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HAZARD ANALYSIS OF MIAMISBURG PARK IMPROVEMENT PROJECT

B. M. Farmer
B. Robinson
W. H. Westendorf

March 17, 1977

ENERGY RESEARCH & DEVELOPMENT ADMINISTRATION USA

Monsanto

MOUND LABORATORY
Miamisburg, Ohio
operated by
MONSANTO RESEARCH CORPORATION
a subsidiary of Monsanto Company
for the
UNITED STATES ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
U.S. Government Contract No. EY-76-C-04-0053

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SUMMARY

The City of Miamisburg plans to modify two existing small ponds just west of Mound Laboratory in the Community Park. The north pond will be deepened and made into a solar energy pond to heat a bath house and swimming pool, and the south pond will be deepened and made into a fishing pond. Because the sediment in both ponds contains small amounts of plutonium and will be moved during the modifications, this work has been reviewed for potential health and safety impacts.

This analysis covered the health and safety of the public on a long-term basis and of the workers involved in the short-term modifications. The doses to man, both long and short term, were calculated for all routes of entry into the body including inhalation, ingestion, and absorption where applicable.

In the preparation of this analysis, very conservative assumptions were utilized. The conclusion in all cases was the same: the potential radiation exposures represent no significant risk to the health and safety of the construction workers or the park visitors. The improvements to be made in the park involve mixing and dilution of the existing sediments with other soils, providing further reductions in the calculated radiation doses to man. The City of Miamisburg can proceed with the improvements to the park, as planned, resulting in no short-term or long-term hazard to the citizens of Miamisburg.

HAZARD ANALYSIS OF MIAMISBURG PARK IMPROVEMENT PROJECT

INTRODUCTION

Mound Laboratory is situated on 180 acres of land in Miamisburg, Ohio. This location is approximately 16 kilometers (10 miles) southwest of Dayton. Predominant to the geographical feature in the five county region surrounding the Laboratory is the Great Miami River which flows from the northeast to the southwest through Miamisburg and west of the Laboratory. This river valley area is generally highly industrialized. The remainder of the region is predominantly agricultural with some light industry and scattered residential communities.

Weather conditions in the area are described as moderate. The average annual precipitation is approximately 91 centimeters (36 inches) and is evenly distributed throughout the year. Winds are predominantly from the west or south except during the summer months when a higher frequency is recorded from out of the southwest. The wind speed averages about 16 kilometers per hour (10 miles per hour) annually.

Mound Laboratory began operations in 1949. Its mission currently includes research, development, engineering and production of components for the ERDA Weapons Program; research, development, and production of explosive materials; separation, purification and sale of stable isotopes of the noble gases; and development, design and fabrication of radioisotopic heat sources for medical application and space exploration. The radionuclides of primary concern currently being handled include plutonium-238 and tritium.

Mound Laboratory Environmental Plutonium Study

In 1974, Mound Laboratory's Environmental Monitoring Program established plutonium concentrations in the sediment of certain waterways adjacent to Mound Laboratory (including the old Miami Erie Canal and adjacent ponds in the Miamisburg Community Park shown in Figure 1) above the expected baseline levels of less than 0.0004 nanocuries per gram (nCi/g). From the very beginning, these deposits did not seem to present any immediate hazard to the public in the area as indicated by air and water monitoring in the area.

However, Mound Laboratory immediately launched the Mound Laboratory Environmental Plutonium Study to fully investigate the extent of the contamination, the source of plutonium and what potential hazards these deposits might present now or in the future. This extensive study involved over 5,000 soil and sediment samples taken from the waterways and nearby land[1]. During the course of the study, interim reports were periodically submitted and reviewed with health, environmental and governmental agencies to keep them informed as the results became available.

Figure 1 - Aerial View (from the North) of Off-Site Waterways

The findings of the Environmental Study were presented to interested local, state and federal government officials, and health and environmental agencies prior to a press conference held at Mound Laboratory on October 2, 1974. The overall conclusions about the health and safety aspects of the plutonium deposited in waterways near Mound Laboratory was that as related to standards or RCG's, the plutonium-238 does not present a hazard to people living in this area or the public at large.

The results of these studies were discussed in two major reports: (1) The Report of the Ad Hoc Committee to Evaluate the Health and Safety Aspects of Plutonium-238 and the Environment Adjacent to Mound Laboratory dated February 1976[2], and (2) Mound Laboratory Environmental Plutonium Study 1974 dated September 1975[3]. Again, neither of these reports found any health and safety problems, although the first report said that any future actions in the area should be reevaluated. The purpose of this report is to reevaluate that portion of the area involved in the 1974 study which is now being physically reshaped and which is known to contain small quantities of plutonium-238 fixed to sediments.

Just west of the Laboratory property (see Figure 1) is a public park of the City of Miamisburg. There is a section of the old Miami Erie Canal running through this park in a north-south direction. Near the north end of this canal and in the park area are two small ponds.

North Pond

The City of Miamisburg has planned to convert the northern pond of the two into what is called a solar pond as part of an overall park improvement project. The northern pond will absorb heat from the sun and use it for heating swimming facilities (see Figures 2 and 3). This pond will first be drained and then recontoured into the desired shape. The solar pond will measure 180 ft x 120 ft at the surface and be 10 ft deep. The bottom dimensions will be 160 ft x 100 ft for a total water volume of 1,400,000 gallons. The effective working area at the 5-ft level is 18,700 ft^2, with an equivalent effective storage volume of 1,118,000 gallons.

Although no soil is expected to be removed from this pond according to the plan, about 1,700 cubic yards will be shifted and another 1,400 yards of new soil will be placed around the pond to effect the ten-foot depth. On the other hand, if problems are encountered when attempting to blend the soil already in the north pond with new soil, then some of the old soil may have to be removed and added to the fill forming the berm near the railroad tracks.

