BRITISH COLUMBIA HYDRO AND POWER AUTHORITY

HAT CREEK PROJECT

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HAT CREEK PROJECT

RADIOLOGICAL IMPACT EVALUATION

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SUMMARY

Trace amounts of radioactive material will be released from the mine, powerplant and ash pile at the proposed Hat Creek Project. The radiological impact of the project is assessed in terms of radiation dose to the most highly exposed worker and member of the general public using conservative assumptions. The exposure pathways considered are inhalation and ingestion of radioactive material emitted from the plant stack and inhalation of radon that has emanated from the ash pile.

The highest individual dose, estimated at 1.7 mrem/a, is received by a worker at the ash pile. The maximum dose to a member of the surrounding population is estimated to be 0.2 mrem/a. These worst-case dose levels are less than 1 percent of the limit recommended for members of the public by the International Commission on Radiological Protection.

By comparison, a person living at the elevation of the proposed Hat Creek Project receives an annual radiation dose of about 130 mrem from natural sources.

This report does not use the SI units for radioactivity terms because it is felt that the introduction of these new units is so recent and the units themselves so unfamiliar as to lead to confusion. For the convenience of those wishing to convert to SI units however, the new units of sievert (Sv) gray (Gy) and becquerel (Bq) which replace rem, rad and curie (Ci) respectively, are as follows:

1 Sv = 100 rem dose equivalent
1 Gy = 100 rad absorbed dose
1 Bq = activity of one distintegration per second
= 2.7 x 10^{-11}Ci

SECTION 1.0 - INTRODUCTION

Radionuclides are unstable elements that disintegrate with the emission of ionizing radiation. All rocks including coal contain trace quantities of the naturally occurring radionuclides ^{235}U, ^{238}U, ^{232}Th, ^{40}K and their radioactive decay products. The radioactive decay chains for ^{235}U, ^{238}U and ^{232}Th are presented in Figs. 1, 2 and 3 respectively. Small quantities of these radionuclides are released to the environment during the mining, combustion and ash storage stages of power generation and can reach members of the public along a number of exposure pathways.

In open-pit mining operations the principal exposure pathways are the inhalation of airborne particulates and radon gas (^{222}Rn) and the ingestion of contaminated water. The average measured concentrations of natural Uranium and Thorium in Hat Creek coal are 1.4 mg/kg and 5.3 mg/kg respectively.[1] Estimates by Peyton[2] of ambient concentrations of airborne radionuclides showed that in the case of open-pit mining the Uranium concentration in the coal would have to exceed 500 mg/kg under severe atmospheric conditions in order to approach the maximum ambient concentrations for general population exposure allowed for facilities licensed by the U.S. Nuclear Regulatory Commission. Proper planning and design of the mine will prevent seepage and runoff of contaminated water from becoming a public or occupational health hazard.

During coal combustion in a powerplant the non-gaseous radionuclides are concentrated in the ash. A small fraction of this ash is discharged to the atmosphere via the plant stack while the bulk is disposed of as solid waste. The principal exposure pathways associated with coal combustion are the inhalation of particulates and radon contained in the plume and the ingestion of food that has become contaminated by airborne particulates which have settled on soil or plants. External irradiation from the plume and from the radioactive material deposited on the ground make a relatively insignificant contribution to the total radiation dose received via stack emission.[3] A calculation has been made of the radiation dose that could be received by a member of the public at greatest risk due to inhalation of radon and radioactive particulates that are released from the stack and ingestion of radioactive materials that reach man through his food chain. These dose estimates are presented and discussed in this report.

The principal exposure pathway associated with ash storage is the inhalation of radon that has emanated from the ash pile. The rate of radon emanation from the ash pile and hence the level of the inhalation hazard will depend on a number of factors including the concentration of ^{226}Ra, the precursor of radon, in the ash, the fraction of radon which is free to diffuse from the ash, the quantity and configuration of the ash pile and several other factors such as moisture content and degree of compaction of the ash. Ground level concentrations of radon above and downwind from a 35-year accumulation of Hat Creek ash have been calculated for an assumed radon release fraction and are discussed in this report.

No attempt is made to assess the radiological impact on flora and fauna in the Hat Creek plant environment. It is generally believed that humans are the most radiosensitive species in the environment and studies in Canada and elsewhere have confirmed this.[4,5,6] Typically, flora and fauna need to be exposed to radiation levels of more than a thousand times background (about 100 rem) before any effects are visible although there is wide variation in radiosensitivity between species.

SECTION 2.0 - EFFECTS OF LOW-LEVEL RADIATION

The health effects of concern associated with the radioactive material that will be emitted to the environment from the Hat Creek site are the long-term effects characteristic of chronic radiation injury from exposure to very low doses of ionizing radiation. Extensive research has demonstrated that carcinogenicity and mutagenicity are associated with ionizing radiation and therefore with exposure to radionuclides.[7] In general, tissues with rapidly dividing cells such as those of the bonemarrow and gonads are the most sensitive to radiation damage. When the deoxyribonucleic acid (DNA) of germ cells of the reproductive organs are exposed, the risk of hereditable genetic damage is increased and deaths, congenital defects, and illness in future generations can result.

The relationship between specific radiation dose and the risk to human health is extremely complex. It depends on both physical parameters such as the energy and type of radiation (e.g. alpha, beta or gamma radiation), the total dose, the dose distribution within the body and the dose rate, and on biological factors such as the specific organ exposed, the radiosensitivity of the individual, errors that occur in biological repair mechanisms, sex, race and age at time of exposure, genetic composition and the state of health. These factors are further complicated by the fact that people are exposed to a multitude of other chemicals that may change the magnitude of radiation effects.

