The Perception of Risk*. London: Earthscan Publications, Ltd. 2000.

28. The Health Physics Society is a nonprofit scientific professional organization whose mission is excellence in the science and practice of radiation safety. The Society has approximately 6000 scientists, physicians, engineers, lawyers, and other professionals. Society activities include encouraging research in radiation science, developing standards, and disseminating radiation safety information. Society members are involved in understanding, evaluating and controlling the potential risks from radiation relative to the benefits.

29. Health Physics Society, Radiation Risk in Perspective, Position Statement of the Health Physics Society. *Health Physics News* **XXXII** (10): 15-16; October 2004.

30. Health Physics Society, *Ionizing Radiation –Safety Standards for the General Public*. Accessed at <http://hps.org/documents/publicdose03.pdf>

APPENDIX G

PRAIRIE ISLAND UPDATED ISFSI RISK ASSESSMENT

**Technical Evaluation SL-018467
Revision 0**

Prairie Island Updated ISFSI Risk Assessment

Prairie Island Nuclear Generating Plant

☐ Safety-Related ☒ Non-Safety-Related

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Technical Evaluation SL-018467
Revision 0
Prairie Island Updated ISFSI Risk Assessment
Prairie Island Nuclear Generating Plant

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Purpose

The purpose of the Risk Assessment is to provide pertinent information on populations at risk, exposure patterns, radiation doses, types of health effects and probabilities of health effects to risk managers, policy makers and regulators so that the best possible decisions can be made regarding management of the risk associated with the ISFSI (Reference 1). Risk assessments are theoretical exercises designed to present different risk scenarios, and as a result, the Risk Assessment is not intended to predict the actual health effects on any particular individual resulting from the Project. Further, risk assessments, particularly those involving very small exposures to hazardous agents, have a high degree of uncertainty. For that reason, conservative safety margins are built into any risk assessment to ensure protection of the public.

As the proposed ISFSI expansion is an increase in the existing fuel storage, the Risk Assessment continues to be informative. The two sections of Reference 1 appropriate for an update are Section 2.2 and Section 4. Section 2.2 discusses the yearly doses to workers and to members of the public at the nearest residence. Section 4 estimates the radiogenic cancer risks to the workers and to members of the public.

Section 2.2 (Dose Estimates) Update

The following worker and public doses were determined using the dose rate and dose information from Reference 2. Annual background dose is from Reference 1. Doses in mrem are due to gamma ray and neutron exposure from radionuclide decay of spent nuclear fuel in dry casks on the ISFSI pads. The annual dose to the nearest resident includes dose contributions due to reactor operations, however, this contribution to the annual dose is not significant. Dose estimates are conservative and assume a 2500 hour-year for full-time employees and a 8760 hour-year for calculation of annual public doses.

The yearly doses in Table 3 are based on dose rates that occur when the ISFSI is fully loaded (48 casks in the original ISFSI and 51 casks in the ISFSI expansion) (Reference 2). Before the ISFSI is fully loaded, the doses to workers and the nearest resident will be lower than the doses in Table 3. After the ISFSI is fully loaded and the spent nuclear fuel continues to decay, the doses to the workers and the nearest resident will be lower than the doses in Table 3 and continue to decrease over time. The annual dose to workers shown in Table 3 represents the average dose to a full-time employee due to the ISFSI expansion. The average dose is determined by calculating the average dose rate (i.e., $1.09\text{E-}01$ mrem/hr) using the dose rates in column 6 of Table 3-17 of Reference 2 and multiplying the average dose rate by 2500 hours (i.e., $1.09\text{E-}01$ mrem/hr \times 2500 hours/yr). The annual dose to a member of the public shown in Table 3 represents the dose to a member of the public living at the nearest residence. The annual dose to a member of the public is taken from Table 6-1 of Reference 2 (i.e., 22.11 mrem/yr) and is rounded up. Due to the conservative assumptions and methodologies (discussed in Reference 2), the actual annual doses to the nearest residence and worker are expected to be less than the doses in Table 3.

Table 3. Estimated Doses to Workers and the General Public from ISFSI Arrays

Group	Annual Dose	Annual Natural Background Level
Workers: Plant Personnel	273 mrem	240 mrem (100-1000)
Public: Nearest Residence	23 mrem	

Both occupational and public dose estimates are within applicable federal regulatory limits. The annual dose limit for workers is 5000 mrem. The nearest real resident cannot receive a dose in excess of 25 mrem per year due to nuclear fuel cycle operations (Reference 2).

Section 4 (Risk Estimation) Update

The nominal lifetime excess cancer risk coefficient used in this Risk Assessment Update is 5.0×10^{-7} lifetime fatal cancers per mrem for members of the public. As discussed in Reference 1, the nominal risk to the general public is 25% higher than the worker risk so the use of the same coefficient for workers results in a conservative estimate of harm in the worker population. Table 4 of Reference 1 presented calculated cancer mortality risks to workers and members of the public for the initial ISFSI. An updated Table 4 which reflects the expanded ISFSI is provided below.