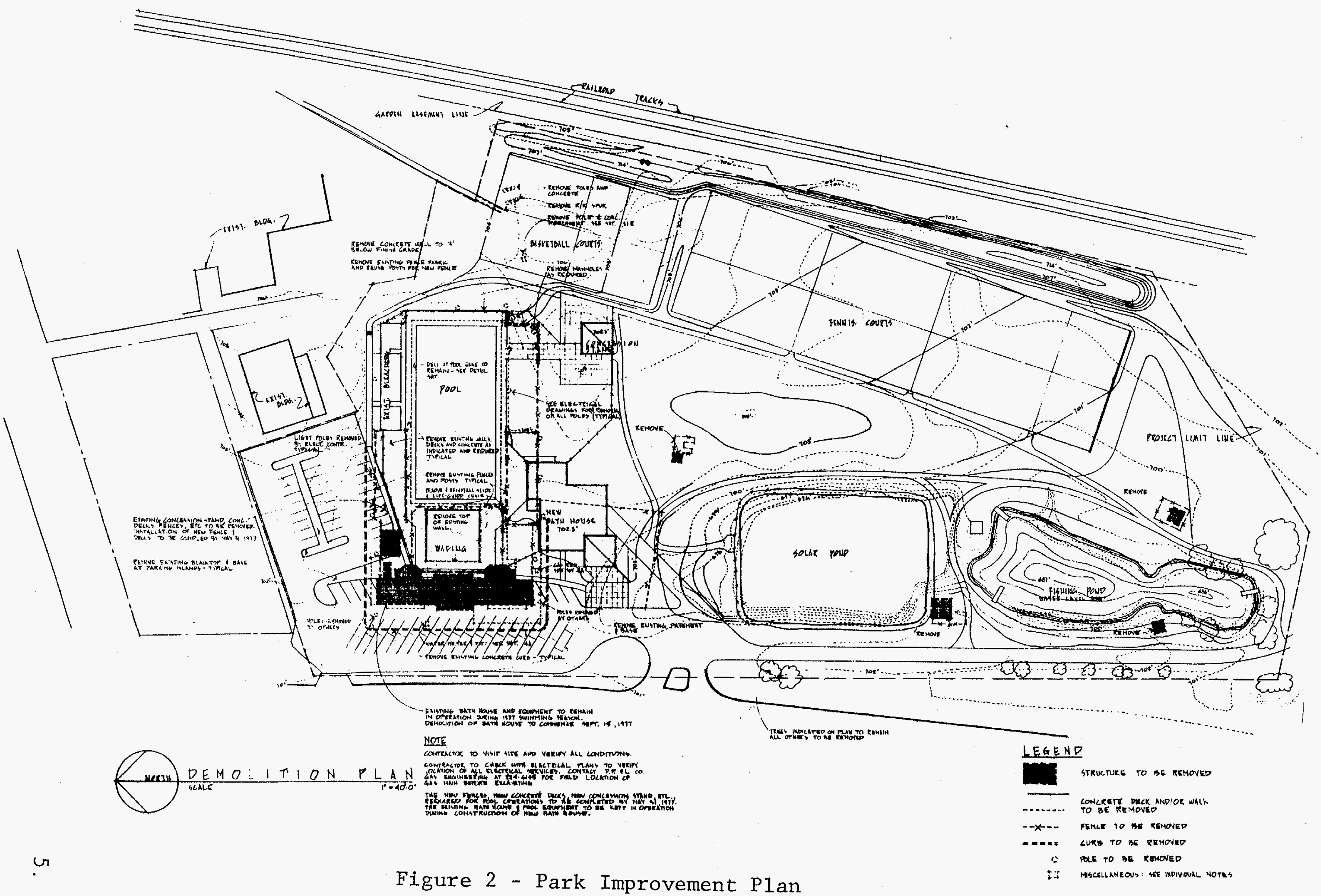

Figure 2 - Park Improvement Plan

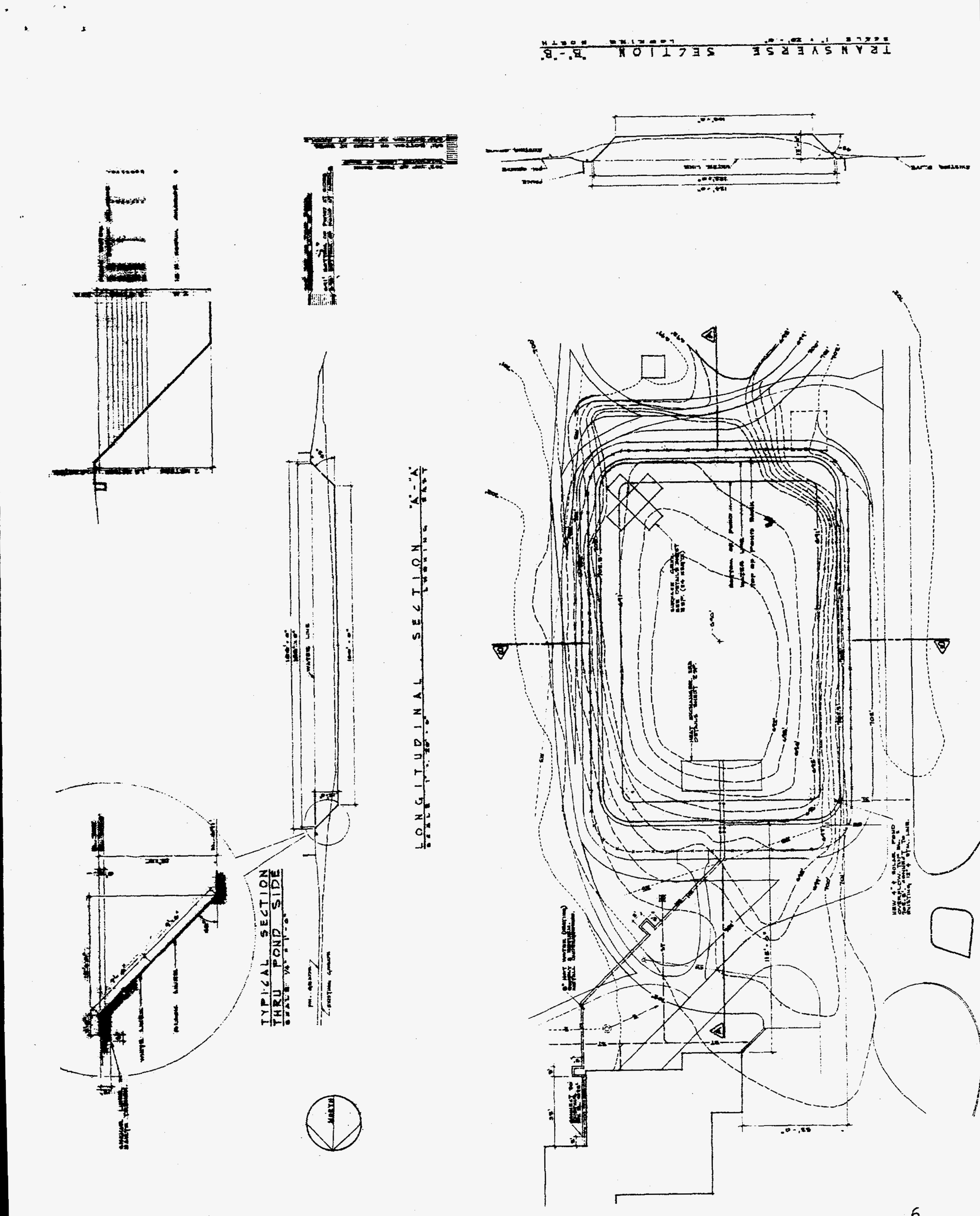

Figure 3 - Solar Pond Site Plan

The solar pond will be lined with heavy duty plastic to prevent leakage and consequent ground contamination. An 18% solution of salt (sodium chloride) and water will be placed in the lower 5 ft of the pond. Salt solutions of decreasing strengths will then be placed in 6-inch layers to within 1-1/2 ft of the top. The top layer will be 1-1/2 ft of fresh water. Roughly 812 tons of salt will be required to make the various solutions. To prevent disturbance of this density gradient and other potential problems from visitors to the area, the solar pond will be surrounded by a suitable fence.

Approximately 30% of all solar radiation reaching the pond will penetrate into the bottom layer and will be absorbed, thus heating the water and the ground below. The heated water which would normally rise to the surface and be cooled will be prevented from doing so by the weight of the dissolved salt. The upper layers will act as a transparent insulator that lets the radiation in and helps retaining it in the bottom region.

Heat collected in the pond will be removed as required to heat the swimming pool water and the building by means of a copper tube heat exchanger located near the bottom of the pond, and piping to and from the equipment room.

South Pond

The southern pond will be improved and used as a fishing pond. About 1,500 cubic yards of soil from this pond will be moved and placed under paved tennis courts and placed along the railroad tracks as a small earthen barrier or berm. Other soil will be brought in to create the required size of this barrier and will be landscaped. It is important to note that the soil to be removed from the fishing pond will not be the top layer of sediment, but rather the soil below this top layer. This is to preserve the already ecologically balanced soil with its quantity and quality of organic materials and organisms so vital to a healthy fish population.

Canal

There is no major modification currently planned for the canal itself. The park will be generaly upgraded and beautified containing an improved fish pond, solar pond, new tennis and basketball courts, and new bath house and swimming pool.

The Mound Plutonium Study showed that levels in the north pond (solar) ranged from <0.0001 to 0.002 nCi/g in the six 1-ft cores taken to a depth of 5 ft (i.e. 30 samples). Most of these samples (15) were less than 0.0001 nCi/g, the lower detection limit. Each of the six coring locations had the five 1-ft cores composited and these six composites showed levels of plutonium-238 from 0.0001 to 0.0006 nCi/g with an average value for the north pond of 0.00036 nCi/g.

The south pond (fishing) was shown to have plutonium-238 levels ranging from <0.0001 to 0.0309 nCi/g, also in 30 samples. Each of the six coring locations had the five 1-ft cores composited and these six composites showed levels of plutonium-238 from 0.0001 to 0.0063 nCi/g with an average value of 0.0023 nCi/g.

Since these soils and sediments will now be disturbed, shifted, relocated, and/or otherwise modified, this report will reevaluate the concentrations of plutonium-238 cited above in light of these proposed changes and show whether any significant exposures are possible. To do this, models will be described and exposures will be calculated using these models for both the short-term exposure to workers shifting the material and long-term (70 years) exposure to the general public after the material has been shifted for all modes of bodily entry, including inhalation, ingestion, and absorption where applicable.

DISCUSSION

The calculations for the Hazard Analysis logically necessitate two considerations; i.e., a short-term (40 day) exposure to the workers such as the bulldozer driver who would be involved in construction and shifting of material in the bed of both the North (solar) and South (fishing) Ponds and a long-term (70 year life) exposure to the public after the pond improvements. The estimated maximum time the workers would be exposed for the pond improvement work is estimated to be eight 5-day work weeks. During the short term these workers could theoretically get plutonium (sediments) into their bodies by three pathways: (1) inhaling sediment which is resuspended into the air by mechanical distrubance at the site, carried home and resuspended into the air or resuspended from clothing; (2) absorption through the skin; or (3) ingestion (eating) of food, water, or sediment.