Results observed at high levels of radiation exposure and in data from animal experiments indicate that radiation can cause cancer and mutations and that the resulting carcinogenesis is related to radiation dose and exposure time. However, there is no conclusive evidence of the effects of very low doses of radiation on human populations. It becomes extremely difficult to associate low levels of radiation exposure, whether man-made or natural, to any particular cancer because of the long latency period to the onset of the consequence. Exposures to low doses and low dose rates of ionizing radiation are less likely to produce cellular damage and it is believed that natural repair mechanisms in the DNA may be effective in offsetting some of the damage.

At this point, it has not been possible to establish unambiguously whether there is a threshold dose, that is, a dose of radiation below which no cancer would result. Therefore, the linear hypothesis which assumes that the fraction of individuals affected would be directly proportional to the dose down to the lowest doses and dose rates has been used as the basis for setting exposure standards. The assumption of the linear hypothesis is considered to be conservative in that it is likely to over-estimate the number of effects that would be produced.[8] Some groups believe that it is an improper estimate of risk for very low doses and dose rates because at these levels, natural repair mechanisms in cells may become proportionately more effective.

SECTION 3.0 - RADIATION STANDARDS

Radiological exposures can be detrimental to individuals and society in general. However, the emission of radiation is also associated with many activities from which society derives benefits. With unavoidable exposures to natural radiation it is not possible to reduce radiation exposures to zero levels. Due to the potential harmful effects of radiation on living organisms, radiation protection guides for the occupational worker and members of the general public have been set forth by a number of bodies including the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection (NCRP).

The ICRP was established in 1928 and is a recommending body of international influence but has no legal authority to enact its recommendations for radiation standards. In formulating its recommendations, the Commission recognizes that all exposures shall be kept as low as reasonably achievable, economic and social factors being taken into account (the ALARA principle). An important feature of the Commission's policy is that "in the case of occupational exposure the hazards should not exceed those that are accepted in most other industrial or scientific occupations with a high standard of safety" and, "the risks to members of the public from man-made sources of radiation should be less than or equal to other risks regularly accepted in everyday life, and should be justifiable in terms of benefits that would not otherwise be received".[9]

The ICRP has developed annual whole body exposure limits of 5 rem/a for an occupational atomic radiation worker and 0.5 rem/a (500 mrem/a) for a member of the general public.[10] These values are intended to protect the most susceptible individual or group in the population. The 1977 ICRP recommendations[10] do not give specific organ dose limits but do provide a list of individual organ weighting factors for application to the whole body dose limits. The radiation dose received by a given organ is multiplied by this factor and when calculated products for all portions of the body are added together, the total risk should not exceed the maixmum permissible for uniform body radiation.

Whereas the dose limit for occupational exposure is set such that the average risk resulting in practice is comparable to the average risk in an occupation with a high standard of safety, the dose limit for members of the public has been set simply by taking one-tenth of the occupational limit. The ICRP departed slightly from this tenth-of-occupational criterion in its 1977 recommendations by suggesting in effect that the limit for the highest exposed members of the public should be one-tenth of the average occupational exposure, which is only 10 to 20 percent of the occupational dose limit. Consequently, the ICRP retained the 0.5 rem annual limit for the public in its 1977 recommendations, but suggested that the average exposure of any individual member of the public should not exceed 0.1 rem/a averaged over his lifetime.[11]

An application of the ALARA principle is to specify a fixed numerical value of dose for some operations. In Canada, experience has shown that modern nuclear power stations can operate with radioactive effluents at about 1 percent of the limit derived from the dose limits and consequently 1 percent has become a design and operating target for Canadian nuclear power stations. The 1 percent target could be considered a type of ALARA value even though it is based on the risk to the highest exposed individuals rather than on the collective risk to all members of the public.[11]

In the United States, nuclear industry guidelines for limiting the amounts of radiation received by individuals and populations are contained in the Code of Federal Regulations (CFR). As of 1 December 1979, new standards for nuclear power operations (except for Uranium mining and milling) contained in 40 CFR 170 become effective, limiting exposures to the whole body and all organs except the thyroid to 25 mrem/a for members of the public. The thyroid exposure limit is

75 mrem/a. The Nuclear Regulatory Commission standard for annual external dose for gaseous effluents only, to an individual, is 5 mrems to the whole body and 15 mrems to the skin (10 CFR 50, Appendix I). 10 CFR 20 requires all nuclear facilities to limit the releases to as low as is reasonably achievable, taking into account the state of technology, the economics of improvements in relation to benefits to the public health and safety, other societal and socio-economic considerations, and in relation to the utilization of atomic energy in the public interest.

In estimating the risks of radiation-induced cancers and the linear hypothesis, the National Academy of Science and the National Research Council's Advisory Committee on the Biological Effects of Ionizing Radiation (BEIR) concluded that the total risk of fatal disease is about 100 to 180 excess cases per million persons per rem.[12] In other words the individual who receives an annual dose of 1 rem to the whole body has a risk of about 1 to 1.8 in 10 000 that he will eventually die of cancer from each year's exposure.