Table 4. Cancer Mortality Risks to Workers and Members of the Public

Risk of Dying of Cancer	Workers: Lifetime Cancer Mortality Risk Percentage (%)	Workers: Cumulative Cancer Deaths per 10,000	Public: Lifetime Cancer Mortality Risk at Nearest Residence (%)	Public: Cumulative Cancer Deaths per 10,000 at Nearest Residence
Cancer Deaths, No ISFSI Radiation	20.0000	2000	20.0000	2000
1 Year of ISFSI Radiation	20.0137	2001 (0-3)	20.0012	2000 (0-0)
10 Years of ISFSI Radiation	20.1365	2014 (0-27)	20.0115	2001 (0-2)
20 Years of ISFSI Radiation	20.2730	2027 (0-55)	20.0230	2002 (0-5)
50 Years of ISFSI Radiation	20.6825*	2068 (0-137)*	20.0575	2006 (0-12)
70 Years of ISFSI Radiation	20.9555*	2096 (0-191)*	20.0805	2008 (0-16)
*As discussed in Reference 1, 50 and 70 years for worker exposure duration is an unrealistic time frame if one assumes that work begins at age 20				

The risk percentages presented in Table 4 are conservative. The actual risks are expected to be lower. As discussed in Reference 1, calculations of risks for 10, 20, 50 and 70 year periods simply assumed that the total dose was delivered all at once. This assumption introduces significant conservatism in the risk calculation because no accounting is made for repair of radiation damage when the dose is actually delivered at a uniform rate over the time period of

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interest. Additionally, as discussed in the Section 2.2 Update, the doses in Table 3 are the maximum doses that will occur when the ISFSI is fully loaded. Table 4 conservatively assumes the workers and all members of the public are exposed to the maximum dose (when the ISFSI is fully loaded) for all the years of exposure to radiation from the ISFSI.

Mortality rates are also expressed as a range of possible values (numbers shown in parentheses in Table 4) based on an uncertainty analysis of lifetime cancer mortality risk estimates. Because of the uncertainties in risk at doses approximating natural background radiation levels, the lower value of the range is zero. The most probable outcome is no increase in cancer deaths as a result of radiation exposure (Reference 1).

A person who lived continuously at the nearest residence for 70 years, receiving the maximum dose from a fully loaded ISFSI each year, would have an additional 0.08% chance of dying of cancer due to radiation from the ISFSI. This same person's chance of dying of cancer without Prairie Island Nuclear Generating Plant ISFSI related radiation exposure is about 20%.

References

- 1) Certificates of Need Application Appendix F, Prairie Island ISFSI Risk Assessment, Kenneth Mossman, 2007
- 2) SL-018015, Revision 0, Dose Study to Support ISFSI Certificate of Need

APPENDIX H

RADIATION PRIMER

RADIATION PRIMER

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1.0 INTRODUCTION

This is a brief primer on radiation for readers who do not have a technical background in radiation science but require some knowledge about radiation, its public health impacts, and how it is controlled.¹ This primer covers the following subject material: characteristics of ionizing radiation, quantities and units used to measure radiation, sources of radiation, public health effects, and principles of radiation safety.

Radiation is an integral part of life. We live in a world in which radiation is naturally present everywhere. Light and heat from nuclear reactions in the Sun are essential to our existence. Radioactive materials occur naturally throughout the environment, and our bodies contain radioactive materials such as carbon-14, potassium-40 and polonium-210 quite naturally. All life on Earth has evolved in the presence of radiation. Without radiation life on Earth as we know it would not exist.

Radiation also can be made by man. This includes hundreds of beneficial uses, including medical X-rays, nuclear medicine pharmaceuticals, television sets and electricity generation from nuclear power plants. Man-made radiation is basically no different from naturally occurring radiation. But, unlike natural background radiation, the use and handling of man-made radiation is strictly controlled and regulated. Most of the public's exposure to man-made radiation comes as a result of medical X-rays, as well as other medical diagnostic treatments using radioactive materials. Nuclear power operations including storage of spent nuclear fuel exposes the population to only a tiny amount of radiation.

2.0 WHAT IS IONIZING RADIATION?

Radiation may be defined as the transport of energy in the form of waves or particles through space. Radiation can be classified according to the effects that are produced when radiation interacts with matter. *Ionizing radiation* (e.g. cosmic rays, X rays and the radiation from radioactive materials) have sufficient energy to ionize the irradiated material. *Non-ionizing radiation* (e.g., ultraviolet light, radiant heat, radio waves and microwaves) have insufficient energy to cause ionization but, nonetheless may cause damage through other physico-chemical processes. In this

1. This paper is based on various publications from the Nuclear Energy Institute and by the International Atomic Energy Agency. The Nuclear Energy Institute has developed a series of primers and reports for non-technical audiences. These may be found at: <http://www.nei.org/index.asp?catnum=1&catid=6>

The International Atomic Energy Agency has published an excellent document titled *Radiation, People and the Environment*. It may be accessed at: http://www.iaea.org/Publications/Booklets/RadPeopleEnv/pdf/radiation_low.pdf

primer only ionizing radiation is considered. Ionizing radiation is produced by radioactive materials that are key components in the nuclear fuel used in electricity generation in nuclear power plants.

