POLONIUM-210 AS A POISON ON AN AIRCRAFT

A Thesis

by

HOLLY REBECCA ELDER

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2008

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Approved by:

Chair of Committee,	John W. Poston, Sr.
Committee Members,	William S. Charlton
	Joseph Cerami
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ABSTRACT

Polonium-210 as a Poison on an Aircraft.

(May 2008)

Holly Rebecca Elder, B.S., The Pennsylvania State University, University Park

Chair of Advisory Committee: Dr. John W. Poston, Sr.

Security efforts at airports have increased globally to prevent terrorist attacks, but it might be possible to use an aircraft as a radiological dispersion device. By placing ^{210}Po in the environmental control system of a Boeing 767-300, the aerosol will circulate throughout the aircraft using the circulation pattern of the aircraft. The ventilation effectiveness in aircraft cabins is a critical factor for minimizing the exposure of passengers to airborne contaminants, since the ventilation system circulates the air more effectively than just stirred settling. Seats located at the center of the plane, D, have the best circulation while seats C and E have the worst circulation.

With an initial concentration of 1.66×10^{-4} mg/m^3 of ^{210}Po delivered instantaneously into the cabin of a Boeing 767-300 by the ventilation system, passengers seated in seat D will have inhaled an activity of 11.6 MBq while passengers seated in C and E will have inhaled an average of 15.0 MBq over 2000 seconds (33.3 min.). Without the circulation system, all passengers regardless of seat location would have inhaled an activity of 15.9 MBq. Although the percent change between seat C with circulation and seat C without circulation is only 27%, the increase in survival rates is

exponential. The median survival time after an uptake of 3 – 26 MBq is expected to be between 180 and 500 days.

DEDICATION

For those who have lost their lives fighting terrorism.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Poston, and my committee members, Dr. Charlton and Dr. Cerami, for their guidance and support throughout the course of this research.

Thanks also goes to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. I also want to extend my gratitude to the Army, which gave me the wonderful opportunity to earn my masters degree, so I could teach at the United States Military Academy.

Finally, thanks to my father, step-mother and sister for their encouragement, patience and love.

NOMENCLATURE

a	air exchange rate
AF(T←S)	absorbed fraction
AMAD	Activity Median Aerodynamic Diameter
Bi	bismuth
C	Celsius
c(t)	concentration at time t
C_c	Cunningham Correction Factor
C_d	coefficient of drag
CDC	Centers for Disease Control and Prevention
cfm	cubic feet per minute
c_o	initial concentration
d	diameter
E	energy
ECS	Environmental Control System
F	fraction
f_l	fraction of radionuclide in GI tract transferred to body fluids
F_D	drag force
fpm	feet per minute
g	gravity
GI	gastrointestinal

Gy	gray
H	chamber height
h	hour
$H_{50}(T \leftarrow S)$	committed dose equivalent
HEPA	high-efficiency particulate air-type filter
ICRP	International Commission on Radiological Protection
inh	inhalation
int	intratracheal
iv	intravenous
J	joules
k	decay rate
kg	kilogram
LD_{50}	lethal dose for 50 percent of people
m	meters
MBq	mega-Becquerel
MeV	mega-electron volt
mg	milligrams
min	minute
mL	milliliter
m_p	mass of the particle
m_T	mass of the tissue
n(t)	number concentration at time t

n_o	initial number concentration
N-P	nasal passages
^oF	degree Fahrenheit
P	pulmonary parenchyma
Pb	lead
Po	polonium
ppm	parts per million
psi	pounds per square inch
Q	quality factor
Ra	radium
RBM	red bone marrow
RDD	radiological dispersal device
Rn	radon
S	source tissue
SEE(T←S)	Specific Effective Energy
SNAP	Space Nuclear Auxiliary Power
STP	standard temperature and pressure
T	target tissue
t	time
T_B	removal half-times
T-B	trachea and bronchial tree
U	uranium

U_S	transformations in the source tissue
V	velocity
VEF	ventilation effectiveness factor
V_{TS}	terminal settling velocity
W	watt
Y	yield
yr	year
η	viscosity
μCi	micro-curie
ρ_g	density of gas
ρ_p	density of particle

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1. INTRODUCTION

On September 11, 2001, terrorists hijacked four planes and crashed two into the World Trade Center, one into the Pentagon, while one plot was foiled by quick-thinking passengers who crash-landed the plane in a field in Pennsylvania. Perspective on threats to Americans changed that day. It was the first major attack on American soil since Pearl Harbor. No longer are Americans concerned with major attacks from world powers, but more concerned with large- scale, terrorist attacks. Security efforts at airports have dramatically increased because of the high possibility of large-scale destruction and loss of human life such as what happened on 9/11. Since that day, plots have been uncovered that included the use of a shoe bomb and building an explosive device in flight using cell phones electronics and liquid explosives brought on board concealed in ordinary food and beverage containers. The threat of terrorist plots has increased and the plots have become more intricate as terrorists try to thwart all the efforts made to stop them. Although not conducted by terrorists, in November 2006, former Russian spy Alexander Litvinenko died of possible poisoning by polonium-210 (^{210}Po) in 21 days (1). Once Litvinenko was successfully diagnosed with radiation poisoning, his story was in the news for days. By linking the terrorist plots to conduct mass disruption and destruction, world-wide panic and financial ruin to world powers and the use of radiological dispersion devices (RDD) to cause panic and death, the idea of using ^{210}Po as a poison on a trans-Atlantic flight was born.

This thesis follows the style of *Radiation Research.*

The objectives of this research are to investigate the aerosol properties of materials such as polonium, with a special focus on the aerosol distribution in an aircraft making a trans-Atlantic flight and to assess the activity of ^{210}Po necessary in such scenarios to result in an inhalation exposure leading to the potential death of the passengers. In the course of this research, the metabolic distribution of the element polonium via inhalation into the human body and the chemical, physical and radiological characteristics on polonium with a focus on the radionuclide ^{210}Po will be reviewed.

2. PROBLEM

2.1. The Chemical and Physical Characteristics of Polonium

Polonium, initially called radium F, was discovered by Madame Marie Curie and her husband Pierre in 1898 while trying to isolate the source of radiation from pitchblend. Marie Curie chemically separated the compounds in the pitchblend and found a substance 400 times more radioactive than uranium, which she eventually called polonium after her native country of Poland.

Polonium can be found ubiquitously throughout the world, in the Earth's crust, in natural water supplies and in the air we breathe. Polonium is part of the uranium (^{238}U) decay chain, commonly referred to as the radium decay series, which is found naturally in the soil to varying degrees. A decay chain is a chain of products formed as a result of one element decaying to another, and that element in-turn decaying to yet another until a stable element is formed. In the uranium decay chain the stable element is lead (^{206}Pb), as shown in Fig. 1. Additional contributions to the amount of polonium in the atmosphere have been made by man through atmospheric nuclear weapons testing, the burning of fossil fuels and through reactor accidents like Windscale (2). Grazing caribou in the Arctic have been found to have internal concentrations greater than 37 Bq kg^{-1} from eating contaminated grass (3). Plankton, shellfish, crabs and fish are often contaminated with ^{210}Po. Cigarettes contain as much as 0.018 Bq per cigarette and it has been suggested that ^{210}Po might be a carcinogenesis of lung cancer (4).

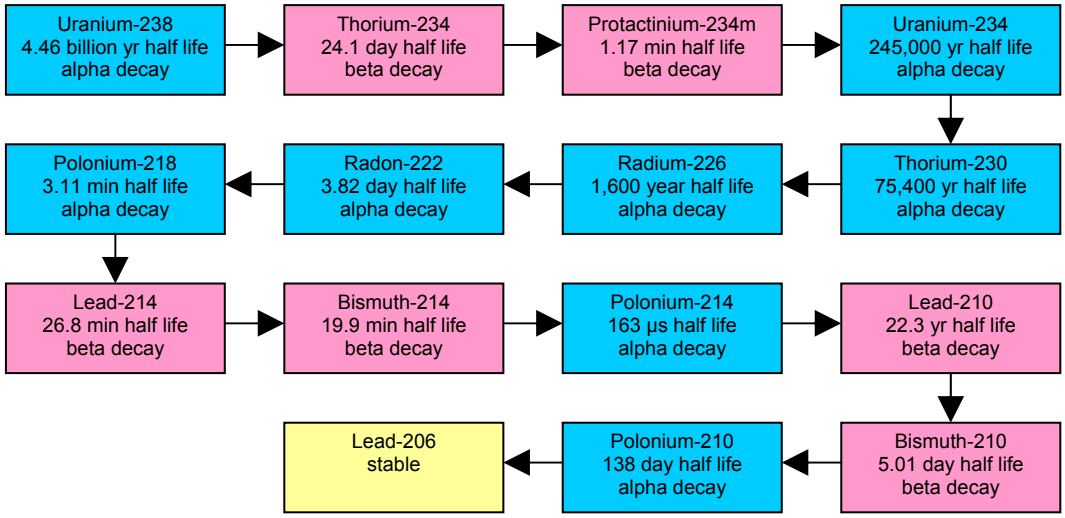

Figure 1. Uranium Decay Chain. Primary components of the uranium decay chain, commonly referred to as the radium decay series.