In keeping with the ICRP's policy that risks to members of the public from man-made sources of radiation should be less than or equal to other risks regularly accepted in everyday life, the hazards associated with radiation exposure can be compared with the hazards of experiences more familiar to the general public. For instance, if the linear hypothesis is applied to the risks of lung cancer associated with cigarette smoking, the reduction in life expectancy due to smoking one cigarette is equivalent to that from an exposure of 5 mrem of radiation.[13] An exposure to 1 rem/a would be equal to smoking 200 cigarettes/a, and the reduced life expectancy due to 5 rem/a which is the maximum permissible occupational exposure, is equivalent to that expected from smoking 1000 cigarettes/a or approximately one pack per week. It has also been estimated the 1 rem of gamma radiation, travelling 45 000 miles by air, rock climbing for 4.5 hours or canoeing for 18 hours may each lead to a casualty rate of 180 per million individuals at risk. The comparisons made are not meant to minimize the hazards of radiation but to express the magnitude of the hazard associated with radiation exposure in familiar terms.

SECTION 4.0 - IMPACT ASSESSMENT

4.1 STACK EMISSIONS

(a) Source Terms

The annual radionuclide emissions from the Hat Creek stack shown in Table 1 (columns 1 and 3) were calculated assuming:

1. continuous operation at the peak coal consumption rate of 40 482 t/d,
2. 23.6 percent moisture content in the "as received" coal,
3. Uranium and Thorium concentrations in the coal of 2.4 mg/kg and 5.3 mg/kg (dry basis) respectively,
4. that 1 percent of the Uranium and 0.11 percent of the Thorium in the coal is emitted to the atmosphere via the stack,[1]
5. that the parent radionuclides ^{235}U, ^{238}U and ^{232}Th are in secular equilibrium with their respective daughters in the undisturbed coal.

Secular equilibrium is a steady state condition in which the activity of parent and daughters is the same. The emission rates for the non-gaseous daughters assume that some radionuclides are enriched in the stack emission relative to their concentration in the mineral content of the coal. The enrichment factors used (Table 2) are those recommended by the U.S. Environmental Protection Agency (EPA) for coal-fired plants of the Hat Creek type.[14]

TABLE 1: RADIOLOGICAL IMPACT OF STACK EMISSIONS

1. DECAY SERIES (parent isotope)	2. RADIONUCLIDE (parent and daughters)	3. STACK EMISSION (Ci/a)	4. MAX. GROUND LEVEL CONCENTRATION (pCi/m^3)	5. INDIVIDUAL INHALATION DOSE (mrem/a) Adult	5. INDIVIDUAL INHALATION DOSE (mrem/a) Infant	6. MAX. SOIL CONCENTRATION (pCi/kg)	7. INDIVIDUAL INGESTION DOSE (mrem/a) Adult	7. INDIVIDUAL INGESTION DOSE (mrem/a) Infant
^{235}U	^{235}U	4.2×10^{-3}	3.3×10^{-7}	^{235}U excluding Actinon daughters		1.9×10^{-2}	4.984×10^{-6}	2.503×10^{-6}
	^{231}Th	2.1×10^{-3}	1.7×10^{-7}			9.5×10^{-3}	2.148×10^{-9}	1.859×10^{-9}
	^{227}Th	2.1×10^{-3}	1.7×10^{-7}			9.5×10^{-3}	1.895×10^{-5}	1.483×10^{-5}
	^{223}Ra	3.2×10^{-3}	2.5×10^{-7}	4.25×10^{-3}	4.90×10^{-3}	1.4×10^{-2}	1.896×10^{-6}	3.750×10^{-6}
	^{231}Pa	2.1×10^{-3}	1.7×10^{-7}			9.5×10^{-3}	1.561×10^{-3}	4.113×10^{-3}
	^{227}Ac	2.1×10^{-3}	1.7×10^{-7}	Actinon daughters		9.5×10^{-3}	1.779×10^{-5}	1.076×10^{-5}
	^{211}Bi	2.1×10^{-3}	1.7×10^{-7}	2.82×10^{-7}	2.82×10^{-7}	9.5×10^{-3}	–	–
	^{211}Pb	1.1×10^{-2}	8.3×10^{-7}			4.8×10^{-2}	–	–
^{238}U	^{238}U	9.0×10^{-2}	6.9×10^{-6}	^{238}U excluding Radon daughters and ^{210}Pb, ^{210}Bi, ^{210}Po		4.0×10^{-1}	9.738×10^{-5}	4.869×10^{-5}
	^{234}U	9.0×10^{-2}	6.9×10^{-6}			4.0×10^{-1}	1.119×10^{-4}	5.594×10^{-5}
	^{234}Th	4.5×10^{-2}	3.5×10^{-6}			2.0×10^{-1}	9.620×10^{-6}	1.843×10^{-6}
	^{230}Th	4.5×10^{-2}	3.5×10^{-6}			2.0×10^{-1}	2.405×10^{-2}	1.843×10^{-2}
	^{226}Ra	6.8×10^{-2}	5.2×10^{-6}	2.62×10^{-2}	2.88×10^{-2}	3.0×10^{-1}	1.787×10^{-3}	2.142×10^{-3}
	^{234}Pa	4.5×10^{-2}	3.5×10^{-6}			2.0×10^{-1}	–	–
	^{214}Bi	4.5×10^{-2}	3.5×10^{-6}	Radon daughters		2.0×10^{-1}	–	–
	^{210}Bi	4.5×10^{-2}	3.5×10^{-6}	3.03×10^{-4}	3.03×10^{-4}	2.0×10^{-1}	3.781×10^{-5}	1.880×10^{-5}
	^{218}Po	2.3×10^{-1}	1.7×10^{-5}			1.0	–	–
	^{214}Po	2.3×10^{-1}	1.7×10^{-5}			1.0	–	–
	^{210}Po	2.3×10^{-1}	1.7×10^{-5}	^{210}Pb, ^{210}Bi, ^{210}Po		1.0	5.809×10^{-3}	5.069×10^{-3}
	^{214}Pb	2.3×10^{-1}	1.7×10^{-5}			1.0	–	–
	^{210}Pb	2.3×10^{-1}	1.7×10^{-5}	3.21×10^{-3}	1.89×10^{-3}	1.0	8.214×10^{-2}	9.879×10^{-2}
	^{222}Rn (gas)	9.0	6.9×10^{-4}			N/A	–	–
^{232}Th	^{232}Th	7.3×10^{-3}	5.5×10^{-7}	^{232}Th excluding Thoron daughters		3.3×10^{-2}	4.164×10^{-3}	3.126×10^{-3}
	^{228}Th	7.3×10^{-3}	5.5×10^{-7}			3.3×10^{-2}	2.320×10^{-3}	4.444×10^{-3}
	^{228}Ra	1.1×10^{-2}	8.3×10^{-7}			5.0×10^{-2}	2.516×10^{-4}	2.979×10^{-4}
	^{224}Ra	1.1×10^{-2}	8.3×10^{-7}	$6 \times 36 \times 10^{-3}$	3.48×10^{-3}	5.0×10^{-2}	1.214×10^{-6}	2.849×10^{-6}
	^{228}Ac	7.3×10^{-3}	5.5×10^{-7}	Thoron daughters		3.3×10^{-2}	–	–
	^{212}Bi	7.3×10^{-3}	5.5×10^{-7}			3.3×10^{-2}	–	–
	^{212}Pb	3.7×10^{-2}	2.8×10^{-6}	1.53×10^{-5}	1.53×10^{-5}	1.7×10^{-1}	–	–
TOTALS	–	10.5	–	4.0×10^{-2}	3.9×10^{-2}	–	1.2×10^{-1}	1.4×10^{-1}