2.1 Radionuclides and radioactivity

Radionuclides (nuclides that are radioactive and emit radiation) are an important source of ionizing radiation. Atoms can be characterized by the composition of the atomic nucleus. *Nuclides* are defined as a species of atom with a given number of protons and neutrons in the nucleus. Chemical and physical properties of a nuclide are determined by the number of neutrons and protons in the nucleus. All nuclides with the same number of protons in the nucleus (but different numbers of neutrons) are called *isotopes* and share the same chemical properties.

Although many nuclides are stable, most are not. An unstable nuclide is called a *radionuclide*. Stability is determined mainly by the balance between the number of neutrons and protons a nuclide contains. Smaller stable nuclides have about equal numbers of protons and neutrons; larger stable nuclides have slightly more neutrons than protons. Radionuclides with too many neutrons are unstable and tend to transform themselves to a more stable structure by converting a neutron to a proton: this process, known as beta decay, results in the emission of a negatively charged electron called a *beta particle*. Radionuclides with too many protons are also unstable and convert the excess protons to neutrons in a different form of beta decay; they lose positive charge through the emission of a *positron*, which is a positively charged electron.

These transformations often leave the nucleus with excess energy that it loses as *gamma rays* — high energy *photons*, which are discrete parcels of energy without mass or charge. The spontaneous transformation of a radionuclide is called *radioactivity*, and the excess energy emitted is a form of ionizing radiation. The act of transformation is termed *radioactive decay*.

Some very heavy radionuclides decay by producing an *alpha particle* consisting of two protons and two neutrons. Identical with a nucleus of helium, the alpha particle is much heavier than the beta particle and carries two units of positive charge.

2.2 Alphas, betas, gammas and neutrons

Alpha particles, beta particles, gamma rays and neutrons are products of the decay of radionuclides important in nuclear power plant operations. Nuclear fuel contains radionuclides that produce these forms of ionizing radiation:

Alpha radiation is a positively charged helium nucleus emitted by large, unstable nuclei. It is a relatively massive particle, but it only has a short range in air (1–2 cm) and can be absorbed completely by paper or skin. Alpha radiation can, however, be hazardous if it enters the body by inhalation or ingestion because large exposures can occur in nearby tissues, such as the lining of the lung or stomach.

Beta radiation is an electron emitted by an unstable nucleus. Beta particles are much lighter than alpha particles and can penetrate further into materials or tissue. Beta radiation can be absorbed completely by sheets of plastic, glass, or metal. It does not normally penetrate beyond the top layer of skin. However large exposures to high-energy beta emitters can cause skin burns. Such emitters can also be hazardous if inhaled or ingested.

Gamma radiation is a very high energy photon (a form of electromagnetic radiation like light) emitted from an unstable nucleus that is often emitting a beta particle at the same time. Gamma radiation causes ionization in atoms when it passes through matter, primarily due to interactions with electrons. It can be very penetrating and only a substantial thickness of dense materials such as concrete, steel or lead can provide good shielding. Gamma radiation can therefore deliver doses to internal organs without inhalation or ingestion.

Neutron radiation is a neutron emitted by an unstable nucleus, in particular during atomic fission and nuclear fusion. Apart from a component in cosmic rays, neutrons are usually produced artificially. Because they are electrically neutral particles, neutrons can be very penetrating. Neutrons interact with matter or tissue in complex ways including collisions with protons (i.e., hydrogen atoms) and can cause the emission of beta and gamma radiation if the neutron is absorbed by an atomic nucleus. Neutron radiation therefore requires heavy shielding to reduce exposures.

3.0 RADIATION QUANTITIES AND UNITS

Ionizing radiation cannot be detected by our senses. But indirect methods are available that take advantage of the fact that ions are produced when radiation interacts with matter. Common methods of detection include *photographic films*, *Geiger–Müller tubes*, and *scintillation counters*, as well as newer techniques using *thermoluminescent materials* and *silicon diodes*. Measurements can be interpreted in terms of the energy that the radiation deposited throughout the human body or in a particular part of the body. When direct measurements are not possible (e.g., a radionuclide is deposited in an internal organ like the liver) the dose absorbed by that organ can be calculated provided that the amount of activity retained in the

organ is known. The amount of energy that ionizing radiation deposits in a unit mass of matter, such as human tissue, is called the *absorbed dose*. It is expressed in a unit called the rad, where 1 rad is equal to 100 erg² per gram. Submultiples of the rad are often used, such as the millirad (mrad), which is one-thousandth of a rad.