Short Term (Exposure to Workers)

For the short term evaluation, only the ingestion of sediment directly was considered since the ponds will be drained of water and there are no food or vegetables to consider.

Obviously, while exposure to the small concentrations of plutonium in the sediments can never be zero, it should be noted that there is only 1/100,000 of an ounce of plutonium in over a million pounds of sediment in the ponds.

For inhalation, all calculations were based on 25% of the dust (sediment) being respirable (breathable) even though preliminary data in reference 3 indicates only 2-3% of this sediment in the respirable range. Additionally, the body discriminates against breathing dust; i.e., of the dust which is small enough to be inhaled about 85% is moved out of the nasal and lung area in one day. Also, to assure that any evaluation of dose by inhalation from resuspension of pond sediments would overestimate any hazard, it was assumed that 100 times more sediment would be resuspended into the air than observed for aged material in this climate for extreme mechanical disturbance. For the calculation this amounts to using a larger resuspension factor (Km^{-1}) which is the ratio of amount of resuspended material per cubic meter of air to the amount of material per square meter on the ground.

The human body also naturally protects itself by allowing less than 1/100,000 of plutonium on the skin to be absorbed into the body per year. This is in addition to the fact that there are only very small amounts of plutonium in the sediments in the first place.

For the short-term evaluation, the highest concentration of plutonium found in any one-foot section was used as if all the sediment had this concentration. This value was 0.03 nanocuries/gram and was found in the top one-foot section at one location in the South Pond. This value would be about 10 times the average value for the South Pond and about 60 times the average value for the North Pond. While the 0.03 nCi/g value is the largest value for one-foot core samples, the average values for the top approximately 0.04 inch of sediment averages less than 3 times the 0.03 value. The very top ($\sim$0.04 inch) of sediment, which is higher in concentration than 0.03 nCi/g, was not used because it would be only 1/1000 of the total volume of material and would be impossible to remove intact with equipment like a bulldozer or backhoe.

These levels are then related to the calculated exposures through the dose equations detailed in appendices B & C. The dose equations used in the evaluations are standard equations and models such as those recommended by the International Commission on Radiological Protection (ICRP)[4,5]. The values used for analyzing exposures to various organs in man from different pathways involve "standard man" values developed by ICRP. Examples of "standard man" values would be a breathing rate of $20M^3$ per 24 hour day, liquid intake of 2 liters per day, etc.

The dose equivalent calculations shown in Table 1 for a short-term exposure to the workers would be less than one millirem of exposure to either the lung or bone for the first year after exposure. The first year after exposure would give the highest dose to the lung and thereafter the dose would decrease by one-half every 500 days as the plutonium is translocated from the lung. As the material is slowly transferred from the lung to the blood and into the bone, the dose to the bone slowly increases each year as material is

TABLE 1

SUMMARY OF RESULTS

Short Term (Worker's Exposure)

North Pond (Solar) and South Pond (Fishing)

	Mrem to Lung (first year)*	Mrem to Bone (per year)
1. Inhalation		
Dust Loading	0.0005	0.0001
Wind Suspension	0.0017	0.0005
Resuspension	0.24	0.07
Clothing	0.0024	0.0007
Home	0.0031	0.0009
2. Ingestion		
Sediment		0.002
Water		**
Vegetables		**
Animals		**
Fish		**
3. Absorption		
Skin		1.9×10^{-6}
Wound		1.9×10^{-6}
4. Natural Background	100	60

*The maximum dose to the lung is received the first year after inhalation because the material is translocated out of the lung at the rate of 50% every 500 days.

**Not applicable.

accumulated. For purposes of maximizing the dose to the bone, the short-term calculation for the bone assumed that the plutonium had already translocated to the bone. The dose to the bone each year thereafter will be essentially the same since the elimination of plutonium from the bone is so slow as to be essentially zero.

The calculated dose of less than one millirem per year is extremely low when compared to international guides for radiation exposure. ICRP guidelines are 1,500 millirem per year to the lung and 3,000 millirem per year to the bone for an individual in the general population[6]. The average dose equivalent rate from internally deposited, naturally occurring radionuclides is about 100 mrem per year for the lung as a whole and for the surface of trabecular bone (bone containing marrow cavities) is ∿60.4[7] mrem per year. Thus, even under the very worst conditions the exposure would be less than 1% of that obtained naturally.

Figure 4 shows typical whole body equivalent doses resulting from nature and other normal activities.

Long Term (Exposure to the Public)

Since plutonium-238 emits very little penetrating radiation, the potential for external exposure from the amount of plutonium-238 under consideration is insignificant. For example, the low energy X-rays emitted by a nanocurie of unshielded plutonium-238 would give a dose equivalent at one meter of only 0.0003 mrem to the whole body for continuous exposure for a period of one year. Natural background in this area is ∿100 mrem per year.

After the sediment from the ponds has been shifted to effect the park improvement, the sediment in its new location must be considered in terms of long-term exposure of the public. Thus, the long-term calculation considers that exposure occurs to the public by every pathway without stopping for a period of 70 years.

Present plans would indicate that part of the sediment from the North (solar) pond may be removed if this soil does not mix well with new soil and, if it is removed, it will be placed under paved tennis courts or in a berm with new soil on top. The sediment in the South (fishing) Pond would be removed temporarily until the material below the sediment is removed and then the sediment would be put back in the South Pond as described in the introduction.

However, since there is some uncertainty about where any of the sediment removed from the ponds may be permanently located, it will be assumed that the sediment will be removed, allowed to dry and be available to expose the public for 70 years. This would represent clearly "a worst case" since the city definitely plans to place removed sediment under the tennis courts or berm.

Figure 4 - Typical Whole Body Equivalent Doses

The concentration of plutonium in the sediment of the ponds as it now exists contains the highest values in the top one foot which is likely to be taken out first and later be covered by material which is below this and perhaps covered with new soil. For long-term calculations, the highest core value (plutonium) found in either pond (0.03 nCi/g) was assumed for all of the material which again clearly overestimates the exposure.

It should be noted that any sediment containing traces of plutonium in the North (solar) Pond which is left after shifting is likely to be covered with new soil, covered again with a plastic liner and fenced off for zero access which again makes the evaluation an overestimation.

Sediment material from the South (fishing) Pond will likely be placed back into the pond after it is deepened, and thus, the most important long-term consideration would be ingestion of water or sediment. Again, the body rejects nearly all plutonium which is ingested - more specifically, only 0.003% of any plutonium ingested would be absorbed into the body from the intestine. Also, for ingestion of sediment it was assumed that an individual would ingest 4 grams per year for 70 years ($\sim$ 1/2 pound of sediment) whereas this is likely to occur for at the most one year of a young child's life.

The remaining 99.997% is passed through the GI tract and eliminated. Thus, ingestion is a difficult way to get a significant exposure to plutonium. Additionally, for food and water the plutonium must be released from the sediment and move into the water, however, the plutonium is so tightly attached to the sediment that only 0.001% will be in the water while the remaining 99.999% is firmly attached to the sediment. Again, the three pathways are evaluated from the standpoint of breathing the sediment; eating sediment, fish, etc.; or absorption of plutonium (in sediment) through the intact skin or wounds. For all pathways, after the plutonium is absorbed into the bloodstream it is assumed that 100% collects in the bone.

The long-term inhalation to the public is estimated using three models: (1) dust loading, (2) wind suspension and (3) resuspension. All models indicate an insignificant hazard from exposure to plutonium in the sediment. The long-term ingestion of water, <u>sediment directly</u>, and fish is also evaluated. The fish ingested was based on the assumption that the average individual's total fish diet (9,000 grams/year) for 70 years came exclusively from fish caught in the South (fishing) Pond. Even with the large overestimations mentioned above, little, if any, hazard from exposure can be calculated. For absorption through intact skin, it was assumed that sediment remained on the skin for a lifetime and for wounds, it was assumed that 1% of skin area is continuously abraded for a lifetime.