TABLE 2

ENRICHMENT FACTORS FOR RELEASED PARTICULATES

Uranium	Radium	Lead	Polonium
2.0	1.5	5.0	5.0

Isotopes of radon occur in all three radioactive decay series but only the ^{222}Rn isotope (radon) makes a significant contribution to the radiological impact.[15] The annual radon stack emission of 9.0 Ci conservatively assumes that all of the radon in the undisturbed coal is released from the stack, i.e. none is lost during the mining and crushing stages.

(b) Atmospheric Dispersion

Annual average radionuclide concentrations at ground level in the vicinity of the Hat Creek plant were calculated using the SO_2 dispersion mode predictions[16] and the ratios of emission rates between each radionuclide and SO_2. The maximum ground level concentration given in Table 1, (column 4) which were used to estimate the inhalation dose, occur at Cornwall Hills about 12 km southeast of the plant. The ground level concentration of radon (6.9×10^{-4}pCi/m^3) assumes that radon is dispersed in the same way as the other gaseous material emitted from the powerplant stack.

(c) Inhalation Dose

The individual inhalation doses shown in Table 1 (column 5) are the products of the maximum ground level radionuclide concentrations, the annual breathing rates of the affected individuals and the dose conversion factors relating intake to whole body dose.[17] The doses are those that result from a single year's exposure integrated over 50 years, i.e. a 50-year committed dose. The breathing rates used for the adult and the infant are $8.4 \times 10^3 m^3/a$ and $1.4 \times 10^3 m^3/a$ respectively as recommended by the ICRP.[18] Dose conversion factors derived by Johnson et al[19] were used to calculate the inhalation doses from all radionuclides except for the short-lived daughters of radon, thoron and actinon. Doses from attached dauthters of radon, thoron and actinon were calculated by determining the working levels of these nuclides based on the airborne concentration data. The equivalent dose conversion factor for inhalation of radon daughters is 1.0 rem/WLM.[17]

The estimated total inhalation doses for the adult and for the infant are essentially the same, 0.04 mrem/a.

(d) Deposition

Deposition rates for Uranium and Thorium were obtained from the B.C. Hydro trace element report[1] and are based on the SO_2 deposition patterns. From the deposition patterns shown in Fig. 3-2 of the report it can be seen that the region of maximum local deposition is located between the Bonaparte River and the Deadman River, some 55 km northeast of the plant.

(e) Soil Concentrations

The maximum radionuclide concentrations in the soil (Table 1) that were used to determine the ingestion dose were derived from the maximum soil concentrations of natural Uranium (1.206 μg/kg) and Thorium (0.296 μg/kg) given in Table 4-14 of the B.C. Hydro trace element report.[1] These reported concentrations are accumulations in soil after 35 years of powerplant operation at a capacity factor of 65 percent and assume that all deposited elements will remain in residence in the top 3 cm of soil and that neither uptake by vegetation nor erosion of soil to watershed drainages will occur. To determine the soil concentrations of the non-gaseous daughters of Uranium and Thorium it was assumed that they were in secular equilibrium with their respective parents and that for certain elements enrichment in the stack emission relative to the ash had occurred. The isotopes of radon that occur in each of the decay series, being gaseous, do not accumulate in the soil.

(f) Ingestion Dose

The FOOD computer program[20] at AECL's Whiteshell Nuclear Research Establishment (WNRE) was used to calculate the adult and infant ingestion dose for the 35-year accumulations of non-gaseous radionuclides in the soil. The calculated dose is due to the ingestion of contaminated food only; it does not include drinking water, animals drinking water, inhalation or external irradiation.