In 1934, scientists discovered that ^{210}Po results from the bombardment of natural bismuth (^{209}Bi) with neutrons. In the summer of 1942, the Corps of Engineers working on the Manhattan Project used ^{210}Po as an initiator, a device that produces a timed burst of neutrons to initiate a fission chain reaction in a nuclear weapon (5). In these early atomic weapons, initiators were made of ^{210}Po and beryllium and located at the center of the fissile cores. The most effective means of producing sizeable quantities (milligrams) of ^{210}Po is by bombarding ^{209}Bi with thermal neutrons using the high neutron fluence rates from nuclear reactors (6). Very small amounts of ^{210}Po can also be produced from the separation of ^{222}Rn daughter nuclides emanated from ^{226}Ra and through the separation of Pb-Bi eutectic, which is used as a coolant in some fast reactors.

Po-210 is a fairly volatile, low-melting, soft-silvery-gray metal in which half will vaporize in 45 hours at 55^{o}C unless sealed in a container (7). Po-210 emits a 5.3044

MeV alpha particle to decay to a stable form of lead (^{206}Pb). The energy released by decay of ^{210}Po is so large (140 W/g) that a capsule containing a half of a gram of ^{210}Po can reach temperatures of 500^{o}C and will glow blue due to the excitation of the surrounding air. Because of this property, ^{210}Po was studied in the 1950s to convert nuclear energy to usable electric energy using a thermoelectric principle. The use of satellites powered by generators that were able to convert thermal energy generated by radioactive sources to electrical energy, called SNAP, was first demonstrated by President Eisenhower in 1961 using a global communication satellite (5). Po-210 can be used as a lightweight heat source for thermoelectric power in short-term space satellites. Polonium is also used as a source for eliminating static electricity in textile and paper mills.

Po-210 is very dangerous to handle even in microgram amounts. The maximum permissible body burden is only 0.03 μCi, which weighs only 6.8 x 10^{-12}g (7). Weight for weight, ^{210}Po is about 2.5 x 10^{11} times as toxic as hydrocyanic acid. Po-210 must be inhaled, ingested or absorbed through a wound for it to assert its dangerous effects on living beings.

2.2. Internal Dose and Metabolic Processing of Polonium

International Commission on Radiological Protection Publication 30 (ICRP-30) divides the respiratory system into three areas: the nasal passages (N-P), the trachea and bronchial tree (T-B) and the pulmonary parenchyma (P) (8). Depending on the size of

the particle inhaled, the fraction deposited in these areas changes significantly. Larger particles are deposited primarily in the N-P region, while smaller particles are deposited in the P region, as shown in Fig. 2. The percent deposited in the T-B region remains relatively unchanged, 8%, for particles with diameters between 0.2 and 10 μm. For example, for a 1μm diameter particle, the percent deposited in the N-P, T-B, and P regions are 30, 8 and 25 respectively, while the percent deposition for a 5 μm diameter particle are 73, 8 and 9, respectively.

Another important factor in determining how the radionuclide will be metabolized in the body is the clearance class. Radionuclides that clear the P region in less than 10 days are considered Class D, between 10 and 100 days are Class W and over 100 days are Class Y. Oxides, hydroxides and nitrates of polonium are classified as class W, while all other chemical compounds of polonium are classified as class D.

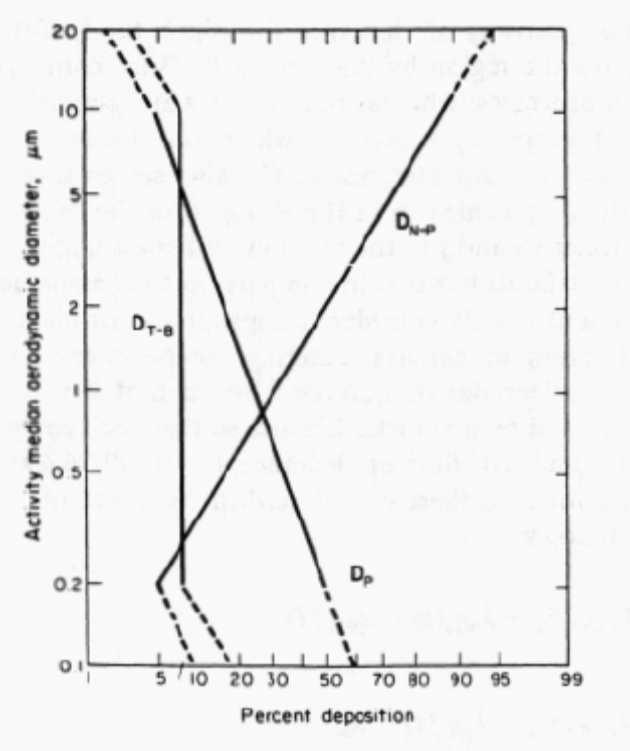

Figure 2. Deposition Percent as a Function of Diameter. A graph depicting the deposition of aerosols in the respiratory system based on particle diameter according ICRP 30. The percentage of activity or mass of an aerosol which is deposited in the N-P, T-B and the P regions can be found based on the Activity Median Aerodynamic Diameter (AMAD). The figure is valid for aerosols with diameters between 0.20 and 10 μm (8).

A mathematical model was developed to describe the clearance process from the respiratory system (Fig. 3). Compartments a, c, and e are associated with the absorption process into the body fluids whereas b, d, f and g are associated with the transport processes, including transport to the gastrointestinal (GI) tract. The clearance of inhaled particles from the lung is described by a set of interlinked, first-order differential equations. Once the particles reach the transfer compartment (body fluids), it is

distributed to various tissue compartments, depending upon how the body metabolizes the element, where it is eventually eliminated from the body.

Region	Compartment	Class D T day	D F	W T day	W F	Y T day	Y F
N–P (D_{N-P} = 0.30)	a	0.01	0.5	0.01	0.1	0.01	0.01
	b	0.01	0.5	0.40	0.9	0.40	0.99
T–B (D_{T-B} = 0.08)	c	0.01	0.95	0.01	0.5	0.01	0.01
	d	0.2	0.05	0.2	0.5	0.2	0.99
P (D_P = 0.25)	e	0.5	0.8	50	0.15	500	0.05
	f	n.a.	n.a.	1.0	0.4	1.0	0.4
	g	n.a.	n.a.	50	0.4	500	0.4
	h	0.5	0.2	50	0.05	500	0.15
L	i	0.5	1.0	50	1.0	1 000	0.9
	j	n.a.	n.a.	n.a.	n.a.	∞	0.1

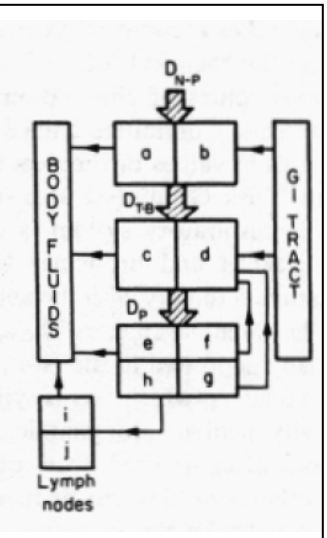

Figure 3. ICRP-30 Respiratory Model. Mathematical model used in ICRP 30 to describe the clearance pathway from the respiratory system. The values for the removal half-times (T) and fractions (F) from sub-compartments a thru j are provided in a tabular form to the left of the figure for all classes of radionuclides, D, W, and Y. The values given for D_{N-P}, D_{T-B}, and D_P are the deposition fractions for a 1μm diameter particle (8).