Types of ionizing radiation differ in the way in which they interact with biological materials, so that equal absorbed doses (meaning equal amounts of energy deposited) do not necessarily have equal biological effects. For instance, 1 rad to tissue from alpha radiation is more harmful than 1 rad from beta radiation because an alpha particle, being slower and more heavily charged, loses its energy much more densely along its path. In order to put all the different types of ionizing radiation on an equal basis with respect to their potential for causing harm, the quantity *equivalent dose* is used. It is expressed in a unit called the rem. Submultiples of the rem are commonly used, such as the millirem (mrem), which is one-thousandth of a rem. Equivalent dose is equal to the absorbed dose multiplied by a factor that takes into account the way in which a particular type of radiation distributes energy in tissue. For gamma rays, X rays, and beta particles, this radiation-weighting factor is set at 1, so the absorbed dose and equivalent dose are numerically equal. For alpha particles, the factor is set at 20, so that the equivalent dose is 20 times the absorbed dose. Values of the radiation weighting factor for neutrons of various energies range from 5 to 20. Equivalent dose accounts for differences in radiation effectiveness to cause biological harm. The equivalent dose provides an index of the likelihood of harm to a particular tissue or organ from exposure to various types of radiation regardless of their type or energy. Accordingly, 1 rem of alpha radiation to the lung, for example, would create the same risk of inducing fatal lung cancer as 1 rem of beta radiation (although the absorbed doses are very different).

Tissues and organs also vary in their sensitivity to radiation induced harm. For a given effective dose one tissue may be more sensitive than another. For example, the risk of fatal malignancy per unit equivalent dose is lower for the thyroid than for the lung. Moreover, there are other important types of harm such as non-fatal cancers or the risk of serious hereditary damage caused by irradiation of the testes or ovaries. These effects are different both in kind and in magnitude and we must take them into account when assessing the overall detriment to the health of human beings arising from exposure to radiation. Differences in tissue and organ radiosensitivity may be accounted for by taking the equivalent dose in each of the major tissues and organs of the body and multiplying it by a weighting factor related to the risk associated with that tissue or organ. The sum of these weighted

2. An erg is the metric unit of energy.

equivalent doses is a quantity called the *effective dose*. This quantity permits the various dose equivalents in the body to be represented as a single number. The effective dose also takes account of the energy and type of radiation, and therefore gives a broad indication of the detriment to health. Moreover, it applies equally to external and internal exposure and to uniform or non-uniform irradiation. It is common to abbreviate effective dose to *dose*.

It is sometimes useful to have a measure of the total radiation dose to groups of people or a whole population. The quantity used to express this total is the *collective effective dose* or just *collective dose*. It is obtained by adding, for all exposed people, the effective dose that each person in that group or population has received from the radiation source of interest. For example, in the United States the effective dose from all sources of radiation is, on average, 360 mrem (or 0.36 rem) in a year. Since the U.S. population is about 300 million, the annual collective effective dose to the whole U.S. population is the product of these two numbers, about 110 million *man rem*. The collective effective dose concept is very useful in describing trends in population exposures over time (e.g., doses to a worker population at a nuclear power plant over a 10 year period), and in comparing (population) exposures from different radiation sources. The concept however has its limitations. It should not be used to calculate probabilities of health effects in large populations from very small individual doses.

4.0 SOURCES OF RADIATION

Humans are exposed to radiation from outer space and from radionuclides in the Earth's crust. Radiation also comes from man-made sources. Natural sources of radiation, account for 82 percent of the radiation to which the public is exposed every year. There is no evidence of any increase in cancer among people living in areas where natural, background radiation is several times higher than average such as Han (China), Kerala (India) or Araxa-Tapira (Brazil).

The average American receives 360 mrem of radiation each year. Three hundred mrem come from natural sources: the sun's rays, rocks, soil, building materials and other background sources. The other 60 mrem come from human activities and products, like medical/dental X-rays and consumer products. According to the National Council on Radiation Protection and Measurements (NCRP),³ an independent scientific body, the major sources of radiation exposure to the public are:

3. National Council on Radiation Protection and Measurements. *Ionizing Radiation Exposure of the Population of the United States*. NCRP Report No. 93. Bethesda, MD: NCRP; 1987.

Natural Radiation: Radon in Indoor Air. Small amounts of radon-222, a radioactive gas, seep from uranium that is widely distributed in the Earth's crust. On average, radon trapped in homes accounts for 55 percent of the radiation to which Americans are exposed -- approximately 200 mrem every year.

Natural Radiation: The Human Body. About 11 percent of the average person's total exposure -- an average of 39 mrem per year -- comes from the human body itself. Potassium-40 and other radionuclides found in air, water and soil are incorporated into the food we eat, then into our bodies' own tissues.