The worst ingestion case is assumed, i.e. that all food is raised in the region of maximum soil concentrations as is all feed for the animals from which the meat, milk and eggs are derived.

The diet used for the adult is that of the average maximum prairie Canadian. To construct this diet, the greatest average intake of each food group by an age-sex group was used. While an individual may take in more food of a given category than listed, no age or sex group will average a greater intake. The average Canadian infant diet is also used.

The calculated ingestion dose for each radionuclide shown in Table 1 (column 7) is the committed whole body dose from a single year's exposure integrated over 50 years. As for the inhalation dose assessment, the factors used to convert soil concentrations to 50-year committed whole body doses were those derived by Johnson et al.[19] Dose conversion factors for some radionuclides are still to be evaluated but the resulting doses are not expected to make a significant contribution to the total ingestion dose.

The total ingestion dose is estimated to be 0.12 mrem/a for an adult and 0.14 mrem/a for an infant.

4.2 ASH PILE EMISSIONS

(a) General

The principal radiological impact associated with coal ash disposal results from the inhalation of radon gas released from the ash. The radon is generated from the radioactive decay of ^{226}Ra, its precursor in the ^{238}U decay series. The concentrations of radon in air above and downwind of the ash pile, which govern the magnitude of the occupational and public risks respectively, are dependent on the concentration of the precursor ^{226}Ra in the ash, the atmospheric conditions that prevail at the time of release and a number of factors that determine the fraction of the radon generated in the ash that emanates to atmosphere. The occupational and public risk associated with radon release from a 35-year accumulation of Hat Creek ash are assessed in the following subsections.

(b) Radium -226 Concentrations in the Ash

Assuming that the ^{226}Ra in the feed coal is in secular equilibrium with ^{238}U and allowing for the ^{226}Ra that is released from the plant stack, (6.8×10^{-2}Ci/a) the maximum annual addition of ^{226}Ra to the ash pile (i.e. at the peak coal consumption rate of 14.8 Mt/a), is calculated to be 8.9 Ci. At an average plant capacity factor of 67 percent the amount of ^{226}Ra that will accumulate in the ash pile over 35 years is 208.7 Ci. If the ash content in the "as received" feed coal is 25.6 percent, the amount of ash that will accumulate in the ash pile over 35 years taking into account the stack loss of 16.8 t/d, is calculated at 88.2 Mt. Therefore the average ^{226}Ra concentration in the ash pile will be 2.4 pCi/g. This estimated average ^{226}Ra concentration in the ash may be compared to a measured ^{226}Ra concentration in ash from the Battle River test burn of Hat Creek coal and a measured value for native soil from the Hat Creek site area.

The measured concentration of ^{226}Ra in the Battle River fly ash is 4.0 ± 1.0 pCi/g. Assuming the ratio of ^{226}Ra concentration in fly ash to bottom ash (1.67) measured elsewhere[21] and the fly ash to bottom ash partitioning coefficient (85/15) measured for the Battle River test burn, the measured ^{226}Ra concentration in the ash is calculated to be 3.8 pCi/g, about 60 percent higher than the average value.

The measured concentration of ^{226}Ra in native soil from the Hat Creek plant area is 2.4 ± 0.8 pCi/a, which corresponds closely to the estimated average value for the ash. This suggests that if the radon emanation rate for the ash and native soil are similar, the presence of the ash does not increase significantly the radon inhalation hazard.

(c) Radon Emanation Rate

It is assumed that the 208.7 Ci of ^{226}Ra contained in the 35-year accumulation of ash is evenly distributed throughout a 1.0 km² pile.[22] Given that 1.0 Ci of ^{226}Ra will generate radon at a rate of 2.1 µCi/s* then the rate of radon generation in the 35-year ash pile is (208.7 Ci x 2.1 µCi/s/Ci) = 438.3 µCi/s.

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* $$\frac{(3.7 \times 10^{10} \text{ atoms/s})\ (\lambda^{222}\text{Rn})}{3.7 \times 10^{4} \text{ dis/s/}\mu\text{Ci}} = 2.1\ \mu\text{Ci/s}$$

where $$\lambda^{222}\text{Rn} = \frac{0.693}{T_{\frac{1}{2}}} = \frac{0.693}{330048 \text{ s}} = 2.1 \times 10^{-6}\text{/s}$$

Assuming that 1 percent of the radon that is generated emanates from the ash pile, the radon flux across the $10^6 m^2$ pile surface would be ($438.3\ \mu Ci/s \times 0.01 \times 10^3 nCi/\mu Ci \times 10^{-6} m^2$) = $4.4 \times 10^{-3} nCi/m^2/s$.

This calculated value for radon flux may be compared to measured values for natural soil. Wilkening et al[23] reported a value of $0.43 \times 10^{-3} nCi/m^2/s$ based on a review of measured data and Biret[23] arrived at a mean of $0.5 \times 10^{-3} nCi/m^2/s$. As the ratio of radon flux for Hat Creek ash to that for natural soil ($4.4 \times 10^{-3}/0.42 \times 10^{-3}$ = 10:1) is substantially larger than the corresponding rato of ^{226}Ra concentrations (2.4/2.4 = 1:1), it suggests that the assumption of 1 percent radon release from the ash pile is quite conservative. Nevertheless this release assumption is used, as set out below, to calculate ground level radon concentrations above (the occupational hazard) and downwind from (the public hazard) the ash pile.