The data obtained in terms of mrem of exposure for 70 years under the very worst conditions is shown in Table 2. The table clearly indicates an incredibly low risk because the maximum values are less than 15 mrem for 70 years of exposure would give a median annual value of less than 0.2 mrem per year. This would be compared to a natural exposure to the lung of 100 mrem per year and ~60 mrem[7] per year to the surface of trabecular bone. Also, the natural exposure to the lung for 70 years would be 7,000 mrem and the natural exposure to the bone for 70 years would be about 4,200 mrem. While no exposure can be zero hazard, this one is clearly essentially zero when compared to the "hazard" from natural background radiation.

CONCLUSION

The plans for improvement of the Miamisburg park, including the conversion of two existing ponds into a solar pond and a fishing pond, were evaluated for potential hazards due to the small quantities of plutonium-238 present in the sediments. Lung and bone dose models were developed for short term (worker) and long term (public) exposures through all modes of bodily entry including inhalation, ingestion, and absorption where applicable.

In all cases, the calculated results indicated extremely low lung and bone doses both to the workers on the project and to the general public utilizing the modified park for 70 years. These exposures were usually fractions of a millirem per year or the maximum being a few millirem per 70 years. This is compared to guidelines of 1500 millirem/yr to the lung and 3000 millirem/yr to the bone for an individual in the population. It should also be compared with natural radiation which amounts to 100 mrem per year to the lung and 60 mrem/year to the bone to further demonstrate the insignificant hazard which can be estimated even under worst conditions.

The final conclusion is that none of the planned modifications to the City of Miamisburg's park adjacent to Mound Laboratory result in any hazard to the worker in the short term or to the general public in the long term, and the City's plans including the Solar Pond should proceed as scheduled.

TABLE 2

SUMMARY OF RESULTS

Long Term (Public Exposure)

	Mrem to Lung (70 years)	Mrem to Bone (70 years)
North Pond (Solar)		
1. Inhalation		
Dust Loading	0.23	0.8
Wind Suspension	1.12	3.8
Resuspension	3.72	12.9
South Pond (Fishing)		
1. Inhalation		
Dust Loading	0.23	0.8
Wind Suspension	1.12	3.8
Resuspension	3.72	12.9
Clothing	3.47	12.0
Home	4.65	16.0
2. Ingestion		
Sediment	*	4.21
Fish	*	0.47
Water	*	3.81
3. Absorption		
Skin	*	0.03
Wound	*	0.03
4. Natural Background	7,000	4,200

*Not applicable.

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3. D. R. Rogers, "Mound Laboratory Environmental Plutonium Study - 1974, MLM 2249, September, 1975.

4. "Report of the International Commission on Radiological Protection Committee II on Permissible Dose for Internal Radiation (1959)", ICRP Publication 2, Pergammon Press New York, N.Y.

5. ICRP Task Group on Lung Dynamics, "Deposition and Retention Models for Internal Dosimetry of the Human Respiratory Tract (1966).

6. International Commission on Radiological Protection, "Recommendations of the International Commission on Radiological Protection (adopted September 17, 1965)" ICRP Publication 9, Pergammon Press, Oxford (1966).

7. National Council on Radiation Protection and Measurements, "Natural Background Radiation in the United States," NCRP Report No. 45, November 15, 1975.

APPENDIX A

Alpha Particle:

A charged particle emitted from the nucleus of an atom having a mass and charge equal in magnitude to a helium nucleus; i.e., two protons and two neutrons.

Curie

The special unit of activity. One curie equals 3.700 x 10^{10} nuclear transformations per second. (Abbr. Ci.) Common fractions are:

Megacurie: One million curies (abbr. MCi)
Microcurie: One millionth of a curie (3.7 x 10^{4} disintegrations per second. Abbr. μCi)
Millicurie: One-thousandth of a curie (3.7 x 10^{7} disintegrations per second. Abbr. mCi)
Nanocurie: One-billionth of a curie (Abbr. nCi)
Picocurie: One-millionth of a microcurie (3.7 x 10^{-2}) disintegrations per second (Abbr. pCi)

Decay, Radioactive:

Disintegration of the nucleus of an unstable nuclide by spontaneous emission of charged particles and/or photons.

Dose

A general form denoting the quantity of radiation or energy absorbed. For special purposes it must be appropriately qualified. If unqualified, it refers to absorbed dose.

Absorbed Dose:

The energy imparted to matter by ionizing radiation per unit mass of irradiated material at the place of interest. The unit of absorbed dose is the rad.

One rad = 100 ergs per gram, or 0.01 J/pg.
Cumulative dose: Total dose resulting from repeated exposure to radiation.

Dose Equivalent (DE):

Quantity that expresses all radiations on a common scale for calculating the effective absorbed dose. It is defined as the product of the absorbed dose in rads and certain modifying factors. The unit of DE is the rem.

Exposure:

A measure of the ionization produced in air by x or gamma radiation. It is the sum of the electrical charges on all ions of one sign produced in air when all electrons liberated by photons in a volume element of air are completely stopped in air, divided by the mass of the air in the volume element. The special unit of exposure is the roentgen.

Acute Exposure: Radiation exposure of short duration.

Chronic Exposure: Radiation exposure of long duration by fractionation or protraction.

ICRP:

International Commission on Radiological Protection.

Isotopes:

Nuclides having the same number of protons in their nuclei, and hence the same atomic number, but differing in the number of neutrons, and therefore in the mass number. Almost identical chemical properties exist between isotopes of a particular element. The term should not be used as a synonym for nuclide.

NCRP:

National Council on Radiation Protection and Measurements

Plutonium-238:

Plutonium-238 is a heavy metal which is radioactive and decays by emission of an alpha particle with a half life of 87.4 years.

Quality Factor (QF):

The linear-energy-transfer-dependent factor by which absorbed doses are multiplied to obtain (for radiation protection purposes) a quantity that expresses -- on a common scale for all ionizing radiations -- the effectiveness of the absorbed dose.

Radiation:

1) The emission and propagation of energy through space or through a material medium in the form of waves; e.g., the emission and propagation of electromagnetic waves, or of sound and elastic waves. 2) The energy propagated through space or through a material medium as waves. The term radiation or radiant energy, when unqualified usually refers to electromagentic radiation. Such radiation is commonly classified by frequency: Hertzian, infrared, visible, ultraviolet, x-ray and gamma ray. 3) Corpuscular emissions, such as alpha and beta radiation, or rays of mixed or unknown type, as cosmic radiation.

Background Radiation: Radiation arising from radioactive material other than the one directly under consideration. Background radiation due to cosmic rays and natural radioactivity is always present. There may also be background radiation due to the presence of radioactive substances in other parts of the building, in the building material itself, etc.

External Radiation: Radiation from a source outside the body.

Internal Radiation: Radiation from a source within the body (as a result of deposition of radionuclides in body tissue).

Ionizing Radiation: Any electromagnetic or particulate radiation capable of producing ions, directly or indirectly, in its passage through matter.

Radioactivity:

The property of certain nuclides of spontaneously emitting particles or gamma radiation or of emitting X radiation following orbital electron capture or of undergoing spontaneous fission.

Artificial Radioactivity: Man made radioactivity produced by particle bombardment or electromagnetic irradiation.

Natural Radioactivity: The property of radioactivity exhibited by naturally occurring radionuclides.

Relative Biological Effectiveness (RBE):

The RBE is a factor used to compare the biological effectiveness of absorbed radiation doses (i.e., rads) due to different types of ionizing radiation; more specifically, it is the experimentally determined ratio of an absorbed dose of a radiation in question to the absorbed dose of a reference radiation required to produce an identical biological effect in a particular experimental organism or tissues. The RBE is the ratio of rem to rad. (If 1 rad of fast neutrons equalled in lethality 3.2 rads of 250 KVP x-rays, the RBE of the fast neutron would be 3.2).

Rem:

A special unit of dose equivalent. The dose equivalent in rems is numerically equal to the absorbed dose in rads multiplied by the quality factor, the distribution factor, and any other necessary modifying factors. The rem represents that quantity of radiation that is equivalent -- in biological damage of a specified sort -- to 1 rad of 250 KVP x-rays.

Roentgen (R):

The special unit of exposure. One roentgen equals 2.58×10^{-4} coulomb per kilogram of air.

Specific Acitivity:

Total activity of a given nuclide per gram of a compound, element, or radioactive nuclide.