Natural Radiation: Rocks and Soil. Rocks and soil account for about 8 percent of the public's exposure to radiation from all sources, or 28 mrem per year. The exposure comes from the Earth's crust and from building materials derived from soil and rocks. Brick and cinder-block homes expose the public to more radiation than do wooden homes. Granite used to build large structures, such as Grand Central Station in New York City, also exposes the public to small amounts of radiation.

Natural Radiation: Cosmic Rays. The average person receives about 8 percent of his total exposure -- 28 mrem per year -- from cosmic radiation from outer space. Actual exposures vary, since cosmic radiation increases with altitude, roughly doubling every 6,000 feet. A resident of Denver (one mile high) receives an average dose of about 50 mrem per year from cosmic radiation; those in Leadville, Colorado, at an altitude of two miles, get a cosmic ray dose of about 125 mrem per year; while a resident of Florida (at sea level) receives about 26 mrem per year from this source. Similarly, a passenger in a jet airliner at 37,000 feet (seven miles) may receive 60 times as much cosmic radiation in a given time as does someone at sea level.

Man-Made Radiation: Medical Procedures. The average American receives about 15 percent of his/her exposure to radiation from X-rays and nuclear medicine procedures -- an average of 45 mrem per year. A typical chest x-ray results in a 10 mrem dose. The contribution from medical sources is increasing rapidly. There were approximately 3 million CT examinations conducted yearly about 25 years ago; now (in 2007) about 60 million CT exams are performed per year. The NCRP is currently revising its estimate of the contribution of medical exposures and now

suggests that about 45% of a person's exposure to radiation is from medical sources.⁴

Man-Made Radiation: Consumer Products. The average American receives about 3 percent of his total exposure to radiation from consumer products, or approximately 9 mrem per year. Radon in natural gas used in cooking ranges contributes about five mrem per year. Smaller exposures can come from some smoke detectors, which use americium-241, and television sets. The use of lawn fertilizer can also expose an individual to radiation. Fertilizer contains potassium, of which a tiny amount is potassium-40, a naturally radioactive material.

Man-Made Radiation. Nuclear Power and Other Sources. Individuals are exposed to tiny amounts of radiation -- less than 1 percent of their total exposure -- from a variety of other activities. This includes radiation exposure from nuclear power plant operations, exposure due to fallout from past atmospheric testing of nuclear weapons, and from the generation of electricity from coal-fired and geothermal power plants.⁵ Nuclear power plant operations do not expose people living near the plants to more than tiny amounts of radiation. Americans on average get less than 0.1 mrem from nuclear power plants per year. This includes radiation from storage of spent nuclear fuel. Extensive epidemiological studies of cancer in populations living near nuclear power plants indicate no long term effects that could be attributed to radiation exposure from nuclear plant operations.⁶

5.0 RADIOLOGICAL HEALTH EFFECTS

Scientists have studied the effects of radiation for more than 100 years, and they know a great deal about how to detect, monitor and control even the smallest amounts. In fact, more is known about the health effects of radiation than about most other physical or chemical agents.

5.1 Interactions of radiation with matter

Health effects of radiation exposure start with the deposition of radiation energy in cells, tissues and organs. When radiation passes through matter, it deposits energy in the material concerned. Alpha and beta particles, being electrically charged, deposit energy through *electrical interactions* with electrons in the material. Gamma

4. NCRP Scientific Committee 6-2 analysis of medical exposures. In: Advanced in Radiation Protection in Medicine, pp. 9-10, 43rd Annual meeting of the National Council on Radiation Protection and Measurements, Arlington, VA, April 16-17, 2007. Available at: http://www.ncrponline.org/Annual_Mtgs/2007_Ann_Meet_Prog.pdf

5. Coal-fired and geothermal power plants release radioactive material into the environment from naturally occurring radioactive materials.

6. Jablon, S. et al. *Cancer in Populations Living Near Nuclear Facilities*. NIH Publication 90-874. Washington, DC: U.S. Government Printing Office; 1990.

rays and X rays lose energy in a variety of ways, but each involves liberating atomic (orbiting) electrons, which then deposit energy in interactions with other electrons. Neutrons also lose energy in various ways, the most important being through collisions with hydrogen atoms (a single proton in the nucleus). The protons are then set in motion and, being charged, they again deposit energy through electrical interactions. So in all cases, the radiation ultimately produces electrical interactions in the material.

The process by which a neutral atom or molecule becomes charged is called *ionization* and the resulting entity an *ion*. Once removed from an atom, an electron may in turn ionize other atoms or molecules. Any radiation that causes *ionization* — either directly, as with alpha and beta particles or indirectly as with gamma rays, X rays, and neutrons — is known as ionizing radiation.

