Biomedical Aspects of Plutonium

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Plutonium is a component of global fallout originating from nuclear weapons testing and from burnup reentry of a satellite that contained plutonium as a heat source in a thermoelectric power device. However, current concerns are largely directed towards possible health effects that might result from the small quantities of plutonium that may enter the environment as a result of planned worldwide proliferation of nuclear power plants.

The toxicity of plutonium has been of concern since milligram quantities were first produced in the Oak Ridge Reactor starting in late 1943. In 1944 milligram quantities were allocated for biomedical studies. Since that time, biological studies with plutonium have been conducted in several laboratories in the United States and abroad. Much has been learned about the toxicology of plutonium. My objective will be to summarize our current knowledge. Details have been published in technical journals and reports. Much of the information has also appeared in several recent reviews (Hodge, Stannard, Hursh; Bair and Thompson; Bair; Thompson; Bair, Richmond, and Wachholz; Dolphin, et al.; Buldakov, et al.; Sanders, et al.; Healy; Thompson; Park; Stover, Wildung and Garland).

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• Physical Properties

Plutonium, element 94 in the Periodic Table is produced in a reactor by neutron bombardment of uranium. There are nine principal isotopes of plutonium. The most common are ^{238}Pu and ^{239}Pu , Table 1. Plutonium-238 is used as a heat source in thermoelectric power devices such as have been used on lunar missions, communications satellites, and heart pacemakers. Plutonium-238 has a half-life of 86 years and emits alpha radiation. Plutonium-239 is used as a fissionable material in explosive nuclear devices and as a fuel in nuclear power reactors. Plutonium-239 has a half-life of 24,000 years and also emits alpha radiation. The data in Table 1 illustrates that a 1 μm diameter PuO_2 particle comprised of ^{238}Pu is almost 300 times more radioactive than the same size ^{239}Pu particle. This high amount of energy causes ^{239}Pu to be thermally hot, a useful property for applications requiring a constant heat source. This property also causes the particles to be unstable resulting in $^{238}\text{Pu}_2$ being more soluble than $^{239}\text{PuO}_2$ which is quite insoluble.

Plutonium oxidizes readily in air and, thus plutonium dioxide is the compound most likely to be encountered following an accidental release from a chemistry laboratory, reactor, fuel processing plant, shipping container, or from a nuclear weapon accident.

Plutonium oxide particles are irregular in shape and size, Figure 1. They are about 10 times the density of water droplets. This electron micrograph illustrates the angular shapes and the broad spectrum of sizes of particles in a plutonium aerosol.

The alpha particle emitted by plutonium is an energetic helium nucleus. It is 7000 times heavier than beta particles or electrons and has a double positive charge. An electron carries a single negative charge. The alpha particles emitted by plutonium have a kinetic energy of about 5 MEV. Because of their mass, relatively low velocity and double positive charge, alpha particles spend more time in the vicinity of atoms they pass, and exert much larger impulses on the electrons of the atoms they pass than beta particles. As a result, the alpha particles give up their energy to the medium through which they pass at a greater rate than beta particles and have a much shorter range. A 5 MEV alpha particle from plutonium travels about 50 μm in tissue while a 1 MEV beta particle will travel 3500 μm . Thus, an alpha particle travels a relatively short distance in tissue but

can be very damaging to the small amount of tissue it traverses.

• Routes to Man

Plutonium released to the environment may reach man through three pathways, Fig 2. Plutonium dispersed in air may be inhaled and deposited in the respiratory tract. Plutonium deposited in soil may be taken up by plants and if the contaminated plants are eaten the plutonium can enter the gastrointestinal tract of man. This pathway may involve animals as well as plants in the food chain. Plutonium deposited in soil can be resuspended in air by wind activity and again made available for inhalation by man and animals. Plutonium released to water may reach man through aquatic organisms such as fish, shellfish, etc.

Detailed analysis of these pathways indicate that the most important route to man is likely to be inhalation of air containing plutonium. For example, only a small percentage of plutonium in soil is incorporated into plants. Table 2 shows data from a laboratory experiment with barley plants. Under these controlled conditions the concentration of Pu in the plant shoots is only 1/60,000 of the concentration in soil. In these studies the roots are confined in pots and thus have access to a large fraction of the plutonium in the soil. Even lower concentration factors would be expected in plants grown outside in fields and gardens contaminated with plutonium.