It should also be noted that B.C. Hydro reclamation plans include covering the ash pile with at least 0.6 m of surficial material prior to seeding.

(d) Ground Level Radon Concentrations

Ground level concentrations of radon downwind from the ash pile were estimated by using a Gaussian plume dispersion model with a ground level area source of $1.0\ km^2$, Class E stability and wind speed of 3 m/s. For a ground level point source with no effective plume rise the diffusion equation is:

$$X = \frac{Q}{\pi\ \sigma_y\ \sigma_Z\ U}$$

Where: X is the radon concentration downwind from the ash pile (Ci/m^3), Q is the uniform emission rate of radon from the ash

(Ci/s), σ_y and σ_Z are the standard deviations of plume concentration distribution in the horizontal (i.e. perpendicular to direction of mean wind) and vertical planes respectively (m), and U is the mean wind speed (m/s). Because the ash pile represents an area source rather than a point source, Turner's[24] approximation of the horizontal dispersion (σ_{yo}) is used where $\sigma_{yo} = s/4.3$ and s represents the side of the square area of the source (1000 m). The calcualted values of σ_y and σ_Z for various downwind distances from the boundary of the ash pile are presented in Table 3.

TABLE 3

GAUSSIAN DISPERSION FACTORS FOR AREA SOURCE

Downwind from Boundary (km)	σ_y (m)	σ_Z (m)
0.1	260	15
0.5	280	21.5
5.0	450	59
10.0	620	82

Ground level concentrations of radon were then calculated at these downwind distances for a radon emission rate (Q) of 4.38 μCi/s (i.e. 1.0 percent of the in-pile generation rate of 438.3 μCi/s). The results are presented on the top line of Table 4.

The radon concentrations calculated using a Gaussian plume model and Turner's approximation of horizontal dispersion were compared to approximated values (line 3 of Table 4) using AIRDOS II (1979).[25] It will be noted that AIRDOS II gives higher values of radon concentration near the boundary of the ash pile than the Gaussian model but lower values beyond about 1 km from the boundary.

TABLE 4

RADON CONCENTRATION AND ANNUAL DOSE ESTIMATES DOWNWIND FROM ASH PILE

(Q = 4.38 μCi/s)

		Downwind from Boundary of Ash Pile (km)				
		0	0.1	0.5	5.0	10.0
Gaussian Plume Model	Radon Concentration (μCi/m^3)	$1.5\text{x}10^{-4}$	$1.2\text{x}10^{-4}$	$7.7\text{x}10^{-5}$	$1.8\text{x}10^{-5}$	$9.1\text{x}10^{-6}$
	Annual Dose (mrem/a)	1.8	1.4	0.9	0.2	0.1
AIRDOS II Estimate	Radon Concentration (μCi/m^3)	$5.0\text{x}10^{-4}$	$3.2\text{x}10^{-4}$	$1.3\text{x}10^{-4}$	$8.5\text{x}10^{-6}$	$3.6\text{x}10^{-6}$
	Annual Dose (mrem/a)	5.9	3.8	1.5	0.1	0.04

(e) Inhalation Dose Estimates

The radon concentrations were converted to annual dose using the AIRDOS II dose conversion factor for radon of 0.0014 rem/μCi inhaled. For the ICRP "Reference Man" inhalation rate of $8.4 \times 10^3 \text{m}^3/\text{a}$, the annual dose for continual exposure can then be calculated as follows:

$$\begin{array}{ccccccccc} \text{Annual Dose} & = & \text{radon concentration} & \times & \text{inhalation rate} & \times & \text{dose conversion factor} & \times & 10^3\ \text{mrem/rem} \\ (\text{mrem/a}) & & (\mu\text{Ci/m}^3) & & (\text{m}^3/\text{a}) & & (\text{rem}/\mu\text{Ci}) & & \end{array}$$

The calculated dose estimates are shown on lines 2 and 4 of Table 4.

If it is assumed that a member of the public is continuously exposed at a distance of 1.0 km downwind from the boundary of the ash pile, his annual dose from airborne radon can be estimated from the data presented in Table 4 (using the AIRDOS II data which gives slightly higher concentrations at this distance) to be 0.8 mrem/a.

A worker on the ash pile will be exposed to higher radon concentrations than a member of the general public, but for a shorter time. To obtain an approximation of the radon concentration above the ash pile the AIRDOS II data (line 3 of Table 4) was extrapolated back to the ash pile boundary giving a value of the order of $5 \times 10^{-4} \mu\text{Ci/m}^3$. This concentration may be compared to measured outdoor radon concentrations at six locations in the U.S.[26] for which the mean values range from $1.2 \times 10^{-4} \mu\text{Ci/m}^3$ to $4.8 \times 10^{-4} \mu\text{Ci/m}^3$. As shown in Table 4 the annual dose resulting from continuous exposure to $5 \times 10^{-4} \mu\text{Ci/m}^3$ radon is about 6 mrem/a. The dose that might be received by a worker exposed for 40 hours per week is about 1/4 of this value, or 1.5 mrem/a.