It is the initial ionization and the resulting chemical changes that cause harmful biological effects. Radiation causes damage at the cellular level. Cells are the basic building blocks of all tissues and organs. When ionizing radiation traverses the cell, damage to a variety of molecules and cell structures may occur depending on the dose. A particularly important molecular target is DNA or deoxyribonucleic acid. This is the master molecule that controls all critical functions of the cell. Damage to DNA can result in death of the cell or mutations that can perturb cell functions.

A most important property of the various types of ionizing radiation is their ability to penetrate matter. The depth of penetration for a particular type of radiation increases with its energy, but varies from one type of radiation to another for the same amount of energy. With charged particles such as alpha and beta particles, the depth of penetration also depends on the mass of the particle and its charge. For equal energies, a beta particle will penetrate to a much greater depth than an alpha particle. Alpha particles can scarcely penetrate the dead, outer layer of human skin; consequently, radionuclides that emit them are not hazardous unless they are taken into the body through breathing or eating or through a skin wound. Beta particles penetrate about a centimeter of tissue, so radionuclides that emit them are hazardous to superficial tissues, but not to internal organs unless they too are taken into the body. For gamma rays and neutrons, the degree of penetration depends on the nature of their interactions with tissue. Gamma rays can pass through the body, so radionuclides that emit them may be hazardous whether on the outside or the inside. X rays and neutrons can also pass through the body.

5.2 High dose effects

Biological effects of radiation at high dose are primarily the result of cell killing in the irradiated tissues or organs. Cells are killed because of extensive, irreparable

damage to the DNA and other critical cell components. Extensive cell killing as a result of radiation exposure may result in observable changes in the irradiated tissue within days or weeks of exposure. Such damage is referred to as acute effects. Radiation doses of different sizes, delivered at different rates to different parts of the body, can cause different types of health effect at different times. Very high doses to the *whole body* can cause death within weeks. For example, an absorbed dose of 500 rad or more received instantaneously would probably be lethal, unless treatment was given, because of damage to the bone marrow and the gastrointestinal tract. Appropriate medical treatment may save the life of a person exposed to 500 rad, but a whole body dose of 5,000 rad or more would certainly be fatal even with medical attention. A very high dose to a *limited area* of the body might not prove fatal, but other early effects could occur. For example, an instantaneous absorbed dose of 500 rad to the skin would cause erythema (i.e. painful reddening of the skin) within a week or so, whereas a similar dose to the reproductive organs might cause sterility. These types of effects are called *deterministic effects* because they occur only if the dose or dose rate is greater than some threshold value (usually in excess of 50 rad delivered in a short period of time), and the effect occurs earlier and is more severe as the dose and dose rate increase. In radiotherapy for the treatment of cancer, a very high dose of radiation is spread over several weeks to the specific area of the body containing the tumor. Doses and the area of the body to be treated are tightly controlled to eradicate the tumor and minimize damage to surrounding healthy tissue.

5.3 Low dose effects-cancer and genetic effects

If the dose is lower, or is delivered over a longer period of time, there is a greater opportunity for the body cells to repair the damage, and there may be no early signs of injury. Even so, tissues may still have been damaged in such a way that effects appear much later in life (perhaps decades). These types of effect are called *stochastic effects*. They are not certain to occur, but the likelihood that they will occur increases as the dose increases. Because radiation is not the only known cause of most of these effects, it is normally impossible to determine clinically whether an individual case is the result of radiation exposure or not.

The most important stochastic effect is *cancer*, which is always serious and often fatal (depending on the type of cancer). Although the exact cause of most cancers remains unknown or poorly understood exposure to agents such as tobacco smoke, asbestos, ultraviolet radiation, and ionizing radiation are known to play a role in inducing certain types of cancer. The development of cancer is a complex, multistage process that usually takes many years. Radiation appears to act principally at the initiation stage, by introducing certain mutations in the DNA of

normal cells. These mutations do not kill the cell but allow it to enter a pathway of abnormal growth that can sometimes lead to the development of a malignancy.

Ionizing radiation is known to cause many different types of cancer. Major cancers that have been observed include cancer of the breast, lung cancer, thyroid cancer and leukemia (cancer of the bone marrow). Not all cancers are fatal. Some cancers like thyroid cancer have a high survival probability (90% or more); other cancers like lung cancer are associated with poor survival (about 10%). In radiological protection the risk of fatal cancer is of primary concern because of its extreme significance. The use of fatal cancer risks also makes it easier to compare them with the other fatal risks encountered in life.

5.4 Risks of cancer

Given that we cannot distinguish between those cancer cases resulting from radiation exposure and those with other causes, how can the risk of cancer be determined? In practice health risks are estimated by conducting epidemiological studies (an observational science concerned with the distribution of diseases in a population and their causes) of specific diseases in specific population groups. Suppose that the number of people in an irradiated group and the doses they have received are known. By observing the occurrence of cancer in the group and comparing with the number of cancers expected in an otherwise similar but unirradiated group, the increased risk of cancer per unit dose can be estimated. It is most important to include data for large groups of people in these calculations so as to minimize the statistical uncertainties in the estimates and take account of factors, such as age and gender that affect the spontaneous development of cancer.