Another modifying factor is the relatively low percentage of plutonium absorbed from the gastrointestinal tract, Table 3. The highest value observed in experiments is 2 percent in rats for a highly acid plutonium nitrate, a form of plutonium that man would not encounter in the environment. Most values reported from experiments with plutonium nitrate and plutonium citrate in rats, dogs, and pigs are much less than 0.1 percent. For plutonium dioxide, values of 0.003 percent and less have been reported.

Experiments have also shown that plutonium is not readily taken up by aquatic organisms. Thus, plutonium dispersed in water is not considered to be a major pathway to man.

Because of the short range of alpha radiation in tissue, plutonium passing through the gastrointestinal tract will not irradiate the sensitive cells deep in the walls of the esophagus, stomach, and intestine. Thus the only potential hazard from ingested plutonium is from the small amount

absorbed into the blood and deposited in other tissues and organs.

Also plutonium deposited on the skin surface is not likely to cause harm because the alpha radiation cannot penetrate to the sensitive germinal cells in the skin.

- Inhaled Plutonium

Airborne plutonium particles are similar to most other particles when they are inhaled in that deposition in the respiratory tract is primarily dependent upon the physical properties of the particles and the respiratory characteristics of the individual inhaling the particles. After deposition in the respiratory tract, plutonium may be retained in the lung for a long time, be translocated to other tissues in the body, accumulated in the lymph nodes associated with the respiratory tract or excreted in urine and feces. The actual disposition of inhaled plutonium depends largely upon the physical and chemical characteristics of the inhaled material.

- A. Clearance of Plutonium from Lung

The clearance of inhaled plutonium from lung has been characterized in animal experiments and to a lesser extent in man following accidental inhalation exposures. Fig 3 illustrates the clearance of plutonium from lung. The fraction of plutonium deposited in the body is plotted against time in days after the inhalation exposure. Within the first week after exposure, a large fraction of the deposited plutonium is usually cleared from the respiratory tract and excreted, mostly through the gastrointestinal tract. The magnitude of the fraction cleared within the first week depends upon the fraction of readily soluble material present and also upon the distribution of the deposited plutonium within the respiratory tract. Plutonium particles deposited on the ciliated epithelium of the upper respiratory tract are trapped in mucus, propelled to the esophagus, and swallowed. Plutonium deposited in the lower regions of the lung, in the alveoli, is not readily available for clearance and may be incorporated into the cellular structure of the lung and retained for a long time. The clearance of plutonium deposited in the lower lung is generally assumed to be exponential over a

reasonably long period of time and a retention half-time is calculated. This is defined as the time required for the lung burden to be reduced by one half.

The kinetics of the clearance of plutonium from lung are complicated and difficult to quantitate. Animal experiments and limited human data provide a range of values for the retention half-times of several plutonium compounds. These are summarized in Fig 4 for ^{238}Pu and ^{239}Pu . The retention half-times for organic complexes of plutonium, plutonium nitrate and fluoride range from less than 100 days to about 300 days in rats and dogs. The retention half-times for PuO_2 are substantially longer, ranging from 200 to 500 days in rats, 300 to 1000 days in dogs and 250 to 300 days in human beings. The wide range of values for dogs is largely due to extensive experimentation with a variety of plutonium oxides with different particle size characteristics. The relatively low retention values for human beings, compared with dogs, suggests either that man clears plutonium particles from his lungs more rapidly than do dogs or that the materials inhaled in the human accident cases were more soluble than plutonium dioxide. Studies with $^{238}\text{PuO}_2$ in dogs indicate a much shorter lung retention time than is observed for $^{239}\text{PuO}_2$. This appears to be due to instability of $^{238}\text{PuO}_2$ particles, possibly caused by radiolysis in tissue fluids increases the solubility.

Figure 5 illustrates the effect of particle size and isotope on retention of plutonium in lung. Retention half-times are given in days for several plutonium oxides. Plutonium oxide prepared by calcining the oxalate at 1000°C was retained with a half-time of 650 to 950 days compared with 300 to 400 days for an oxalate calcined at 350° . Oxides prepared from metal powder at temperatures of 123° to 450° were retained in lung longer than the low fired oxalate. Particle size is also important. The small particle size high-fired oxide was retained with a half-time of 400-500 days, compared with half-times up to 900 days for the larger particle size high fired oxide. Retention of the small particle size $^{238}\text{PuO}_2$ was less than for the comparable $^{239}\text{PuO}_2$.