When the radionuclide enters the GI tract, it will travel directly to the stomach then to the small intestines. A fraction of the radionuclide in the small intestines will be transported to the body fluids while the remainder will travel from the small intestines through the upper and lower large intestines before being excreted from the body. The fraction going to the body fluids is dependent upon the element and chemical form and is based on how the body metabolizes the element. The f_1 value, the fraction of

radionuclide in the GI Tract that is transferred to the body fluids, is used to determine the fraction transferred from the small intestines to the body fluids. Once the radionuclide reached the body fluids, it is distributed to various soft tissues based on metabolic data and ,eventually, eliminated from the body.

To determine the distribution and excretion of ^{210}Po, Berke and DiPasqua conducted an inhalation experiment using 24 rats and 24 mice (9). Two rats were sacrificed immediately after a five-hour exposure to 3.17 x 10^{-6} μCi/mL (0.117 Bq/mL) of air in order to determine uptake. Each rat received a body burden of 51.0 x 10^{-3} μCi (1887 Bq), which was estimated to be 53% of the inhaled aerosol deposited in the body. The ^{210}Po was about equally divided between the lung-trachea and the entire GI tract. Only 5% of the activity was located in the upper nasal passages and buccal cavity, while nearly 49% of the aerosol was found in the GI tract. The procedure used did not preclude ingestion by licking or account for nasal filtration. A calculated estimate of 25% of the inhaled ^{210}Po was deposited in the lungs and trachea (18.6 x 10^{-6} μCi), and after 5 hours after exposure, 79% (23.5 x 10^{-3} μCi) was retained there.

According to Fig 4. from Berke and DiPasqua, the polonium content in the lungs declined rapidly for about a month. They postulated an exponential removal rate from the lungs occurred in two phases (lines A and B on a semi-log plot in Fig 4). The biological half-life for the initial lung burden was about 10 days (curve B), and the biological half-life of the remaining burden was 42 days (curve C).

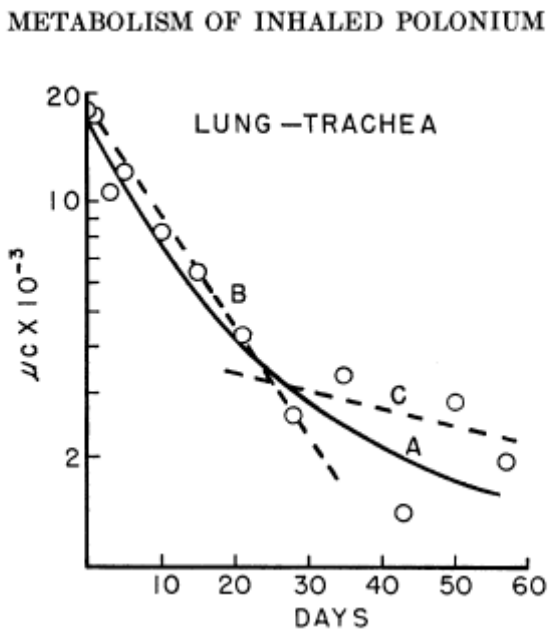

Figure 4. Metabolism of Inhaled Polonium. Clearance of ^{210}Po from the lung and trachea of a rat after a single inhalation exposure. Curve A is a fitted curve, while Curve B and Curve C are estimated to represent two-phase exponential clearance of the lung (9).

The percentage of body content among eight organs as a function of time is shown in Fig. 5. Two animals were sacrificed at each point and averaged except at 42 days when only one animal was available. Of the organs shown, only the lung-trachea and the head show an initial rapid decline in body burden. Whole blood saw a gradual increase in body burden to a maximum while the spleen, liver, kidney and heart initially increased then decreased after 30 to 50 days. This initial increase implied either the redistribution of ^{210}Po within the body or that the uptake of polonium was more avid by some tissues than by others. The maximum body burdens occurred at the kidney (12%) and liver (5.7%) at 35 days and in the spleen (5.3%) at 43 days.

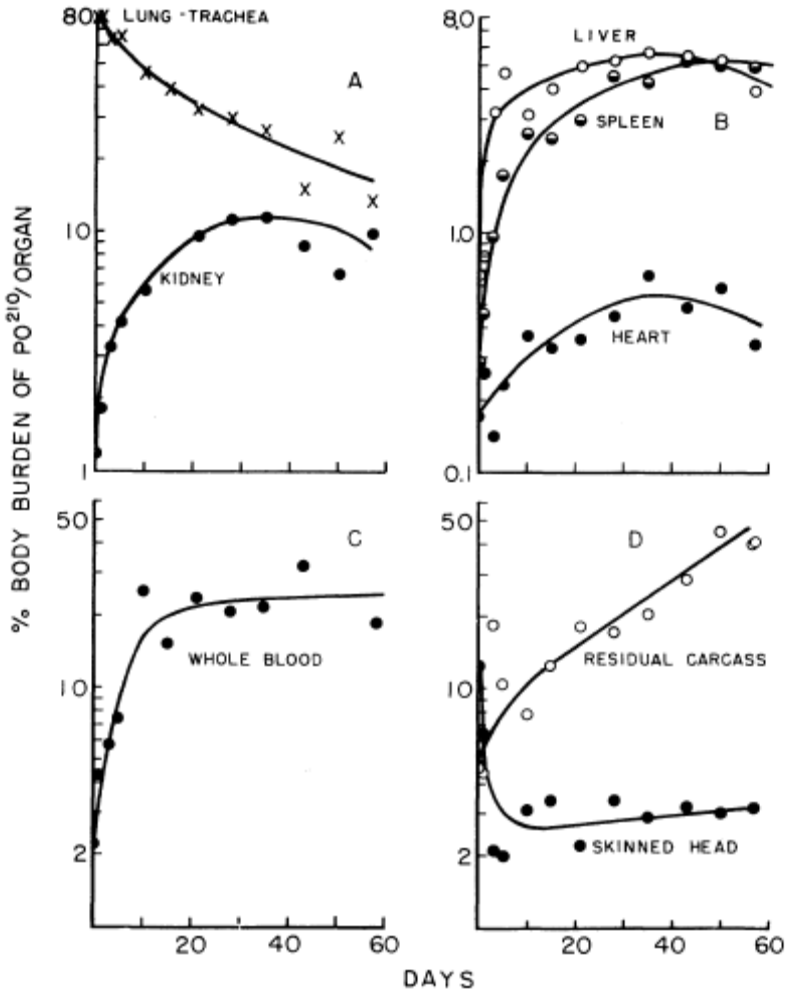

Figure 5. Relative Tissue Distribution of ^{210}Po as a Function of Time. Relative tissue distribution of ^{210}Po expressed as percentages of body content per organ at the time of sacrifice. Each point represents the mean of two animals sacrificed except at day 42 when only one animal was available (9).

Excretion was also measured during the course of this experiment and shown in Figure 5. The data are corrected for radioactive decay and presented as a fraction of the total recovered activity (body burden at sacrifice plus total excretion). The cumulative

fecal excretion is much higher than urinary excretion, note the difference in the abscissa values in graphs A and B in Fig. 6.

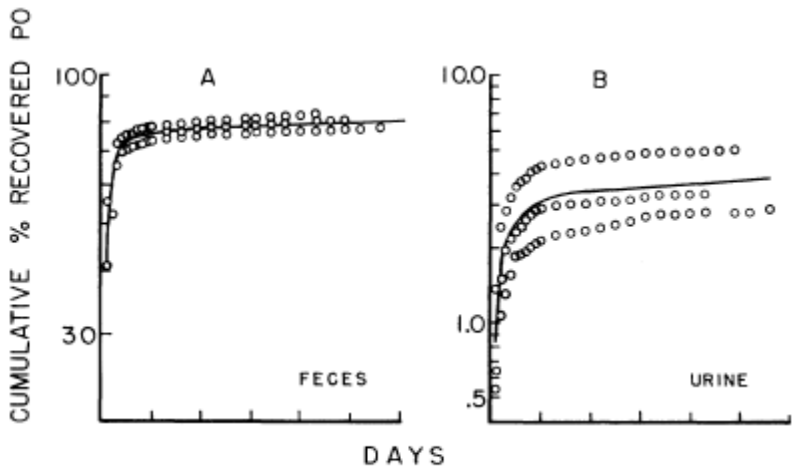

Figure 6. Fecal and Urine Excretion as a Function of Days. Fecal and urinary excretion of polonium as expressed as a percentage of the total recovered dose. The solid line represents the average values. Each point represents 24-hour and 48-hour collections for each of three animals (9).