The main sources of information on the additional risk of cancer following exposure of the whole body to gamma radiation are studies of the survivors of the atomic bombs dropped on Hiroshima and Nagasaki in 1945. Various occupational and medical exposure situations (including radiation treatments for non-cancerous diseases) have also provided important information in support of the atomic bomb-derived risk estimates.⁷ Authoritative bodies such as the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the International Commission on Radiological Protection (ICRP), the National Council on Radiation Protection and Measurements (NCRP), and the National Research Council's Biological Effects of Ionizing Radiation (BEIR) Committees periodically

7. For a summary of many epidemiological studies see United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources and Effects of Ionizing Radiation*. Volume II: Effects. UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes. New York: United Nations; 2000; National Research Council, *Health Risks from Exposure to Low Levels of Ionizing Radiation*. BEIR VII Report. Washington, DC: The National Academies Press; 2005.

review published epidemiological and scientific data for the purposes of refining cancer risk estimates.

Most of the Japanese atomic bomb survivors and other exposed groups studied received high doses over short periods of time. Observations of the cancer incidence in these groups, along with estimates of the doses they received, indicate that, for high doses and high dose rates, there is a linear relationship between dose and risk. Thus, for example, doubling the dose would double the risk. However, most radiation exposure, particularly in the nuclear industry, involves low doses delivered over long periods.

At these low levels of exposure, studies of cancer incidence in the exposed population do not provide any direct evidence about the relationship between dose and risk, because the number of extra cancers that might be expected to result from the radiation exposure is too small (compared to the total number of cancer cases in the population from all causes) to detect. It is, therefore, necessary to consider other scientific information about the effects of radiation on cells and organisms and to form a judgment as to the most likely form of the dose–risk relationship. For many years, the internationally accepted solution has been to assume that the relationship is linear for low doses, all the way down to zero (known as the ‘linear–no threshold’ or LNT theory), i.e. that any radiation dose has a potential detrimental effect, however small. But, some recent radiobiological experiments have been interpreted as suggesting that low doses of radiation have no detrimental effect, because the body can successfully repair all of the damage caused by the radiation, or even that low doses of radiation may stimulate the repair mechanisms in cells to such an extent that they actually help to prevent cancer. Other experiments have been used as the basis for theories that low doses of radiation are more harmful (per unit of dose) than high doses, or that the hereditary effects of radiation could get worse from generation to generation.

After a major review of biological effects at low doses of ionizing radiation, UNSCEAR concluded in 2000 that “...an increase in the risk of cancer proportionate to radiation dose is consistent with developing knowledge and it remains, accordingly, the most scientifically defensible approximation of low dose response.” However, UNSCEAR also accepted that there are uncertainties and stated that “... a strictly linear dose response relationship should not be expected in all circumstances.”⁸

8. United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources and Effects of Ionizing Radiation*. Volume II: Effects. UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes. New York: United Nations; 2000

In reality, the risk to an actual person from a given dose will depend on that person's age at the time of the exposure and on their gender. For example: if a person receives a dose late in life, a radiation-induced cancer may not have time to appear before the person dies of another cause; and the risk of breast cancer is virtually zero for men. Furthermore, recent scientific advances indicate that a person's genetic constitution can influence their risk of cancer after irradiation. At present, we can identify only rare families who may carry increased risk, but experts may in the future be able to take some account of such inherited traits in predicting radiation risks.

Risk factors are also different for different populations. This is partly because different populations have different distributions of ages and different natural incidences of disease. For example, since the average age of a population of workers is generally higher (and therefore their life expectancy is shorter) than that of the population as a whole, the risk factor for workers is lower than the risks in the general population.

An important consequence of the assumption that risk is proportional to dose, without a threshold, is that the collective effective dose becomes an indicator of communal harm. Under this concept it makes no difference mathematically whether, in a community of 50,000 people, each receives an effective dose of 200 mrem, or in a community of 20,000 people, each receives 500 mrem; the collective dose in each community is 10,000 person-rem, and the communal cost in each community would be expected to be the same. However, members of the smaller community run the greater individual risk of fatal cancer. As indicated in Section 3.0 "Radiation Quantities and Units," calculations of collective dose for the purposes of predicting public health effects should not be taken too far: the product of a very large number of people and a very small dose is likely to be meaningless.

6.0 RADIOLOGICAL PROTECTION

Radiation exposures particularly from man-made sources are strictly controlled so as to avoid deterministic effects and to keep the probability of stochastic effects as low as possible. The current system of radiation protection in place in the U.S. and many other countries is based on three fundamental principles. Each of these is based on an in depth scientific understanding of radiation and radiological health effects but there are also social issues involved that require a considerable need for the use of professional and policy judgment.