X-Rays:

Penetrating electromagnetic radiations whose wave lengths are shorter than those of visible light. They are usually produced by bombarding a metallic target with fast electrons in a high vacuum. In nuclear reactions, it is customary to refer to photons originating in the nucleus as gamma rays, and those originating in the extranuclear part of the atom as X-rays. These rays are sometimes called roentgen rays, after their discoverer, W. C. Roentgen.

APPENDIX B

Methodology for short-term dose evaluation of individuals involved in construction of the Miamisburg Park Improvement Project.

The short-term effect from the construction effort on the ponds in the Miamisburg Park involved the establishment of several assumptions. The assumptions used were very conservative and yet effectively described the construction effort.

Both the North and South Ponds were considered together with the contaminated soil being readily available for transport into the environment or readily available for human uptake. In most realistic situations, this is not practical, however, it is the purpose of this evaluation to provide conservatism with credibility.

The soil concentration used for all the short-term evaluations was the maximum found in the first full foot of core samples taken in the North and South Ponds. This concentration was 0.03 nanocuries per gram of soil (0.03 nCi/g). This value is ten times higher than the average of the total 5' core samples taken in the South Pond and approximately 60 times higher than the average value for the North Pond.

The time used for exposure of construction workers was assumed to be 40 days of construction work for eight hours per day. During this construction, each individual involved with the construction is assumed to be subjected to possible (worst case) contamination from the soil which contains minute quantities of plutonium contamination.

One other assumption which was used is the resuspension inhalation model. The value is a factor of 100 greater (i.e., $K = 1 \times 10^{-7}$) than that used previously,[3] (1×10^{-9}) to provide a conservative estimate of additional soil disturbance during the construction project.

One last consideration concerning the short term effect of plutonium during the construction is that final disposition of the plutonium inhaled. At the last part of this section, calculations are shown in which the plutonium assumed to have been inhaled is deposited in the bone.

The general equation used for all inhalation models provides the dose equivalent to the lung of an individual for one year after the time of construction. This equation is:

$$D_R = \frac{51.1\ C\ Ia\ Tfa\ fr\ \Sigma EF(RBE)n}{(1000)\lambda m} \quad (1-e^{-\lambda t})$$

Where:

D_R = dose equivalent delivered to the lung in 365 days from exposure to plutonium-238 in air, rem/year
C = average airborne concentration, μCi/cc.
I_a = average air intake = 2 x 10^7 cc/day.
T = time exposed = 40 days.
f_a = fraction of inhaled material reaching organ of interest = 0.25 for pulmonary region.
f_r = fraction of pulmonary deposition undergoing long-term retention = 0.6 for actinide (class y)
$\Sigma EF(RBE)n$ = effective energy deposition for disintegration = 57.
λ = effective removal rate = 0.0014 day^{-1} for actinides (class y) from the pulmonary region.
m = lung mass = 1000 grams.
1000 = 1000 mrem/rem.

The calculated average concentrations used for the lung dose calculations are dependent upon several types of inhalation models. These are 1) dust loading model, 2) wind suspension model, 3) resuspension model, 4) personal clothing contamination model, and 5) home contamination model. Each model is derived in a different way and each model is used to determine an average concentration of plutonium in air which could be breathed by an individual directly involved in the construction project. The mathematical description of this relationship is:

$$C = S_{max} \cdot f \cdot I$$

where:

C = average concentration of plutonium in air during the 40 days of exposure.
S_{max} = maximum concentration of plutonium found in the first full foot of core samples taken in the ponds - 0.03 nCi/g.
f = a multiplication factor to convert other units to μCi/cc.
I = inhalation model factor.

Each inhalation model provides a different inhalation model factor to arrive at an average concentration. Each of these inhalation model factors and method of calculation is shown in the following:

Dust Loading Model (I_d)

$$I_d = \frac{Cp \cdot As}{Ap} = 1.5 \times 10^{-13} \text{ g/cc}$$

Where:

Cp = total dust loading this area = 100×10^{-12} (max.)
As = area of contaminated sediment = 0.0015 mi^2 (ponds)
Ap = total area supplying particulate matter to area = >1 mi^2

Wind Suspension Model (I_w)

$$I_w = \frac{X\bar{\mu}}{Rp\Omega w} \frac{Rp}{\bar{\mu}^2} \bar{\mu} (G/a)_w = 5.46 \times 10^{-7} \text{ g/m}^3$$

Where:

$\frac{X\bar{\mu}}{Rp\Omega w}$ = dust concentration = 34.1 (max) integral (plume parameter)

$\frac{Rp}{\bar{\mu}^2}$ = wind pickup rate constant = 2×10^{-12} sec/m^2

$\bar{\mu}$ = wind velocity = 5 m/sec

$(G/a)_w$ = sediment available for suspension per unit area = 1600 g/m^2

Resuspension Model

$$I_R = K (G/a)_r F_t = 8.0 \times 10^{-5} \text{ g/m}^3$$

Where:

K = resuspension factor = 10^{-7}/m
$(G/a)_r$ = resuspendable sediment per unit area = 1600 g/m^2
F_t = fraction of time exposed per day (8 hrs/day) = .50 per day (breathing rate for 8 working hours = 1 x 10^7 cc.)

Personal Clothing Contamination Model

$I_p = K\ (G/a)_c\ F_t = 7.5 \times 10^{-7} g/m^3$

Where:

K = clothing resuspension factor = $10^{-6}/m$
$(G/a)_c$ = grams of sediment per unit area of clothing = 1 g/m^2
F_t = fraction of time exposed per day (16 hours/day) = 0.75 day
(breathing rate for 16 hours = 1.5×10^7 cc)

Home Contamination Model

$I_H = K\ (G/a)_h\ F_t = 10 \times 10^{-7}$

Where:

K = resuspension factor (indoors) = $10^{-6}/m$
$(G/a)_h$ = grams of sediment per unit area of home (10% of total dirt) = 1 g/m^2
F_t = fraction of time exposed (24 hours/day = 1

As mentioned earlier, each of the above inhalation model factors are different, and are multiplied by each respective conversion factor to convert each factor to μCi/cc. In each of the following dose calculations, the actual concentration calculated from the different inhalation models are shown.

Dust Loading Model

$$D_R = \frac{51.1(.046 \times 10^{-16}\ \mu Ci/cc)(2 \times 10^7)(40d)(0.25)(0.6)(57)}{(1000)(.0014)(1000)} \left(1 - e^{-(.0014)(365)}\right)$$

D_R = 0.00046 mrem/year to lung

Wind Suspension Model

$$D_R = \frac{51.1(.17 \times 10^{-16})(2 \times 10^7)(40d)(0.25)0.6)(57)}{(1000)(.0014)(1000)} \left(1 - e^{-(.0014)(365)}\right)$$

$D_R = 0.0017$ mrem/year

Resuspension Model

$$D_R = \frac{51.1(.24 \times 10^{-14})(2 \times 10^{7})(40d)(0.25)(0.6)(57)}{(1000)(.0014)(1000)}$$

$$\left(1 - e^{-(.0014)(365)}\right)$$

$D_R = 0.24$ mrem/year to lung

Personal Clothing Contamination Method

$$D_R = \frac{51.1(.23 \quad \times 10^{-16})(2 \times 10^{7})(40d)(0.25)(0.6)(57)}{(1000)(.0014)(1000)}$$

$$\left(1 - e^{-(.0014)(365)}\right)$$

$D_R = 0.0023$ mrem/year to lung

Home Contamination Model

$$D_R = \frac{51.1(.309 \times 10^{-16})(2 \times 10^{7})(40d)(0.25)(0.6)(57)}{(1000)(.0014)(1000)}$$

$$\left(1 - e^{-(.0014)(365)}\right)$$

$D_R = 0.0031$ mrem/year to lung

The following calculations give the dose equivalent to the bone per year from plutonium that was theoretically inhaled in earlier calculations. The fraction to be theoretically transferred to the bone was assumed to be already in the bone for purposes of calculating the dose equivalent.

$$D_R = \frac{51.1(C)(I_a)(T_E)(f_a)\Sigma EF(RBE)n}{(1000)\ \lambda m} \qquad (1 - e^{-\lambda t})$$

where: D_R = dose equivalent delivered to bone in 365 days from 40 days of exposure to plutonium-238 in air, rem
C = average airborne concentration $\mu Ci/cc$
I_a = average air intake = 2×10^7 cc/day
T_E = time exposed = 40 days
f_a = fraction of inhaled material reaching organ (bone) of interest = .05
$\Sigma EF(RBE)n$ = effective energy deposition per disintegration = 284
λ = effective removal rate = 3.0×10^{-5} day^{-1}
m = bone mass = 7 x 10 g
T = 365 days
1000 = 1000 mrem/rem

The following calculations show the dose equivalent values to the bone from the final deposition of the plutonium theoretically inhaled.