The metabolism of inhaled polonium is different than ingestion, intratrecheal intubation or intravenously administered polonium (Table 1). Regardless, the kidney appeared high after exposure from any route, but was the highest with intratracheal intubation. The spleen appeared to have less activity when inhaled than with other methods of entry, while the heart and liver showed little variation as a function of route of entry. Total excretion was lower after inhalation (38%) than after intratracheal (43%) or intravenously (53%) administration.

Table 1. Distribution of ^{210}Po after Different Routes of Entry. Distribution of ^{210}Po after different routes of entry as a percentage of systemic body content per gram of tissue (wet weight) for mice and rats (9).

Tissue	*Day 1*				*Day 6*				*Day 10*			
	Oral	*Iv.*	*Int.*	*Inh.*	*Oral*	*Iv.*	*Int.*	*Inh.*	*Oral*	*Iv.*	*Int.*	*Inh.*
Blood plasma	0.06	0.20	—	—	0.06	0.06	—	0.03	0.3	0.4	—	0.03
Blood cells	2.8	2.7	—	—	18.9	1.3	—	3.6	12.4	1.2	—	3.1
Whole blood[b]	1.3	1.3	4.2	1.2	8.5	0.62	2.1	1.3	5.8	0.8	0.9	2.85
Lung[c]	2.0	1.0	49.0	41.0	1.0	0.10	31.0	27.0	1.2	0.8	29.0	23.0
Kidney	1.0	4.5	5.0	4.3	1.9	6.3	7.4	6.4	2.6	4.3	8.2	5.0
Spleen	1.0	5.6	4.2	2.0	3.7	9.2	9.2	3.5	4.8	8.7	7.7	3.1
Liver	3.3	3.9	1.4	1.1	1.3	2.9	1.3	1.3	0.8	3.2	1.2	0.6
Heart	0.3	0.5	—	1.0	0.8	0.5	—	0.72	0.9	0.3	—	0.7
Omental or cervical lymph nodes	0.3	1.0	—	3.7	0.8	1.8	39.0	1.6	0.9	2.1	23.0	2.4

	Day 30				*Day 50*				*Day 60*			
	Oral	*Iv.*	*Int.*	*Inh.*	*Oral*	*Iv.*	*Int.*	*Inh.*	*Oral*	*Iv.*	*Int.*[d]	*Inh.*
Blood plasma	0.2	—	—	—	—	—	—	—	0.05	0.03	—	—
Blood cells	17.0	—	—	—	—	—	—	—	12.3	3.3	—	—
Whole blood[b]	7.8	—	2.0	1.4	—	—	2.7	1.4	5.63	1.5	2.7	0.9
Lung[c]	0.9	0.9	18.0	12.0	—	—	9.1	6.0	0.8	1.2	8.0	5.0
Kidney	2.8	4.9	15.0	6.8	—	—	12.5	3.0	3.5	5.0	10.0	4.4
Spleen	4.3	8.8	9.7	4.4	—	—	10.5	5.1	6.8	5.8	7.8	3.9
Liver	0.9	0.7	1.7	0.6	—	—	2.1	0.5	0.5	0.5	0.9	0.4
Heart	0.9	—	—	0.7	—	—	—	0.5	1.3	0.5	—	0.3
Omental or cervical lymph nodes	0.8	3.5	32.0	6.2	—	—	16.0	3.2	0.7	2.3	22.0	0.9

[a] Intratracheal data based on body burden of Po^{210} less that in lung. Calculated from data of Thomas and Stannard (12). Inhalation data based on body burden of Po^{210} less that in lung and gastrointestinal tract and contents. Intravenous and oral data taken from Stannard (*13*, *14*).

[b] Whole blood values calculated from oral and intravenous data for cells and plasma by assuming 45% hematocrit value.

[c] Lung data after inhalation as per cent of body burden less gastrointestinal tract and contents for first day postexposure.

[d] 62-day value.

As a radionuclide metabolizes through the body, it is distributed non-uniformly throughout the body and retained in various organs. Polonium is deposited mainly in the liver, kidneys and spleen and is associated with the red blood cells. Of the polonium entering the transfer compartment (body fluids), 10% is assumed to go to the spleen, liver and kidneys while the remaining 70% is equally spread through the remaining organs and is assumed to be retained in these organs with a biological half-life of 50 days (8). Other radionuclides will possibly be retained in different organs and have different biological half-lives.

ICRP-66 took into account more recent data and included the red bone marrow in assessing the dose to tissues (10). Radiographic studies in 1991 indicated that virtually all skeletal polonium is retained in the marrow (11). Using these data, a model in ICRP-66 suggested that of the polonium entering the body fluids, 30% is assumed to go to the liver, 10% to the kidneys, 5% to the spleen, 10% to the red bone marrow and 45% to all other tissues. In 2001, Leggett and Eckerman developed a biokinetic model for polonium based on the extensive biokinetic studies conducted (12). Interpretation of the data was complicated by the potential metabolic differences in various species of laboratory animals tested as well as the questionable reliability of the excretion data for man. For this research, the dosimetric model developed in ICRP-30 as well as the metabolic data published in ICRP-30 were used.

The dose to a specific organ or tissue from a known inhalation of activity can be calculated if the metabolic data of the element are known. Using the ICRP-30

formulation, the specific effective energy, SEE, is the energy absorbed per unit mass of the target tissue from one disintegration of activity in the source tissue:

$$SEE(T \leftarrow S) = \frac{E \times Y \times AF(T \leftarrow S)}{m_T} \quad (1)$$

where E is the energy of the particle emitted from the radionuclide in the source tissue (MeV), Y is the yield per transformation, AF(T←S) is the absorbed fraction of energy in the target tissue, T, from the radionuclide in source tissue, S, and m_T is the mass (g) of the target tissue, T.

Total dose is then calculated by multiplying the total number of transformations in the source organ, U_S, during a 50-year period following intake of the radionuclide by the SEE(T←S) and converting the units from MeV/g absorbed energy to J/kg and then to grays. The equivalent dose in sieverts or gray can be obtained by multiplying this dose by the radiation quality factor, Q:

$$H_{50}(T \leftarrow S) = U_S \times SEE(T \leftarrow S) \times 1.6 \times 10^{-10} \times Q. \quad (2)$$

The radiation quality factor for ^{210}Po is 20 because it is an alpha emitter. Different radiations will have different radiation quality factors. If the target organ or tissue is irradiated by a radionuclide deposited in several source tissues or organs, the total dose to the target over 50 years is the sum of the doses from each of the sources. In ICRP-66, the radiation quality factor was reevaluated and renamed the radiation weighting factor although the radiation weighting factor for alpha particles remained the same as the alpha particle quality factor.

2.3. Po-210 as a Poison

Po-210 has a half life of 138 days and decays by emitting a 5.3-MeV alpha particle with a specific energy of 1.66. Uptake of ^{210}Po by either ingestion or inhalation will result primarily in deposition in the soft tissues, principally in the liver, spleen and kidneys. Po-210 is not a poison to the body, but the high-energy alpha particles emitted from decay of the radionuclide causes internal damage to the body. Deposition of ^{210}Po in the red bone marrow is also of importance because of the sensitivity of the haematopoietic tissue to radiation. Whole-body retention, or biological half-life, of ^{210}Po is 50 days (8). Because dead cells make up the top layer of skin, alpha particles do not have sufficient energy to penetrate the skin and, therefore, ^{210}Po does not pose a great external exposure hazard.

Numerous studies on the effects of polonium uptake have been conducted, although only a few have been conducted on humans. An LD_{50} value (dose to cause death for 50% of people) of 5 Gy has been proposed for otherwise healthy patients who receive proper and prompt medical attention in the form of barrier nursing, antibiotics, and blood transfusions (13). If patients receive more aggressive radiation treatment such as cytokine therapy or stem cell transplantation, it is suggested that the LD_{50} can be extended to about 9 Gy. An LD_{50} value of 3 Gy has been proposed for those patients who have not received proper, immediate medical attention. Taking into account the additional dose received as ^{210}Po moves through the body to the red bone marrow, the LD_{50} is about 2.5 Gy with an LD_{10} to LD_{100} ranging from 1.2-3.5 Gy with minimal

medical care, as shown in Fig. 7. The corresponding values for persons receiving medical attention are an LD_{50} of about 3.5 – 4 Gy and an LD_{10} – LD_{100} range of 1.7-5 Gy (12, 14).