These data indicate that the retention time of plutonium in lung varies depending upon the plutonium compound inhaled and, in the case of PuO_2 , the particle size and the isotope.

B. Spatial Distribution of Plutonium Within Lung

From the moment plutonium is deposited in the respiratory tract, biological and physical forces are at work to cause the removal of the plutonium. That these forces are not as effective for plutonium as for other inhaled material is indicated by the relatively long retention times observed for plutonium. Particles deposited in alveolar or air spaces in the lung may be cleared via the lymphatic system, a complex network of vessels in the lung which collect excess fluid and foreign material. The lymphatic vessels pass through a series of lymph nodes which act as filters removing foreign material such as plutonium before the lymphatic fluid is returned to the blood stream. Plutonium particles may also be transported from the lung on a layer of mucus which is continually moved up the airways by the action of cilia which line the airways. Plutonium removed from the lung by this route is swallowed and excreted. Plutonium may also be slowly dissolved and absorbed into the blood. With all of these processes at work removing plutonium from the lung, even at low rates, it is difficult to visualize plutonium remaining static throughout its residence time in lung. It is not possible to document the course of individual particles and aggregates of plutonium in lung. However, the temporal and spatial characteristics of plutonium within tissues can be inferred from autoradiographs of tissue sections prepared from animals exposed to plutonium aerosols.

The first observation is that plutonium and especially insoluble plutonium compounds are nonuniformly deposited throughout lung. Further, plutonium may deposit unequally among the lung lobes or among portions of lung lobes. Studies of inhaled plutonium nitrate in both rats and dogs show that immediately following the inhalation exposure, plutonium is present in both particulate and nonparticulate forms, as evidenced by the presence of alpha stars and single tracks in autoradiographs, Figure 6. Autoradiographs from dogs exposed to inhaled $^{239}\text{PuO}_2$ show an initial relatively diffuse distribution of plutonium throughout the entire lung. Some of the plutonium will be rapidly removed from the respiratory tract by the mucociliary pathway and some may be dissolved and absorbed into the blood. The remaining plutonium may be engulfed or phagocytized by cells called macrophages.

Phagocytized plutonium particles are rapidly localized in the cells, Fig 7. The alveolar macrophage appears to be capable of transporting plutonium from the alveoli or air sacs to the ciliated epithelium lining the bronchioles. These phagocytic cells containing plutonium particles and aggregates can then be removed from the lung in the mucous blanket which is propelled up the respiratory passage by ciliary action.

Both soluble and insoluble plutonium not immediately cleared from the lung tend to become further aggregated. This mobility and aggregation of plutonium may have large effects on the temporal and spatial distribution of the alpha radiation dose. A few days after inhalation of plutonium nitrate, single tracks in autoradiographs decrease and after several weeks nearly all of the plutonium appears to be aggregated, Figure 8.

Plutonium particles, and to a lesser extent aggregates of soluble plutonium, are transported via lymphatic vessels and collected in the thoracic lymph nodes. Autoradiographs of lung tissues taken from dogs several weeks and months after inhalation of PuO_2 show alpha stars concentrated in subpleural areas, apparently in lymphatic vessels, Figure 9. Autoradiographs also suggest that some plutonium particles become immobilized in scar tissue in subpleural areas. Figure 10 is an example of a $^{238}\text{PuO}_2$ particle located in scar tissue of a dog 5 years after exposure. Areas around the scar tissue appear to be normal.

Plutonium particles transported to lymph nodes eventually appear sequestered in "hot spots" of scar tissue and do not appear to be mobile. The residence time for plutonium in lymph nodes appears to be very long.

There is also much experimental evidence for the absorption of plutonium into the blood almost immediately after deposition of soluble and even "insoluble" plutonium compounds in the respiratory tract.

Although the kinetics are unknown and even a qualitative description is still rather primitive, there is ample evidence that plutonium deposited in lung is subjected to biological and physical forces. This argues against either particles or aggregates of plutonium remaining static indefinitely, except for the plutonium that becomes immobilized in scar tissue. To the contrary, while the rates may be low, movement of plutonium within lung tissue by several mechanisms certainly occurs as the lung attempts to expel plutonium and other foreign material which may have been inhaled. The migration of deposited plutonium particles in lung partially compensates for the nonuniformity of the radiation exposure from plutonium particles.