Dust Loading Model

$$D_R = \frac{51.1(.046 \times 10^{-16}\ \mu Ci/cc)(2 \times 10^7)(40)(.05)(284)}{(1000)(3 \times 10^{-5})(7 \times 10^3)}$$

$$\left(1 - e^{-(3 \times 10^{-5})(365)}\right)$$

$D_R = 1.4 \times 10^{-4}$ mrem/year

Wind Suspension Model

$$D_R = \frac{51.1(.17 \times 10^{-16})(2 \times 10^{7})(40)(.05)(284)}{(1000)(3 \times 10^{-5})(7 \times 10^{3})}$$

$$\left(1 - e^{-(3 \times 10^{-5})(365)}\right)$$

D_R = .0005 mrem/year

Resuspension Model

$$D_R = \frac{51.1(.24 \times 10^{-14})(2 \times 10^{7})(40)(.05)(284)}{(1000)(3 \times 10^{-5})(7 \times 10^{3})}$$

$$\left(1 - e^{-(3 \times 10^{-5})(365)}\right)$$

D_R = .07 mrem/year

Personal Clothing Contamination Method

$$D_R = \frac{51.1(.23 \times 10^{-16})(2 \times 10^{7})(40d)(.05)(284)}{(1000)(3 \times 10^{-5})(7 \times 10^{3})}$$

$$\left(1 - e^{-(3 \times 10^{-5})(365)}\right)$$

D_R = .0007 mrem/year

Home Contamination Model

$$D_R = \frac{51.1(.309 \times 10^{-16})(2 \times 10^{7})(40d)(.05)(284)}{(1000)(3 \times 10^{-5})(7 \times 10^{3})}$$

$$\left(1 - e^{-(3 \times 10^{-5})(365)}\right)$$

D_R = .0009 mrem/year

Models were also developed for ingestion of plutonium during the construction period. The only model considered was ingestion of sediment. Ingestion of water, vegetables, and fish was not considered because there are no vegetables or fish in the ponds and the pond will be drained of water before the modifications.

For calculation of the dose equivalent from direct ingestion of sediment, it was assumed that a worker ingested four grams during 40 days.

The general equation used for all ingestion models provides the dose equivalent to bone of an individual for one year after the time of construction. This equation is:

$$D_R = \frac{51.1\ C\ I\ f\ w\ \Sigma\ EF\ (RBE)\ n}{(1000)\lambda m}\ (1 - e^{-\lambda t})$$

where:

D_R = dose equivalent delivered to bone during the first full year after ingestion of plutonium-238 in rem.
C = concentration of plutonium in ingestion media - μCi/gram = 0.03×10^{-3} μCi/g
I = quantity of ingestion media in grams

fw = fraction of ingested material reaching organ or interest = 2.4×10^{-5}
$\Sigma EF(RBE)n$ = effective energy deposition per disintegration = 284.
λ = effective removal rate = 3.10×10^{-5} day^{-1}
m = bone mass = 7×10^{3} g
T = 365 days
1000 = 1000 mrem/rem

The following dose calculations show the result of each ingestion model:

<u>Ingestion of Sediment</u>

$$D_R = \frac{51.1\ (.03 \times 10^{-3}\ \mu Ci/g)(4\ g)(2.4 \times 10^{-5})(284)}{(1000)(3 \times 10^{-5})(7 \times 10^{3}\ g)}$$

$$(1 - e^{-(3 \times 10^{-5})(365)})$$

D_R = 0.002 mrem/year

Models were also developed for absorption of plutonium during the construction period both through the skin and through wounds.

The general equation used for both absorption models is:

$$D_R = \frac{51.1\ q\ f2^1 \Sigma\ E\ F\ (RBE)\ n}{(1000)\lambda m} \quad (1\text{-}e^{-\lambda t})$$

where:

D_R = dose equivalent delivered to bone during the first full year after absorption of plutonium-238 in rem.
q = quantity of plutonium entering the body via absorption in µCi.
$f2^1$ = fraction from blood to organ of reference = 0.8
$\Sigma EF(RBE)n$ = effective energy deposition per disintegration = 284.
λ = effective removal rate = 3.0×10^{-5} day
m = bone mass = 7×10^3 grams.
T = 365 days
1000 = 1000 mrem/rem

The calculated quantity of plutonium (q) entering the body depends upon the absorption models. In the following, the values for q are calculated from the mathematical equations below for each absorption model:

Absorption through Skin

q = C(G/a)w Am Rabs Sw/s d/y

where:

C = concentration of plutonium in sediment = $.03 \times 10^{-3}$ µCi/g.
(G/a/w) = amount of sediment deposited per unit area = 0.1 g/m^2
Am = skin area, standard man = 1.85 m^2
Rabs = absorption rate through skin = 1.4×10^{-4}/day.
Sw/s = fraction of plutonium soluble = 1×10^{-4}
d/y = days per year absorption = 40 days

Absorption through Wounds

$q = C(G/_a)_w A_w \text{ Rabs } Sw/s \; d/y$

Where:

C = concentration of plutonium in sediment = 0.03×10^{-3} μCi/g.
$(G/_a)_w$ = amount of sediment deposited per unit area = 0.1 g/m²
A_w = skin area continuously abraded (1% of the total skin area) = 1.85×10^{-2} m²
Rabs = absorption rate through wounds = 1.4×10^{-2}/day
$Sw/_s$ = fraction of plutonium soluble = 1×10^{-4}
d/y = days/year of absorption = 40 days

Both absorption model doses are shown below.

Absorption through Skin

$$D_R = \frac{51.1\ (.03 \times 10^{-3})(0.1\ g/m^2)\ (1.85\ m^2)(1.4 \times 10^{-4}/day)(1 \times 10^{-4}) \times (40\ day)(.8)(284)}{(1000)(3 \times 10^{-5})(7 \times 10^3\ g)}$$

$$\times\ (1 - e^{-(3 \times 10^{-5})(365)})$$

$D_R = 1.9 \times 10^{-6}$ mrem/year

Absorption through Wounds

$$D_R = \frac{51.1(.03 \times 10^{-3})(0.1\ g/m^2)(1.85 \times 10^{-2}\ M^2)(1.4 \times 10^{-2}/day) \times (1 \times 10^{-4})(40\ d)(.8)(284)}{(1000)(3 \times 10^{-5})(7 \times 10^3\ g)}$$

$$\times\ (1 - e^{-(3 \times 10^{-5})(365)})$$

$D_R = 1.9 \times 10^{-6}$ mrem/year

APPENDIX C

Methodology for Long-Term Dose Evaluation of Public from Miamisburg Park Improvement Project

The North Pond was evaluated only from the inhalation pathway since access will be restricted to zero because of a constructed fence. However, if necessary to estimate other pathways for the North Pond, it is considerably less than the same pathways considered for the South Pond since the plutonium levels are less. The concentration of sediment used for the North Pond evaluation was the highest core value (0.03 nCi/g) for any core sample in either pond and higher than all values in the North (Solar) Pond.

The South Pond was evaluated for the inhalation, ingestion, and absorption pathways. The concentration of sediment used for the South Pond evaluation was the highest (0.03 nCi/g) of the South Pond core sampling data.

The time was considered for 70 years of continuous exposure and the dose equivalent for each pathway is that total during the 70 years.

The general dose equation used for continuous exposure for the inhalation models covering the North Pond is mathematically expressed by:

$$D_R = \frac{51.1\ C\ I_a\ Tf_a\ fr\ \Sigma EF(RBE)n}{1000\ \lambda m} \left(1 - \frac{1-e^{-\lambda t}}{\lambda t}\right)$$

where:

- D_R = dose equivalent delivered to the lung in 70 years from exposure to plutonium-238 in air.
- C = average airborne concentration, μCi/cc.
- I_a = average air intake = 2×10^7 cc/day.
- T = time exposed =70 years = 2.555×10^4 days.
- f_a = fraction of inhaled material reaching organ of interest = 0.25 for pulmonary region.
- f_r = fraction of pulmonary deposition undergoing long-term retention = 0.6 for actinide (class y).
- $\Sigma EF(RBE)n$ = effective removal rate, 0.0014 day^{-1} for actinides (class y) from pulmonary region.
- m = lung mass, 1000g.
- 1000 = 1000 mrem/rem.