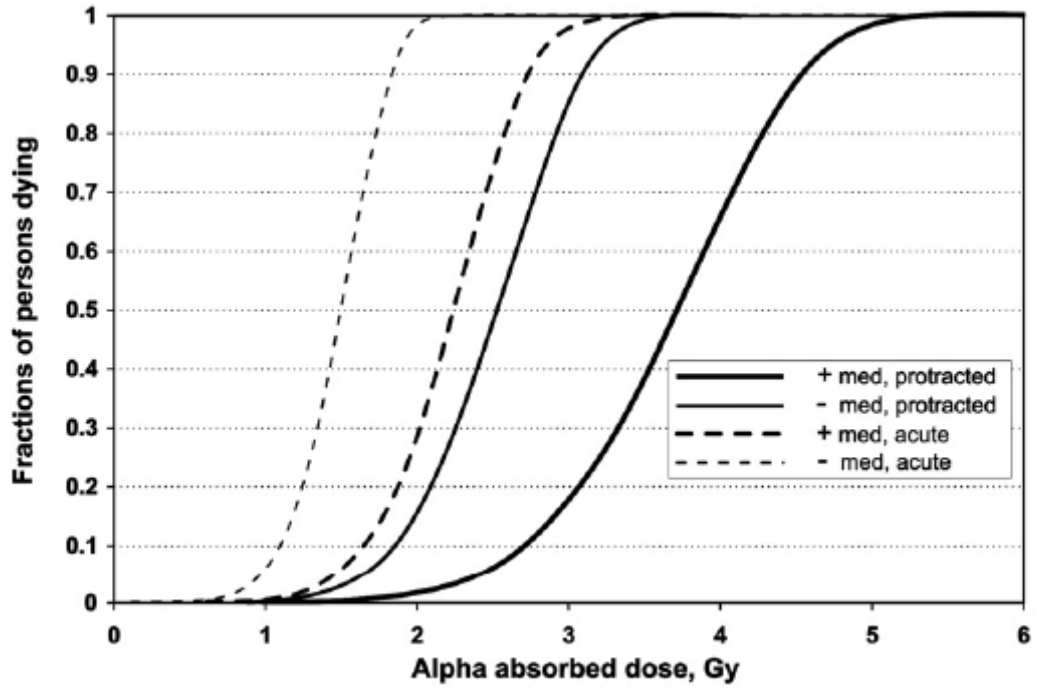

Figure 7. Mortality Dose Response Curves. Dose-response curves for mortality due to bone marrow failure after exposure to alpha particle irradiation. Curves are given for good medical attention quickly after exposure (+) and poor medical attention after exposure (-) for both acute and protracted dose (13).

The organs estimated to receive the highest dose after inhalation of ^{210}Po are the kidneys, liver and spleen. Della Rosa suggests that toxicity of ^{210}Po is not to one specific organ, but as a result of multiple-organ failure (15). In one case of a Russian male worker who accidentally inhaled an aerosol of ^{210}Po in 2001, death occurred in 13

days with organ content estimated as 13.3 MBq in spleen, 4.5 MBq in kidneys and 21 MBq in liver. Daily urinary excretion was estimated as about 0.4 MBq. Total retention was estimated as about 100 MBq (14). Posthumous examinations of his organs showed that the activities in the spleen, kidneys and liver were 13.3 MBq, 4.5 MBq and 21 MBq, respectively. Based on equations 1 and 2 and Table 2, the absorbed dose in these tissues equates to 10.3, 2.0 and 1.6 Gy, respectively.

Table 2: Transformations, SEE and Dose for Inhaled ^{210}Po. The number of transformations, the SEE and dose (Sv/Bq) for the inhalation of a 1 μm AMAD ^{210}Po particle with an activity of 1Bq.

1Bq	Transformations	SEE (MeV/transformation/kg)	Conversion factor	Dose (Sv/Bq)
Kidney	1.65×10^{5}	0.342	1.60×10^{-10}	9.02×10^{-6}
Liver	1.65×10^{5}	0.059	1.60×10^{-10}	1.55×10^{-6}
Spleen	1.65×10^{5}	0.589	1.60×10^{-10}	1.55×10^{-5}
Other	1.16×10^{6}	0.002	1.60×10^{-10}	2.89×10^{-7}
				2.61×10^{-5}

Extensive studies have been conducted on animals, summarized by Harrision *et. al.* and recreated in Table 3 (14). The minimal activity absorbed in the blood to have negative effects on life span was conducted on rats with an activity of 0.02 – 0.04 MBq kg^{-1} resulting in a 10-20% life-span reduction. This equates to an uptake amount of 1-3 MBq in blood for a 70 kg man. Rats and dogs receiving a slightly higher uptake in the blood stream of 0.04 – 0.4 MBq kg^{-1} had a median survival time of 180 – 500 days. Equivalent uptake for a 70 kg man is between 3 and 26 MBq. With an uptake between 90 and 130 MBq in his blood, a man is expected to survive for only 14 – 40 days.

Table 3. Median Survival Times Based on Absorption of ^{210}Po in the Blood. Summary of median survival time as a result of toxic effects of ^{210}Po on various laboratory animals evaluated as a function of absorption to blood in MBq (14).

Absorption to blood (MBq kg^{-1})	**Equivalent uptake for a 70 kg man** (MBq)	**Animal**	**Median Survival Time** (days)
4.4 - 6.3	300 - 400	Rat	7
1.9 - 3.7	130 - 260	Cat, dog, rabbit, mouse, rat	20
1.3 - 1.9	90 - 300	Rat, mouse	14 - 40
0.4 - 1.1	26 - 77	Rat	40 - 250
0.04 - 0.4	3 - 26	Rat, dog	180 - 500
0.02 - 0.04	1 - 3	Rat	10 - 20% life span reduction

According to the metabolic data for ^{210}Po provided in ICRP-30, inhalation classes D and W are assigned an f_1 value of 0.1, meaning that 10% of the radionuclide deposited in the GI tract is transferred to the blood, or transfer compartment. In ICRP-60, the f_1 value for class F and M is still 0.1 for inhalation by adults, but increases to 0.5 for dietary intakes (16). However, the biokinetic model of polonium constructed by Leggett and Eckermann in 2001 suggests an f_1 value of 0.15, based on the extensive animal studies and the one lethal case published by Ilyin (17). The value chosen for this experiment was 0.1 because it was the suggested value for inhalation in both ICRP reports. If a higher f_1 value is used, a smaller amount of polonium is needed to induce damage to the haematopoietic system from radiation sickness.

According to Harrison *et. al*., absorption of 0.1 to 0.3 GBq in the blood is considered fatal (14). The metabolic model in ICRP-30 suggests that once ^{210}Po has reached the transfer compartment, 10% is assumed to go to each of the liver, spleen and the kidney, while the other 70% is assumed to be uniformly distributed throughout all

other organs and tissues of the body and is retained there with a half-life of 50 days. Because the aerosol used for this research ^{210}Po was assumed to be a 5 μm AMAD, highly-soluble particle (Class D), a total of 73% will be deposited in the nasopharyngeal (NP) region, 8% will be deposited in the tracheobronchial (TB) region and 9% in the pulmonary region, while 10% will be exhaled. Based on the respiratory model in ICRP-30, one-half of the particles deposited in the NP region, 95% of the particles deposited in the TB region and 100% of the particles deposited in the P region are transferred directly to the blood:

$$(0.5\times 0.73)+(0.95\times 0.08)+(1\times 0.09) = 0.531. \quad (3)$$

In addition, particles deposited in the respiratory tract and transported to the GI tract will contribute to the total dose to the blood. The parameter, f_1, represents the fraction of the radionuclide deposited in the GI tract that is absorbed in the blood:

$$(0.5\times 0.73\times f_1)+(0.05\times 0.08\times f_1) = 0.369f_1. \quad (4)$$

According to the published metabolic data in ICRP-30, the f_1 value is 0.1. The total fraction of 0.568 of the radionuclide will be deposited in the blood. Based on the conclusions of Harrison *et al*, an activity of 0.1 - 0.3 GBq to the blood is considered fatal, inhalation of only 0.18 to 0.53 GBq will deliver that lethal dose. If one uses the biokinetic model developed by Leggett and Eckermann, the total fraction of radionuclide deposited in the blood increases slightly to 0.586.