C. Translocation of Plutonium from Lung to Other Tissues

Plutonium may be removed from lung via bronchial and tracheal mucociliary processes, introduced into the gastrointestinal tract and excreted. This accounts for only a part of the plutonium cleared from the respiratory tract. Another fraction is accumulated by the lymphatics and deposited in lymph nodes. Another fraction may be solubilized, absorbed into the circulatory system and either deposited in other tissues in the body or excreted in urine. The relative distribution among body tissues of plutonium translocated from lung by the circulating blood is essentially the same for all plutonium compounds, but may differ quantitatively depending upon the chemical and physical state of the plutonium inhaled.

In beagle-dogs within several months after inhalation of plutonium nitrate, the fraction remaining in lung decreased to 40 percent or less of the amount deposited in the lower respiratory tract, Figure 11. Translocation of plutonium from lung resulted in bone accumulating about 30 percent, and liver about 10 percent of the alveolar-deposited plutonium. A small percentage was found in spleen, lymph nodes, and other soft tissues and the remainder was excreted in urine and feces.

When plutonium dioxide is inhaled, the lymphatic system accounts for a large fraction of plutonium cleared from lung, Figure 12. Data from a 11-year

study with beagle dogs shows that after 5 years both lung and thoracic lymph nodes each contained 30 percent of the plutonium initially deposited in the lower respiratory tract. After 11 years the amount in the lung had decreased to about 9 percent and the thoracic lymph nodes had accumulated 40 percent. Translocation of plutonium from lung resulted in levels in liver of about 10 percent of the alveolar deposited plutonium, in bone of about 5 percent and in the abdominal lymph nodes of about 7 percent.

The average radiation doses to these tissues bear the same relationship as the plutonium concentration in the tissues, Table 4. The average concentration of plutonium was highest in the thoracic lymph nodes and next highest in the abdominal lymph nodes. Average concentrations in lung and liver were over 1000 times less than those in the thoracic lymph nodes. The concentrations in spleen and bone were about one-fifth to one-tenth those in lung. Thus, the lymph nodes received a much higher average radiation exposure than other tissues in the body.

Data was presented showing that $^{238}\text{PuO}_2$ may be cleared from lung more rapidly than $^{239}\text{PuO}_2$. It has also been found that translocation of ^{238}Pu from lung to other tissues in the body may be greater than for ^{239}Pu , Figure 13. Distributions of plutonium in tissues of beagle dogs 5 years after inhalation of $^{238}\text{PuO}_2$ and $^{239}\text{PuO}_2$ are compared. After 5 years only 10 percent of the body burden of the ^{238}Pu was in lung compared with 46 percent for ^{239}Pu . Accumulation in thoracic lymph nodes was three times greater for ^{239}Pu than for ^{238}Pu ; however, the bone burden of ^{238}Pu was 12 times that of ^{239}Pu . This illustrates that the behavior of $^{238}\text{PuO}_2$ in the body may differ significantly from that of $^{239}\text{PuO}_2$.

Because of the concern for possible genetic effects of plutonium deposited in the body, measurements have been made of the amount of plutonium which accumulates in the gonads of experimental animals. This is summarized in Table 5. About 0.05 percent of the plutonium in the circulating blood may deposit in testes and only about 0.01 percent in ovaries.

The data presented so far have been obtained from animal experiments. Human contamination has occurred as a result of occupational exposures in the nuclear industry and as a result of exposure to fallout plutonium from nuclear weapons testing. Tissues obtained from a number of human autopsy cases have been analyzed for plutonium. Examples of relative plutonium concentrations in human tissues from fallout and occupational exposures in Table 6 are calculated on the basis of 1 for lung. Although the concentration of plutonium in thoracic lymph nodes is higher than in lung and bone, so is the concentration in liver and kidney. This suggests that fallout plutonium contained a relatively soluble fraction, i.e., the particle size may have been quite small. The data from an occupational case suggest the individual was exposed to a relatively insoluble plutonium compound, probably PuO_2 . The relative concentrations in the tissues are similar to data obtained from dogs exposed to PuO_2 .