SECTION 5.0 - RESULTS

For the purpose of radiological impact assessment the person at greatest risk is assumed to be a worker who spend 40 hours per week on the 35-year accumulation of ash and his remaining time in residence at the locations of maximum ground level ambient air concentration and maximum soil radionuclide concentrations via deposition (even though these locations are widely separate geographically). The contribution to his total dose from the inhalation of radon released by the ash pile is estimated at 1.50 mrem/a. The contribution to his dose from the inhalation of stack emissions, assuming residency for three-quarters of each year at the location of maximum ground level concentrations, is estimated (from Table 1) at 0.03 mrem/a. To estimate the contribution from ingestion of contaminated food it is assumed that all his food is obtained from the location of maximum radionuclide concentrations in the soil. This gives an estimated ingestion dose (from Table 1) of 0.14 mrem/a. The total estimated dose to the most highly exposed person is therefore 1.67 mrem/a.

This "worst case" dose level is one-third of 1.0 percent of the ICRP whole body dose limit (500 mrem/a) for members of the public. By comparison, a person living continuously at the elevation of the Hat Creek powerplant (1500 m above sea level) would receive about 130 mrem/a from natural back ground radiation.

The design and operating target imposed on nuclear powerplants in Canada by the Atomic Energy Control Board is an individual dose of 5 mrem/a or 1 percent of the ICRP limit. The "worst case" dose estimated for the Hat Creek Project is well within the AECB target.

For a person who is not employed at the ash pile but lives continuously in the regions of maximum ground level and soil concentrations the annual dose is calculated (from Table 1) as 0.18 mrem/a. In this case, the maximum dose would be received by an infant.

The health effects of radiation and other carcinogens can be compared in terms of reduced life expectancy. The reduced life expectancy that results from receiving a dose of 5 mrem/a for 70 years is about 3.5 hours. The same reduction in life expectancy results from smoking one cigarette per year.[13] By comparison, the average natural lifetime radiation dose (at sea level) of 7000 mrem reduces life expectancy by 3 days.

Although the potential for larger than predicted radioactive emissions may exist in nuclear plants this situation is not possible with coal-fired plants.

SECTION 6.0 - CONCLUSIONS

Although it still remains to be proven whether the biological response to radiation exposure follows the linear hypothesis or whether there is a threshold dose below which no cancer would occur, the dose projected to result from the Hat Creek facility is well within both the internationally accepted dose limit and the range of background radiation that populations have been exposed to for thousands of years as a result of cosmic and terrestrial radiation. At the estimated low annual doses, it is not expected that adverse public health effects would occur.

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GLOSSARY

daughter element	The immediate product of radioactive decay of an element.
dose	The amount of energy imparted by ionizing particles to a unit mass of irradiated material at the point of interest.
ionizing radiation	Particles or photons that have sufficient energy to produce ionization directly in their passage through matter.
nuclide	A species of atom characterized by the number of protons, number of neutrons, and energy content in the nucleus, or alternatively by the atomic number, mass number and atomic mass.
radionuclide	A nuclide that exhibits radioactivity.
radon dauthters	The four radioactive, short-lived decay products of radon: polonium-218, lead-214, bismuth-214 and polonium-214.
rem	The unit of biological dose given by the product of the absorbed dose in rads and the relative biological efficiency of the radiation (Roentgen Equivalent Man).