2.4. Stokes's Law and Settling Velocity

Steady, straight-line motion of a particle is typically a result of two forces: an external constant force such as gravity or an electric field and the resistance of the gas to particle motion (18). The resisting force is the same whether the particle is moving through the gas or the gas is moving past the particle and depends on the relative velocity between the gas and the particle. Newton derived the general equation of a sphere passing through a gas as a result of his study of cannonball ballistics. The equation is valid for a wide range of particle motion but is most useful for Reynolds numbers greater than 1000. Reynolds number is a dimensionless number that characterizes the flow of a particle through a pipe or around an obstacle and can be derived from the ratio of the inertial and frictional forces acting on the particle. Newton's resistance equation is better suited for cannonballs than aerosol particles because most aerosols have a Reynolds number less than 1 from higher viscous forces and near negligible inertial forces.

The resistance on the cannonball traveling through the air is a result of the air being pushed aside to allow the cannonball to pass through. Newton's resistance equation (Eq. 5) is valid for high Reynolds numbers, where inertial forces are much larger than viscous forces. In Eq. 5, C_d is the coefficient of drag, ρ_g is the density of the gas, d is the diameter of the particle and V is the velocity of the particle:

$$F_D = C_d \frac{\pi}{8} \rho_g d^2 V^2. \tag{5}$$

In 1851, Stokes derived an expression for drag in which inertial forces are negligible compared to viscous force. Stokes's Law is a solution of the Navier-Stokes equations, which are differential equations used to describe fluid motion. The total resisting force on a spherical particle, F_D, moving with a velocity, V, through a fluid with a viscosity of η is described in equation 6, which is Stokes's Law:

$$F_D = 3\pi\eta V d. \tag{6}$$

When a particle is released in still air, it quickly reaches its terminal settling velocity, V_{TS}, a condition of constant velocity where the drag force, F_D, of the air is exactly equal to the opposing gravitational force, F_G, g is the acceleration of gravity (9.81 m/s^2) and m is the mass of the particle (Eq. 5):

$$F_D = F_G = m_p g. \tag{7}$$

The mass of a particle, m, can be calculated using equation 8, where ρ_g is the density of the gas, ρ_p is the density of the particle or aerosol, and d is the diameter of the particle or aerosol:

$$m_p = \frac{(\rho_p - \rho_g)\pi d^3}{6}. \tag{8}$$

Equation 9 can be obtained by combining Eqs. 6, 7, and 8, and solving for V, which would be the terminal settling velocity, V_{TS}, as a result of the boundary conditions set forth in Eq. 7. The viscosity of air, η, is 1.81 x 10^{-5} N·s/m^2 at standard temperature and pressure (STP). The equation is valid for diameters greater than 1 μm and a Reynolds number less than 1.0. For particles smaller than 1 μm, a slip correction factor, called the Cunningham Correction Factor, C_c, needs to be applied. The correction factor

increases as the particle diameter decreases. The Cunningham Correction Factor for particles with a diameter of 1 μm or greater is 1:

$$V_{TS} = \frac{\rho_p d^2 g C_c}{18\eta}. \quad (9)$$

In a tranquil setting, the motion of the particle is solely based on gravitational settling and the particles will eventually be deposited on the floor. When the air is stirred, the aerosol concentration is constantly decreasing but always uniform within the chamber. Particles are constantly moving in all directions in the chamber. Diffusion, resuspension and deposition on the walls are negligible. The up and down motion of the particles are complimentary and will cancel out over a long period of time. As a result, every particle will have an average net velocity equal to V_{TS}. The concentration of particles undergoing stirred settling decays exponentially with time and as such will never reach zero (Eq. 10), where n_o is the initial number concentration, n(t) is the number concentration at time t, and H is the height of the chamber:

$$\frac{n(t)}{n_o} = e^{(\frac{-V_{TS}t}{H})}. \quad (10)$$

Brownian motion is the irregular wiggling of aerosol particles in still air caused by random collisions between the particles and the gas molecules. Diffusion of the aerosol particles is the net transport of these particles in a concentration gradient, always from a higher concentration to a lower concentration. Brownian motion and diffusion are the most important mechanisms for transporting particles with diameters less than 0.1μm through still air. For aerosols larger than 0.1μm in diameter or in stirred settling, gravitational settling is the most important mechanism for particle transport.

2.5. Environmental Control Systems on a Boeing 767

Commercial airliners use recirculated air in their environmental control systems to improve fuel efficiency. The modern Boeing 767 uses approximately 50% recirculated air and 50% outside air (19). The engine in a Boeing 767 is a Pratt & Whitney 4000 turbofan engine with a "core" that provides power and a "bypass" which provides thrust. Only about one-fifth of the air drawn into the engine is pulled through the core while the rest of the air passes through the bypass. When outside air passes through the core, some of the air is extracted through bleed ports after being compressed. The bleed port system is the primary air supplied to the environmental control system (ECS). The bleed system consists of a series of valves, controls and a heat exchanger that electronically controls the temperature and pressure of the air needed for all pneumatic services on the airplane, including air conditioning packs, cabin ventilation, de-icing, potable water pressure as well as cargo heat and cabin pressure. The system is automatic with emergency control valves controlled by the pilot.

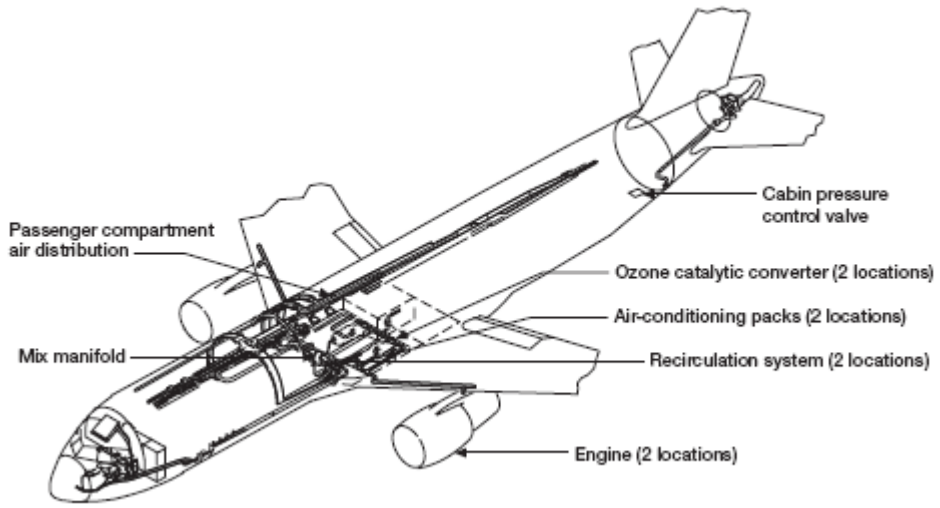

Figure 8. Components of a Boeing 767 Environmental Control System. Typical components and system layout for the environmental control system on a Boeing 767 (19).

During takeoff, the pilot increases the thrust of the engine to the highest levels and the engine compresses the air to 1200 ^{o}F and 430 psi. Because air at this energy is too high to meet the requirements of the pneumatic systems on the aircraft, the bleed system discards the excess energy as waste heat. At cruising altitude (39,000 feet), the outside air is -70 ^{o}F at 2.9 psi, with the partial pressure of oxygen at 0.5 psi. The compressor is able to compress the low-pressure, cold air to 400 ^{o}F and 30 psi. The temperature of the air supplied to the bleed system is high enough to kill any microorganisms present on the outside of the plane during all stages of flight and is considered sterile. The air leaving the bleed system passes through an ozone converter and then to the air conditioning packs located under the wings at the center of the plane,

which can be seen in Fig. 8. Ozone is removed using an ozone converter and approximately 95% of the ozone is converted to oxygen.