It can be concluded from the results of animal experiments and the relatively few human data that the translocation of plutonium from lung to other tissues, while qualitatively similar, may vary quantitatively depending upon the plutonium compound and isotope inhaled and the time after exposure.

• Biological Effects

It has been shown that the distribution of plutonium and the radiation dose among the tissues in the body will vary depending upon the physical and chemical characteristics of the plutonium inhaled. The biological effects that occur will depend upon the radiation exposure and the relative radiation sensitivity of each tissue into which plutonium is transported and deposited. These are primarily blood, bone, liver, lung, and lymphatic system. The biological effects of greatest interest are those that might occur at low doses, such as cancer. Since no detrimental biological effects have been observed in persons occupationally exposed to plutonium that can be unequivocally related to plutonium, all our knowledge of the biological effects of plutonium have come from animal experiments.

A. Blood

Plutonium is cleared from the circulating blood within a few days after absorption. Therefore, any effects seen in blood cells probably would be due to irradiation of hematopoietic tissue in which plutonium is deposited or to irradiation of blood circulating through plutonium-containing tissues.

Although plutonium deposits in bone and lymphatic tissue, leukemia has not been a common finding in animal experiments. The only effect seen in blood is a reduction of the number of circulating lymphocytes, Figure 14. In current experiments with dogs this is the most sensitive indicator of a biological effect occurring after inhalation of $^{239}\text{PuO}_2$. It has been observed at plutonium levels less than those that have resulted in lung cancer. However, since the experiments are incomplete, the possibility of neoplasia developing still remains. The possible health consequences of a reduced level of circulating lymphocytes are not yet known.

B. Bone

Radiation-induced bone cancer is the most sensitive effect of plutonium deposited in bone. Because plutonium deposits on bone surfaces, a large fraction of the alpha energy is absorbed in sensitive cells. Statistically significant increases in cancer incidence have not occurred at doses less than 30 to 50 rads, Figure 15.

Bone cancer has been observed in mice, rats, rabbits, and dogs after intravenous injection, inhalation, or intratracheal injection of several plutonium-239 compounds including organic complexes and plutonium nitrates. Bone cancer has also been observed in rats after inhalation of $^{238}\text{PuO}_2$, but has not been reported in any animal species after inhalation of $^{239}\text{PuO}_2$.

C. Liver

Liver accumulates levels of plutonium similar to bone. However, liver tumors have not been a common finding in experimental animal studies. Bile duct tumors have been observed to occur in beagle dogs at doses as low as 60 rads. However, not only was the incidence very low, but bile duct tumors also occurred in control dogs.

D. Lung

Inhalation of relatively soluble plutonium compounds such as organic complexes, plutonium nitrate, and $^{238}\text{PuO}_2$ has resulted in primary lung cancer in

rodents, rabbits, and dogs in addition to bone cancer already mentioned, Figure 16. Lung cancer has also been observed in beagle dogs, baboons and rodents after inhalation of $^{239}\text{PuO}_2$. Statistically significant increases in lung cancer occurred at doses of about 30 rads and above.

E. Lymph Nodes

It was shown that plutonium accumulates in lymph nodes following deposition of plutonium in the respiratory tract. Months or years after the contaminating event, lymph nodes may attain concentrations of plutonium many times the average concentrations remaining at the site of deposition and consequently the accumulated radiation dose to some lymph nodes may be greater than to any other tissue. The fact that the biomedical significance of plutonium concentrations in lymph nodes is unknown is a major concern in establishing permissible limits for plutonium.

Although dogs have been studied for 11 years after inhaling $^{239}\text{PuO}_2$ and rodents have been studied in life-span experiments after inhalation of a variety of plutonium compounds, primary cancer of lymphatic tissue has not been a common observation. Therefore, it can be concluded that the lymph nodes are not especially susceptible to the carcinogenic action of alpha radiation from plutonium.

F. The "Hot Particle" Issue

It was recognized in the early 1940's that plutonium particles deposited in the lung would irradiate cells in the immediate vicinity of the particle rather than the entire lung. This gave rise to the concern that plutonium particles might be exceptionally efficient in causing lung cancer. Research during the past nearly 30 years has provided no evidence for an enhanced effect of the localized radiation dose from plutonium. Although not conclusive, experimental results to date suggest that plutonium particles might be less hazardous than the same amount of plutonium distributed throughout the lung because many fewer cells would be exposed to alpha radiation. However, experiments to resolve this question are technically difficult because inhaled plutonium does not remain distributed throughout the lung but tends to aggregate. Also, such experiments require

life time studies with large numbers of animals.