FIGURE 1

URANIUM - 235 RADIOACTIVE DECAY CHAIN

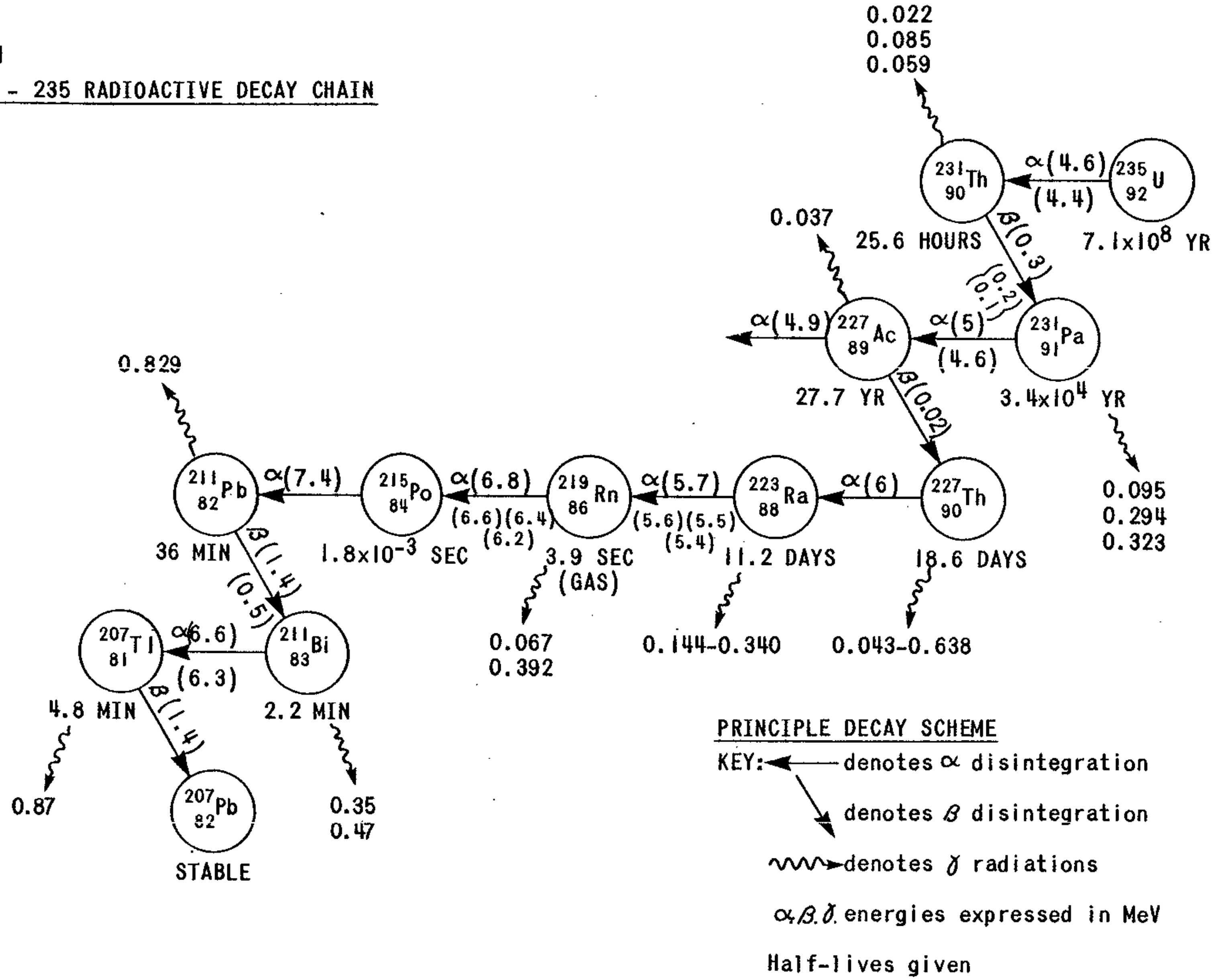

FIGURE 2

URANIUM - 238 RADIOACTIVE DECAY CHAIN

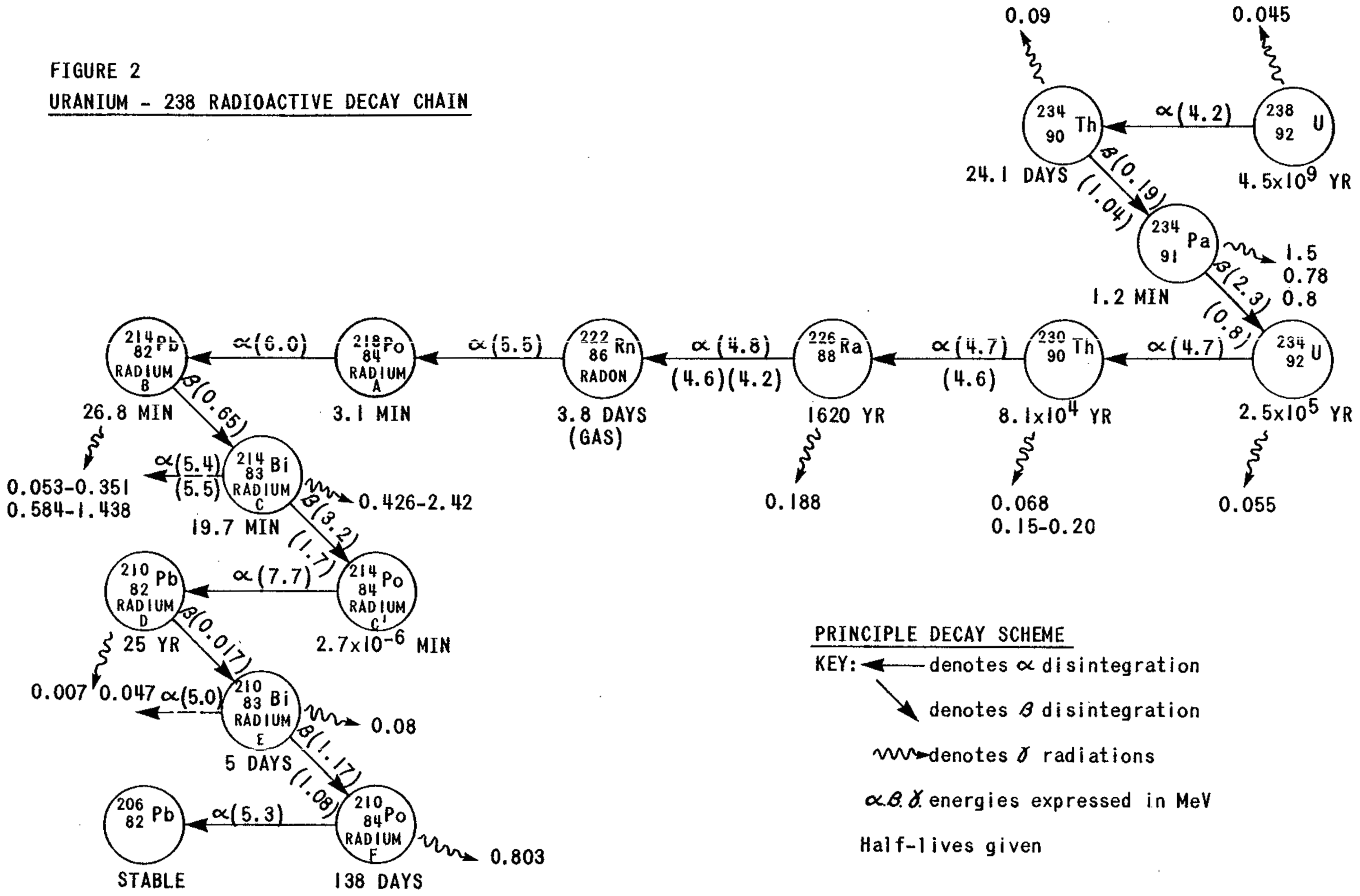

FIGURE 3

THORIUM - 232 RADIOACTIVE DECAY CHAIN