The calculated average concentrations are obtained by the same methodology as that used for the short-term evaluation.

The mathematical description of this relationship is:

$$C = S_{avg} \cdot f \cdot I$$

where:

C = average concentration of plutonium-238 in air during 70 years of exposure.
S_{avg} = average concentration of plutonium found in the North Pond = 0.03 nCi/g.
f = a multiplication factor to convert other units to µCi/cc.
I = Inhalation model factor.

Each of the inhalation models for the North Pond and the method of calculation is shown in the following:

<u>Dust Loading Model (Id)</u>

$$I_d = \frac{Cp \cdot As}{Ap} = 5.0 \times 10^{-14}$$

where:

Cp = total dust loading this area = 100×10^{-12} (max)
As = area of contaminated sediment = 0.0005 mi^2
Ap = total area supplying particulate matter to area >1 m^2

<u>Wind-Suspension Model (I_W)</u>

$$I_W = \frac{X\bar{\mu}}{Rp\Omega_W} \frac{Rp}{\bar{\mu}^2} \bar{\mu} (G/a)_W = 2.4 \times 10^{-7}$$

Where $\frac{X\bar{\mu}}{Rp\Omega_W}$ = dust concentration = 15 integral (plume parameter) for unstable conditions wind from east or west and "worst case" of 100 m (300') width of strip infinitely long.

$\frac{Rp}{\bar{\mu}^2}$ = wind pickup rate constant = 2×10^{-12} sec/m^2

$\bar{\mu}$ = wind velocity = 5 m/sec

$(G/a)_W$ = sediment available for suspension per unit area = 1600 g/m^2 (the "very surface" or top .1 centimeter)

Resuspension Model (I_R)

$$I_R = K\ (G/a)_r\ F_T = 8.0 \times 10^{-7}$$

where:

K = resuspension factor = 1×10^{-9} /m
$(G/a)_r$ = resuspendable sediment per unit area = 1600 g/m^2
F_T = fraction of time exposed per day (8 hours per day) = (.5). (Breathing rate for 8 hours = 1×10^7 cc)

In each of the following dose calculations, the results for each inhalation model considered for the North Pond is shown.

Dust Loading Model

$$D_R = \frac{51.1(1.5 \times 10^{-18}\ \mu Ci/cc)(2 \times 10^7)(2.555 \times 10^4 d)(.25)(0.6)(57)}{(1000)(.0014)(1000)} \times \left(1 - \frac{1-e^{-(.0014)(2.555 \times 10^4)}}{(.0014)(2.555 \times 10^4)}\right)$$

D_R = 0.23 mrem/70 years.

Wind Suspension Model

$$D_R = \frac{51.1(7.2 \times 10^{-18}\ \mu ci/cc)(2 \times 10^7)(2.555 \times 10^4\ d)(.25)(0.6)(57)}{(1000)(.0014)(1000)} \left(1 - \frac{1-e^{-(.0014)(2.555 \times 10^4)}}{(.0014)(2.555 \times 10^4)}\right)$$

D_R = 1.12 mrem/70 years.

Resuspension Model

$$D_R = \frac{51.1(2.4 \times 10^{-17}\ \mu Ci/cc)(2 \times 10^7)(2.555 \times 10^4\ d)(.25)(.6)(57)}{(1000)(.0014)(1000)} \left(1 - \frac{1-e^{-(.0014)(2.555 \times 10^4)}}{(.0014)(2.555 \times 10^4)}\right)$$

D_R = 3.72 mrem/70 years.

The general dose equation used for the 70-year continuous exposure for the inhalation models concerning the South Pond is the same as that for the North Pond. In addition, the inhalation model factors are also the same. The following calculations show the dose of each inhalation model:

Dust Loading Model

$$D_R = \frac{51.1(1.5 \times 10^{-18}\ \mu Ci/cc)(2 \times 10^7)(2.555 \times 10^4\ d)(.25)(0.6)(57)}{(1000)(.0014)(1000)}$$

$$\left(1 - \frac{1-e^{-(.0014)(2.555 \times 10^4)}}{(.0014)(2.555 \times 10^4)}\right)$$

D_R = 0.23 mrem/70 years.

Wind Suspension Model

$$D_R = \frac{51.1(7.2 \times 10^{-18})(2 \times 10^7)(2.555 \times 10^4\ d)(.25(.6)(57)}{(1000)(.0014)(1000)}$$

$$\left(1 = \frac{1-e^{-(.0014)(2.555 \times 10^4)}}{(.0014)(2.555 \times 10^4)}\right)$$

D_R = 1.12 mrem/70 years.

Resuspension Model

$$D_R = \frac{51.1(2.4 \times 10^{-17})(2 \times 10^7)(2.555 \times 10^4\ d)(.25)(.6)(57)}{(1000)(.0014)(1000)}$$

$$\left(1 - \frac{1-e^{-(.0014)(2.555 \times 10^4)}}{(.0014)(2.555 \times 10^4)}\right)$$

D_R = 3.72 mrem/70 years.

Other inhalation models were used for the South Pond evaluation for continuous exposure. These were inhalation from clothing and home contamination. These inhalation models are calculated by the equations shown below:

Personal Clothing Contamination Model (I_P)

$$I_P = K\,(G/a)c\;F_T = 0.75 \times 10^{-6}$$

where:

K = clothing resuspension factor = 10^{-6}/m

$(G/a)_C$ = grams of sediment per unit area of clothing = 1g/m^2

F_T = fraction of time exposed per day (16 hours per day) = .75

= 1.5×10^7 cc (breathing rate) for 16 hours.

Home Contamination Model (I_H)

$$I_H = K\,(G/a/h\;F_T = 1 \times 10^{-6})$$

where

K = resuspension factor (in-doors) = 10^{-6}/m

$(G/a/h)$ = grams of sediment per unit area of house (10% of total dirt) = 1 g/m^2

F_T = fraction of time exposed (24 hours/day) = 1

These inhalation model dose results are shown below:

Personal Clothing Contamination Model

$$D_R = \frac{51.1(2.24 \times 10^{-17})(2 \times 10^7)(2.555 \times 10^4\ d)(.25)(0.6)(57)}{(1000)(.0014)(1000)} \left(1 - \frac{1-e^{-(.0014)(2.555 \times 10^4)}}{(.0014)(2.555 \times 10^4)}\right)$$

D_R = 3.47 mrem/70 years.

Home Contamination Model

$$D_R = \frac{51.1(3 \times 10^{-17})(2 \times 10^{7})(2.555 \times 10^{4}\ d)(.25)(0.6)(57)}{(1000)(.0014)(1000)}$$

$$\left(1 - \frac{1-e^{-(.0014)(2.555 \times 10^{4})}}{(.0014)(2.555 \times 10^{4})}\right)$$

D_R = 4.65 mrem/70 years.

Models were developed for ingestion of plutonium-238 continuously for 70 years in the south pond. These models included ingestion of sediment, fish, and water.

The general equation used for ingestion is:

$$D_R = \frac{51.1\ C\ I\ T_y\ f_w\ \Sigma EF(RBE)n}{1000\ \lambda m} \left(1 - \frac{1-e^{-\lambda T}}{\lambda T}\right)$$

where:

D_R = dose equivalent delivered to bone during the 70 years of exposure in rem.

C = concentration of plutonium in ingestion media.

I = quantity of ingestion media in grams.

T_y = time = (70 years).

f_w = fraction of ingested material reaching organ on interest = 2.4×10^{-5}.

$\Sigma EF(RBE)n$ = effective energy deposition per disintegration = 284

λ = effective removal rate = 3.0×10^{-5} day^{-1}

m = bone mass = 7×10^{3} grams

T = time = 70 years x 365 d/yr = $2.5\text{-}5 \times 10^{4}$ days

1000 = 1000 mrem/rem

In the calculation of the sediment ingestion model, a value of 4 grams of sediment per year was assumed to have been ingested. Also, 9000 grams of fish per year was assumed to have been ingested with a ratio of fish to water concentration of 5 and of water to sediment concentration of 1×10^{-5}.

The following calculations show the results of the ingestion models.