6.1 Justification of a practice

No practice involving exposure to radiation should be adopted unless it produces at least sufficient benefit to the exposed individuals or to society to offset the radiation detriment it might cause. Nuclear power generation provides tremendous benefits for society and to the workers who operate the plants. Although the costs of generating electricity, complying with regulations, and otherwise maintaining a safe work environment are high, the benefits to society outweigh the risks. In diagnostic medicine, patients are routinely given small doses of radiation in the process of diagnosing or ruling out certain diseases. The benefits for the patient almost always outweigh the usually small risks of exposure. However, when there is no benefit to be gained by the proposed activity, even a small radiological risk would negate justification of a practice. For example use of diagnostic ultrasound *only* to determine the sex of an unborn child carries no benefit for the mother or the child. This practice is not justified even though ultrasound risks are small.

6.2 Optimization of protection (ALARA)

In relation to any particular source of radiation within a practice, the dose to any individual from that source should be below an appropriate dose constraint, and all reasonable steps should be taken to adjust the protection so that exposures are ALARA (as low as reasonably achievable), economic and social factors being taken into account.

Since we assume that no radiation dose is entirely free from risk, it is important to pay attention to all doses and to reduce them whenever it is reasonably achievable. Eventually the point must come when further reductions in dose become unreasonable, because social and economic costs would outweigh the value of the reductions. Any residual risk as a consequence of an ALARA program would be considered acceptable (otherwise additional resources would be allocated to reduce dose further) and protection would then be considered optimized.

The key to an effective ALARA program is identifying what is “reasonable” in terms of costs and benefits. Unfortunately there is no clear decision rule that can be applied across all radiological environments. What may be reasonable and acceptable in one setting may not be in another because of differences in cost constraints and site-specific requirements.

6.3 Application of individual dose limits

The third principle establishes dose limits for individuals and populations.⁹ For a practice that is justified there is an obligation not to expose individuals to an unacceptable risk. This is accomplished by imposing strict dose limits and applying

⁹ Radiation exposure for the purposes of medical diagnosis and therapy are excluded from dose constraints.

the principle of optimization of protection to keep doses ALARA. In the U.S. dose limits are set by several federal agencies. For nuclear power plant operations, the U.S. Nuclear Regulatory Commission sets standards and dose limits. In the U.S., nuclear workers are limited to 5000 mrem per year to the whole body. The public is limited to an annual exposure of 100 mrem from all sources (25 mrem per year from any single source). These prime limits, expressed in terms of effective dose, are intended to control the incidence of serious effects such as cancer that involve an element of probability. The limits are set far below doses that produce observable health effects.

The U.S. dose limits reflect the prevailing assumption among government (and industry and many academic) authorities that an individual must receive a whole-body dose of about 25,000 mrem (15,000 mrem for a pregnant woman) before there is a significant increase in the risk of serious human health effects, and a dose of about 500,000 mrem (500 rem) before probable death as a result of radiological health effects. The ALARA objective is to maintain worker and public doses as far below the applicable limits as reasonably achievable given social, technical, economic and policy considerations. The ALARA concept recognizes the uncertainties associated with the risk of low level exposure to ionizing radiation. Coupled with this uncertainty is considerable technical controversy about the magnitude of the probability of individual health effects as a result of any additional exposures above background levels.

There are two common misconceptions about dose limits. The first is that they mark an abrupt change in biological risk, a line of demarcation between safe and unsafe. It should be clear from the discussion on dose and risk that this is not so. This is also apparent from the fact that there are different dose limits for workers and members of the public. These limits differ because higher risks are deemed more acceptable for workers, who receive a benefit from their employment, than for members of the public, whose risk is involuntary. The second misconception is that keeping doses below the limits is the only important requirement in radiological protection. On the contrary, the overriding requirement is to keep doses as low as reasonably achievable. This is reflected in the increasing emphasis on investigation levels, which are, of course, set below dose limits.

7.0 PUBLIC PERCEPTIONS OF RISK

The greatest concern about ionizing radiation stems from its potential to cause malignant diseases in exposed persons. The likelihood of such effects depends on the amount of radiation that a person receives, whether from a natural or an

artificial source. As the effects of ionizing radiation have become better understood during recent decades, a system for radiological protection has been developed to protect people from exposure to sources of radiation. But public anxiety remains.

Radiation is one cause, among many, of the ‘dread disease’ cancer. Our senses cannot detect radiation, making this invisible risk seem even more insidious. Our collective anxiety is strengthened by memories of accidents at nuclear power plants and other facilities, and by the common tendency to associate any form of radiation with all things ‘nuclear’, including nuclear weapons. Another contributory reason for general heightened sense of concern about radiation may be the lack of reliable and accessible information and the misunderstandings that arise. Efforts to inform the public through public information campaigns can go a long way to address many concepts and facts about radiation and radiation safety that have been chronically misunderstood.