The air conditioning packs provide clean, sterile, essentially dust-free air to passengers at a specific temperature, flow rate and pressure to satisfy the settings on the temperature control valve. Approximately 5 cubic feet per minute (cfm) per passenger is provided by each air conditioning pack. There are two packs on a 767, providing 10 cfm of "fresh" conditioned air per passenger. In addition, 10 cfm of recirculated air is mixed with the fresh air in the mix manifold and provides for a total of 20 cfm of air per passenger. This equates mathematically to a complete air exchange every two and a half minutes, or 24 air changes per hour. Cabin air temperature is the predominant driver in outside air requirements, which is controlled by the pilot by an overhead panel. The air leaving the air-conditioning packs at 60 ^{o}F and 11.8 psi. The relative humidity is less than 5% with an ozone concentration of less than 0.25 ppm.

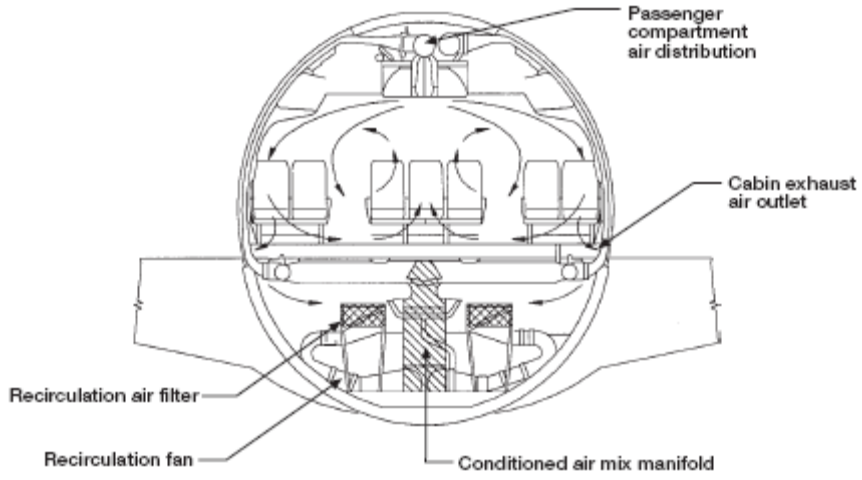

Figure 9. Cabin Airflow Patterns (19).

The recirculated air entering the mix manifold passes through a high-efficiency particulate air-type filter (HEPA). Gases cannot be removed by the filter but is controlled by the high volume of outside airflow circulated per cubic volume of space. After passing through the mix manifold, the air is divided into air ducts that run from below the floor to the overhead cabin ventilation system for each seating zone, as shown in Fig. 9. This air is essentially dust free and sterile with a relative humidity between 10 and 20%. Outlets of the overhead cabin ventilation system are specifically designed to prevent draftiness while still allowing a large volume of air to flow and create a carefully controlled circulation airflow patterns. Air leaves the vents at a velocity more than 500 feet per minute (fpm). The air maintains enough momentum to sweep along the cabin wall and floors for maximum air circulation while not blowing directly on exposed areas of a passenger, i.e., arms, neck, head and neck. The velocity of the air by the time it reaches the passengers is between 20 and 70 fpm, depending on the personal preference of the passenger. Air volume will circulate and mix with cabin air for two to three minutes before being sucked into the return air grills. Approximately one half of this air will be exhausted overboard while the other half will be sterilized through the recirculation system. The cabin ventilation system is designed to allow air circulation within a row while minimizing airflow in the fore and aft directions. The outflow valve that controls the exhaust air is the same valve that helps control the cabin pressure. At 39,000 feet, the cabin air pressure is 11.5 psi, which is equivalent to an altitude of 6,900 feet above sea level. (20)

Because recirculated air must pass through a HEPA filter as well as travel through the extensive recirculation system on the aircraft, very few particles sucked up in the air return vents will recirculate in the aircraft. For this reason, it is assumed that once particles exit the cabin, the particles will not reenter.

2.6. Aircraft Cabin Circulation System

A series of simulations and experiments has been conducted to investigate the potential for transport of bacteria, viruses, germs and other infectious microorganisms through the air in the cabin of a commercial airliner. The typical main cabin air flow has a circular air-flow pattern with the main circulation vents located in the center of plane and the return air grills located along the outer wall near the floor of the cabin, as shown in Fig. 10. Air is provided and exhausted from these vents on a continuous basis at a supply rate of 0.252 m^3/min and exchanged at a rate of 10.3 h^{-1}. Air leaves the vents at a velocity of 2.54 m/s and has a seated passenger impingement velocity between 0.10 and 0.36 m/s. Variation in impingement velocity is based upon individual air flow preference (19).

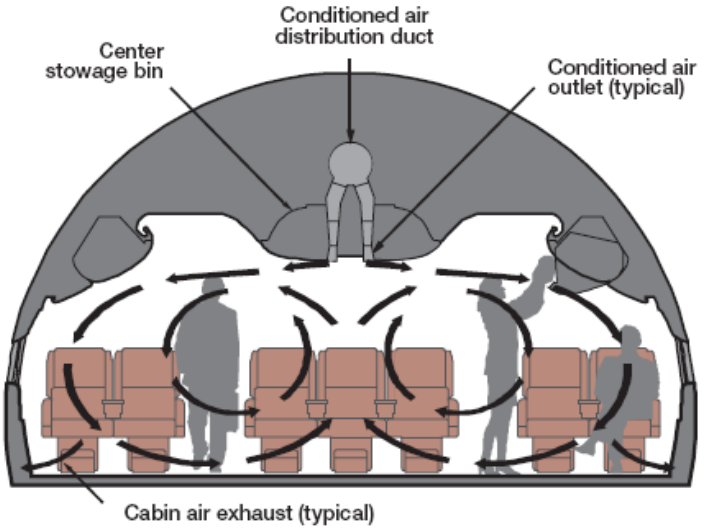

Figure 10. Typical Main Cabin Airflow Patterns (21).

In a series of projects supported by the Centers for Disease Control and Prevention (CDC) with collaboration from The Boeing Company, researchers built a five-row section of a Boeing 767-300 aircraft cabin mockup to help characterize airflow and particle transport within the cabin (Fig. 11) (22). The mockup included clothed mannequins with small heating sources, and actual aircraft equipment including seats, internal panels, diffusers and a section of the air supply duct of a Boeing 767-300. Supply air was provided by an external air conditioning unit through the air supply duct located at the ceiling of the mockup. Exhaust air exited the cabin through exhaust air grills near the floor of the mockup, but was not recirculated. Neutrally buoyant helium bubbles were used to quantitatively measure air velocities in the whole cabin (23).

Figure 11. Mockup of a Boeing 767-300 Aircraft Cabin. The mockup of a Boeing 767-300 aircraft cabin built at the University of Illinois at Urbana-Champaign with support from the CDC and The Boeing Company (22).

Figure 12 shows the instantaneous air velocity at the center of the third row of seats (i.e. the center of the mock-up). The experiment was used to show the difference in the air velocities when the number of passengers changes as well as when the cabin wall temperature is different from the ambient air temperature. The cold fuselage wall increased the air velocities and could potentially cause air drafts for passengers in the window seats, with a velocity of 0.228 m/s for 100% occupancy. The main driving force of the air circulation pattern was provided by the air supply jet. The central seats showed an upward air flow, opposite to the direction of the fresh air supply. Areas toward the center of the two recirculation patterns showed very low air velocities, 0.034

m/s with 50% occupancy. These areas correlate to the left and right aisles between the double and triple seats. Such low air velocities could be an indication of poor ventilation effectiveness and possibly indicate near stagnant air conditions.

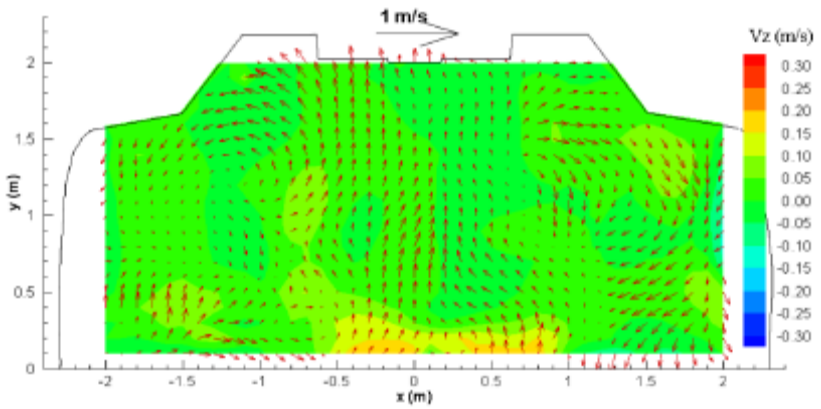

Figure 12. Instantaneous Air Velocities in a Boeing 767-300. The instantaneous air velocities measured at the center of row 3. Vector maps of the air velocity components in the x-y plane and a contour map in the z-direction (23).