This issue continues to be the subject of controversy and will not be settled to everyone's satisfaction until these difficult and expensive experiments are completed.

- Countermeasures for Inhaled Plutonium

An important consideration in evaluating the potential health effects of plutonium is the availability of effective countermeasures for plutonium exposures. Since no acceptable therapy exists for radiation exposures, the only really effective countermeasure for inhaled plutonium would be the removal of the plutonium from the body. Inhaled insoluble plutonium is not effectively mobilized by a wide variety of agents which have been tested.

A chelating agent, Diethylenetriaminepentaacetic acid (DTPA), has had wide application for treating persons occupationally exposed to plutonium. It reduces the liver burden and, to a lesser extent, the bone burden causing an increased urinary excretion of plutonium. However, it is not effective in removing insoluble plutonium from lung or lymph nodes.

Therefore, it must be recognized that there is no truly effective countermeasure for plutonium contamination, and that for all practical purposes all plutonium deposited in the body will remain there until removed by natural processes, most of which are very slow. The development of therapeutic procedures for removing plutonium from the body are high priority research projects in several laboratories.

- Conclusions

Biomedical research has shown that plutonium is not readily incorporated into foodstuffs and that much less than 1 percent of plutonium ingested is absorbed from the gastrointestinal tract. The most important potential pathway of plutonium to man is in the air he breathes. However, much of the plutonium deposited in the lungs is removed by the normal processes which remove other foreign materials that are inhaled. The plutonium that remains in the lung is capable of causing lung cancer and the plutonium that is transported to the skeleton can cause bone cancer. While these health effects of plutonium have been observed in experimental animals, they have not been seen in any human being contaminated with plutonium. The health effects of inhaled

plutonium observed in experimental animals are summarized in Figure 17 relative to the maximum permissible lung burden of 0.016 μCi for occupational exposure. (The permissible lung burden for non-occupational exposures is a factor of 10 less.) In experimental animals lung cancer has been observed at levels of exposure equivalent to about 100 times the maximum permissible lung burden for occupational exposure. Current research is directed towards determining whether health effects will occur at very low levels of exposure. This requires life span observation of large numbers of experimental animals as well as extensive studies to determine how alpha radiation from plutonium causes cancer or other detrimental effects.

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Table 1

PROPERTIES OF PLUTONIUM

	<u>Half-Life (Years)</u>	<u>Specific Activity (Curies/Gram)</u>	<u>1 μm PuO₂ Particle</u>	
			<u>Mass (Grams)</u>	<u>Radioactivity (Curies)</u>
²³⁸ Pu	86	17.0	5×10^{-12}	8×10^{-11}
²³⁹ Pu	24,000	0.06	5×10^{-12}	3×10^{-13}

Table 2

UPTAKE OF PLUTONIUM BY BARLEY PLANTS

	<u>Pu Concentration</u>	<u>Concentration Factor (Plant/Soil)</u>
Soil	5×10^{-8}	-
Shoots	3×10^{-11}	6×10^{-4}
Roots	6×10^{-11}	1×10^{-3}

(from Wildung and Garland)

Table 3

ABSORPTION OF PLUTONIUM FROM
GASTROINTESTINAL TRACT

	<u>Percent Absorbed</u>
Plutonium Citrate	0.007 to 0.4
Plutonium Nitrate	0.003 to 2
Plutonium Dioxide	0.0001 to 0.003

Table 4

RELATIVE CONCENTRATIONS OF PLUTONIUM IN TISSUES OF
DOGS 7-9 YEARS AFTER INHALATION OF $^{239}\text{PuO}_2$

<u>Tissue</u>	<u>Relative Concentration of Plutonium</u>
Lung	1
Thoracic Lymph Nodes	1400
Abdominal Lymph Nodes	100
Liver	0.5
Spleen	0.2
Bone	0.06

Table 5

DEPOSITION OF PLUTONIUM IN GONADS

	<u>Percent of Pu in Blood</u>
Testes	0.05
Ovaries	0.01

Table 6

RELATIVE CONCENTRATIONS OF PLUTONIUM IN HUMAN TISSUES

<u>Tissue</u>	Type of Exposure	
	<u>Fallout*</u>	<u>Occupational**</u>
	Relative Concentration of Pu	
Lung	1	1
Thoracic Lymph Nodes	8	60
Hepatic Lymph Nodes	-	0.4
Liver	3	0.1
Kidney	2	-
Bone	1	0.2

*Calculated from Bennett, 1974 (9).