Ingestion of Sediment

$$D_R = \frac{51.1(0.03 \times 10^{-3}\ \mu Ci)(4\ g)(70\ y)(2.4 \times 10^{-5})(284)}{(1000)(3 \times 10^{-5})(7 \times 10^{3})}$$

$$\left(1 - \frac{1-e^{-(3 \times 10^{-5})(2.555 \times 10^{4}\ d)}}{(3 \times 10^{-5})(2.555 \times 10^{4}\ d)}\right)$$

D_R = 4.21 mrem/70 yr

Ingestion of Fish

$$D_R = \frac{51.1(0.03 \times 10^{-3}\ \mu Ci)(.45\ g)(70\ y)(2.4 \times 10^{-5})(284)}{(1000)(3 \times 10^{-5})(7 \times 10^{3}\ g)}$$

$$\left(1 - \frac{1-e^{-(3 \times 10^{-5})(2.555 \times 10^{4}\ d)}}{(3 \times 10^{-5})(2.555 \times 10^{4}\ d)}\right)$$

D_R = 0.47 mrem/70 yr

Ingestion of Water

The 70-year dose equivalent from ingestion of water at the rate of one liter (1,000 grams) per day for 365 days would be 8 times the dose equivalent from fish. The water concentration is assumed to be 5 times less than fish, but the grams ingested for water would be ∿40 times greater; thus, the overall 70-year dose would = 3.81 mrem/70 yrs.

Models were developed for absorption of plutonium from the south pond continuously for 70 years. Two absorption models were developed, one through the skin and one through wounds.

The general equation used for both absorption models is:

$$D_R = \frac{51.1\ q\ T\ f_2'\ \Sigma EF(RBE)n}{1000\ \lambda m}\left(1 - \frac{1-e^{-\lambda T}}{\lambda T}\right)$$

where:

D_R = dose equivalent delivered to bone during 70 years of continuous absorption of plutonium in rem.

q = quantity of plutonium entering the body via absorption in µCi.

T = time (70 years)

f_2' = fraction from blood to organ of reference = .8

$\Sigma EF(RBE)n$ = effective energy deposition per disintegration = 284

λ = effective removal rate = 3.0×10^{-5}/day.

m = bone mass = 7×10^3 grams

1000 = 1000 mrem/rem

The calculated quantity of plutonium (q) entering the body depends upon the absorption models. In the following the values for q are calculated from the mathematical equations below for each absorption model.

Absorption Through Skin

$$q = C\ (G/a)_w\ Am\ Rabs\ S_{w/s}\ d/y$$

where:

C = concentration of plutonium in sediment = 0.03 nCi/g

$(G/a)_w$ = amount of sediment deposited per unit area = 0.1 g/m²

Am = skin area standard man = 1.85 m²

Rabs = absorption rate through skin = 1.4×10^{-4} day

$S_{w/s}$ = fraction of plutonium soluble = 1×10^{-4}

d/y = days per year absorption = 365 days

Absorption Through Wounds

$$q = C\ (G/a)_w\ Am\ Rabs\ S_{w/s}\ d/y$$

where:

C = concentration of plutonium in sediment = 0.03 nCi/g

$(G/a)_w$ = amount of sediment deposited per unit area = 0.1 g/m^2

Am = skin area continuously abraded (1% of total skin area) = 1.85×10^{-2} m^2

$Rabs$ = absorption rate through wounds = 1.4×10^{-2}/day

$S_{w/s}$ = fraction of plutonium soluble = 1×10^{-4}

d/y = days/year of absorption = 365 days

The calculations of the absorption model dose are shown below:

Absorption Through Skin

$$D_R = \frac{51.1(0.03 \times 10^{-3})(0.1g/m^2)(1.85m^2)(1.4 \times 10^{-4}/d)(1 \times 10^{-4})}{(1000)(3 \times 10^{-5})(7 \times 10^3 g)}$$

$$\times \frac{(2.555 \times 10^4)(0.8)(284)}{} \left(1 - \frac{1-e^{-(3 \times 10^{-5})(2.555 \times 10^4)}}{(3 \times 10^{-5})(2.555 \times 10^4)}\right)$$

D_R = 0.033 mrem/70 yr

Absorption Through Wounds

$$D_R = \frac{51.1(0.03 \times 10^{-3})(0.1)(1.85 \times 10^{-2})(1.4 \times 10^{-2})}{(1000)(3 \times 10^{-5})(7 \times 10^3 \text{ g})}$$

$$\times \frac{(1 \times 10^{-4})(2.555 \times 10^4 \text{ d})(0.8)(284)}{}$$

$$\times \left(1 - \frac{1-e^{-(3 \times 10^{-5})(2.555 \times 10^4)}}{(3 \times 10^{-5})(2.555 \times 10^4)}\right)$$

D_R = 0.033 mrem/70 yr

One last consideration concerning the long term effect of plutonium is that final disposition of the theoretical plutonium inhaled. At the last part of this section, calculations are shown in which the plutonium assumed to have been inhaled is deposited in the bone.

The following calculations describe the final desposition of plutonium that was theoretically inhaled in earlier calculations. The average concentration of plutonium from each inhalation model is used in a general dose calculation which is mathematically described by:

$$D_R = \frac{51.1\ (C)(I_a)(T)(f_a)\ \Sigma EF(RBE)n}{1000\ \lambda m} \left(1 - \frac{1-e^{-\lambda T}}{\lambda T}\right)$$

where:

D_R = dose equivalent delivered to bone in 70 years from continuous exposure to plutonium-238 in air, rem.

C = average airborne concentration, μCi/cc

I_a = average air intake = 2×10^7 cc/day

T = time exposed = 2.555×10^4 days

f_a = fraction of inhaled material reaching organ of interest = .05

ΣEF(RBE)n = effective energy deposition per disintegration = 284

λ = effective removal rate = 3.0×10^{-5} day^{-1}

m = bone mass = 7×10^3 g

1000 = 1000 mrem/rem

The following calculations show the dose equivalent values to the bone from the final deposition of the plutonium theoretically inhaled.

Dust Loading Model

$$D_R = \frac{51.1(1.5 \times 10^{-18})(2 \times 10^7)(2.555 \times 10^4 d)(.05)(284)}{(1000)(3 \times 10^{-5})(7 \times 10^3\ g)}$$

$$\left(1 - \frac{1 - e^{-(3 \times 10^{-5})(2.555 \times 10^4)}}{(3 \times 10^{-5})(2.555 \times 10^4)}\right)$$

D_R = 0.80 mrem/70 yr

Wind Suspension Model

$$D_R = \frac{51.1(7.2 \times 10^{-18})(2 \times 10^7)(2.555 \times 10^4 \text{ d})(.05)(284)}{(1000)(3 \times 10^{-5})(7 \times 10^3 \text{ g})}$$

$$\left(1 - \frac{1 - e^{-(3 \times 10^{-5})(2.555 \times 10^4)}}{(3 \times 10^{-5})(2.555 \times 10^4)}\right)$$

D_R = 3.84 mrem/70 yr

Resuspension Model

$$D_R = \frac{51.1(2.43 \times 10^{-17})(2 \times 10^7)(2.555 \times 10^4 \text{ d})(.05)(284)}{(1000)(3 \times 10^{-5})(7 \times 10^3)}$$

$$\left(1 - \frac{1 - e^{-(3 \times 10^{-5})(2.555 \times 10^4)}}{(3 \times 10^{-5})(7 \times 10^4)}\right)$$

D_R = 12.9 mrem/70 yr

Personal Clothing Contamination Model

$$D_R = \frac{51.1(2.24 \times 10^{-7})(2 \times 10^7)(2.555 \times 10^4 \text{ d})(.05)(284)}{(1000)(3 \times 10^{-5})(7 \times 10^3)}$$

$$\left(1 - \frac{1 - e^{-(3 \times 10^{-5})(2.555 \times 10^4)}}{(3 \times 10^{-5})(2.555 \times 10^4)}\right)$$

D_R = 11.96 mrem/70 yr

Home Contamination Model

$$D_R = \frac{51.1(3 \times 10^{-17})(2 \times 10^7)(2.555 \times 10^4 \text{ d})(.05)(284)}{(1000)(3 \times 10^{-5})(7 \times 10^3)}$$

$$\left(1 - \frac{1 - e^{-(3 \times 10^{-5})(2.555 \times 10^4)}}{(3 \times 10^{-5})(2.555 \times 10^4)}\right)$$

D_R = 16.0 mrem/70 yr