**Calculated from Nelson, et al., 1972 (10).

Figure 1
Electron Micrograph of ^{239}PuO Particles

ROUTES OF PLUTONIUM TO MAN

Figure 2

WHOLE BODY AND LUNG RETENTION OF ^{239}Pu

Figure 3

RETENTION OF PLUTONIUM IN PULMONARY REGION OF LUNG

Figure 4

PULMONARY RETENTION OF INHALED PuO_2 IN DOGS

Figure 5

Figure 6

Autoradiograph showing particulate and non-particulate plutonium in lung of a rat immediately after inhalation of $^{239}\text{Pu}(\text{NO}_3)_4$

Figure 7

Electronmicrograph of plutonium dioxide particles (inset) from an aerosol inhaled by rats and of a cell from the lung of an exposed rat. The dense appearing material in the cell is plutonium dioxide which had been engulfed by the cell.

Figure 8

Autoradiograph showing aggregation of ^{238}Pu
in a lung of a rat 100 days after inhalation
of $^{238}\text{Pu}(\text{NO}_3)_4$.

Figure 9

Autoradiograph showing $^{239}\text{PuO}_2$ particles in a subpleural area of lung from a dog.

Figure 10

Autoradiograph showing ^{238}Pu particles in scar tissue in a lung of a dog 5 years after inhalation of $^{238}\text{PuO}_2$.

**DISTRIBUTION OF PLUTONIUM IN DOGS AFTER
INHALATION OF $^{239}\text{Pu}(\text{NO}_3)_4$**

Figure 11

**DISTRIBUTION OF PLUTONIUM IN DOGS AFTER
INHALATION OF $^{239}\text{PuO}_2$**

Figure 12

**DISTRIBUTION OF PLUTONIUM IN TISSUES OF DOGS
5 YEARS AFTER INHALING $^{238}\text{PuO}_2$ OR $^{239}\text{PuO}_2$**

Figure 13

EFFECT OF INHALED $^{239}\text{PuO}_2$ ON BLOOD LYMPHOCYTE LEVELS

Figure 14

PLUTONIUM-INDUCED OSTEOSARCOMA IN EXPERIMENTAL ANIMALS

Figure 15

PLUTONIUM-INDUCED LUNG CANCER IN EXPERIMENTAL ANIMALS

Figure 16

OBSERVED BIOLOGICAL EFFECTS OF INHALED PLUTONIUM

Figure 17

CLASSIFICATION	DOCUMENT IDENTIFICATION NO. BNWL-SA-5230				
<div style="display: flex; align-items: center; justify-content: center;"> <div style="text-align: left; margin-right: 10px;"> BATTELLE <small>BATTELLE MEMORIAL INSTITUTE</small> <small>POST OFFICE BOX 999 /</small> </div> <div style="font-size: 2em; margin: 0 10px;">B</div> <div style="text-align: left; margin-left: 10px;"> NORTHWEST <small>PACIFIC NORTHWEST LABORATORY</small> <small>POST OFFICE BOX 999 / RICHLAND, WASHINGTON 99352</small> </div> </div>	COPY AND SERIES NO.				
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TITLE AND AUTHOR BIOMEDICAL ASPECTS OF PLUTONIUM W. J. BAIR <div style="font-size: 1.5em; margin-top: 20px;">7059</div>	<table border="1" style="width:100%; border-collapse: collapse;"> <tr> <td style="width:50%; vertical-align: top;"> CONTRACT ☐ - 1830 ☐ - 1831 </td> <td style="width:50%; vertical-align: top;"> PROJECT NO. </td> </tr> <tr> <td colspan="2" style="vertical-align: top;"> RESERVED FOR TECH. INFO. USE </td> </tr> </table>	CONTRACT ☐ - 1830 ☐ - 1831	PROJECT NO.	RESERVED FOR TECH. INFO. USE	
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