In a subsequent experiment, the ventilation effectiveness and air velocity distribution was evaluated (24). Carbon dioxide was used as a tracer gas. The initial concentration and the continued recorded concentrations were used to calculate the mean age of the air at each seat. The local mean age of the air at each seat is shown in Fig. 13. Consistent with the previous experiment, the areas that showed very low air velocities in Fig. 12 were the same areas that had the highest local mean age of the air in Fig. 13. The

authors suggested that the mean age of the air at seat G was possibly skewed from non-symmetrical sampling locations at seats A and G.

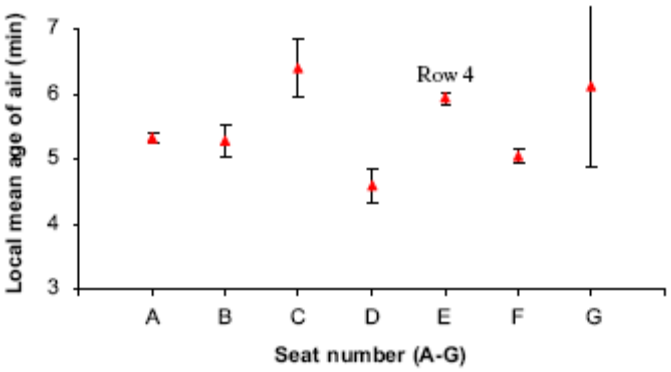

Figure 13. Local Mean Age of Air for Individual Seats. Local mean age of air for individual seats in row 4 of a 5-row cabin mock-up (24).

Other than the variation between seats A and G, the right and left sides mirrored each other in mean age of the air. Rows 2 and 3 showed similar air ages. When the air supply rate was increased from 70% to 120%, the local mean age of the air decreased. In row 4, the air age decreased from 3.5 – 4.5 min to a lower range of 2.5 – 3.5 min.

Ventilation effectiveness is essentially the effectiveness of the circulation system to exchange old air for new air. The ventilation effectiveness factor (VEF) is a ratio of inlet, outlet and measuring point concentrations. A smaller local mean age of air usually corresponded to a larger ventilation effectiveness factor, as shown in Fig. 14. Increasing the air supply rate did not improve the VEF. The authors concluded that increasing the ventilation rate may not be the solution to improving the ventilation effectiveness (24).

Seats C and E had the highest mean age of air and had nearly the lowest ventilation effectiveness.

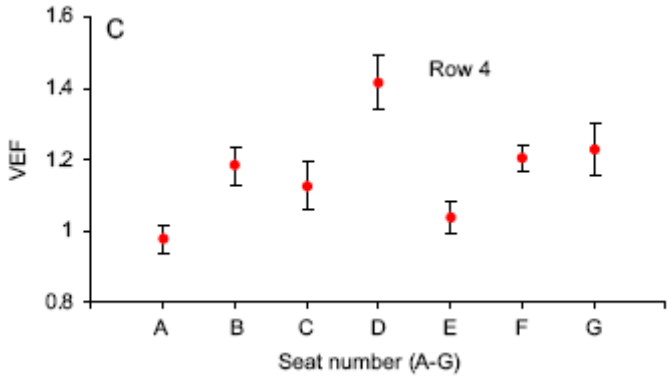

Figure 14. Ventilation Effectiveness Factor for Individual Seats. Ventilation effectiveness factor (VEF) for each seat in Row 4 of a 5-row cabin mock-up.(24).

Using the experimental data of the air velocities and the mean age of the air, air concentrations of ^{210}Po can be recalculated to account for various positions within a Boeing 767-300.

The height of a Boeing 767-300 cabin is a total of 80 inches (2.032 m). Due to the complicated circulation pattern inside the cabin, the aerosol is assumed to be stirred vigorously. Thus, the concentration is quickly dispersed evenly throughout the cabin. Even after the flow of the aerosol has stopped, the aerosol does not just settle out of the air but is continuously circulated, reducing the concentration in the volume over time. The concentration will decrease with time, but the removal rate will also decrease with time because the removal rate is proportional to the number of particles left suspended in

the chamber (18a). The concentration of particles decreases exponentially with time, as shown in equation 11:

$$n(t) = n_o e^{-(\frac{V_{TS}t}{H})} \tag{11}$$

where V_{TS} is the particle terminal velocity, H is the height of the ceiling and n is the number concentration. In tranquil settling, the air is immobile so particle motion is solely due to the effect of gravitational settling. Neglecting diffusion, the particles would settle with the same constant velocity, the terminal settling velocity. The concentration would become zero after a time equal to the height of the room divided by the terminal settling velocity. With stirred settling, the concentration can never mathematically reach zero. In the time it would take the concentration to become zero with tranquil settling, 1/e of the original concentration is still suspended in the air for stirred settling.

Terminal settling velocity (V_{TS}) is a function of the particle density and diameter and is only valid for particle diameters greater than 1 μm unless slip correction factors are applied, and for particles with a Reynolds number less than 1.0 (18b):

$$V_{TS} = \frac{\rho d^2 g}{18\eta} = \frac{9320\frac{g}{m^3} \times (5x10^{-6}m)^2 \times 9.8\frac{m}{s^2}}{18 \times (1.81 \times 10^{-5})} = 0.007\frac{m}{s} \tag{12}$$

The Reynolds number is equal to the 66,000 times the terminal settling velocity and particle diameter. The Reynolds number for 5-μm diameter particles with a terminal settling velocity is equal to 0.002, which is well within the boundary conditions of equation 12.

3. SOLUTIONS

3.1. Concentration Calculations

The atomic mass of ^{210}Po is 210 grams per mole and 1 Bq of polonium weights 6.02 x 10^{-13} grams. Inhalation of 3 - 28 MBq should deliver a lethal activity of 3 to 26 MBq to the blood and would have a mass between 1.8 and 17 μg. There are approximately 3.1 x 10^{14} – 9.1 x 10^{14} molecules in 0.11 to 0.31 μg of ^{210}Po. The volume of the passenger compartment in a Boeing 767-300 aircraft is 319 m^3 and it can hold up to 220 passengers (20). Therefore, a total number concentration of ^{210}Po for a fully loaded plane would be 9.72 x 10^{11} – 2.85 x 10^{12} molecules/m^3, with a mean concentration of 1.47 x 10^{13} molecules/m^3.

Tidal volume is the amount of air breathed in or out during normal respiration. An average male has a tidal volume between 0.5 and 0.75 liters of air per breath and takes 12 – 16 breathes per minute (20). At an altitude of 39,000 feet, the aircraft cabin air pressure is 79.3 kPa (0.78 atm) (19). At standard temperature and pressure (STP), there are approximately 2.68 x 10^{22} molecules in one liter of air. At 0.78 atmosphere, there are only 2.01 x 10^{22} molecules per liter. With a tidal volume of 0.75 liters per breath, a person would breathe 1.567 x 10^{22} molecules per breath, which equates to 1.9 x 10^{23} – 2.5 x 10^{23} molecules per minute. The air flow volume is 4.2 L/s (0.252 m^3/min) or 5.3 x 10^{24} molecules per minute. Each passenger is assumed to breathe only 3.6 to 4.7 percent of the air provided.

The calculation assumed that filters, uniformly laced with 5-µm diameter ^{210}Po particles, were placed in the ventilation system of a Boeing 767-300. Further, it was assumed that the ^{210}Po aerosol was instantaneously blown into the aircraft cabin at a volumetric flow of 4.2 liters of air per second (20). Assuming nearly all of the particles were released into the air at one time, the aerosol gradually settled at a rate of:

$$c = c_o * e^{-(a+k)*t} \quad (12)$$

where c_0 is the initial concentration, c is the concentration at time t, a is the air exchange rate per hour and k is the decay rate due to diffusion, sedimentation and/or gravitational settling (25). In a Boeing 767-300, the published air exchange rate is 10.3 h^{-1} and the average decay rate due to gravitational settling is 0.1 h^{-1} (20, 25). With a concentration of 4.2 x 10^{14} molecules/m^3, it will take approximately 33 minutes (2000 s) for the 5-µm, ^{210}Po particles to essentially settle out of the air, as shown in Fig. 15.

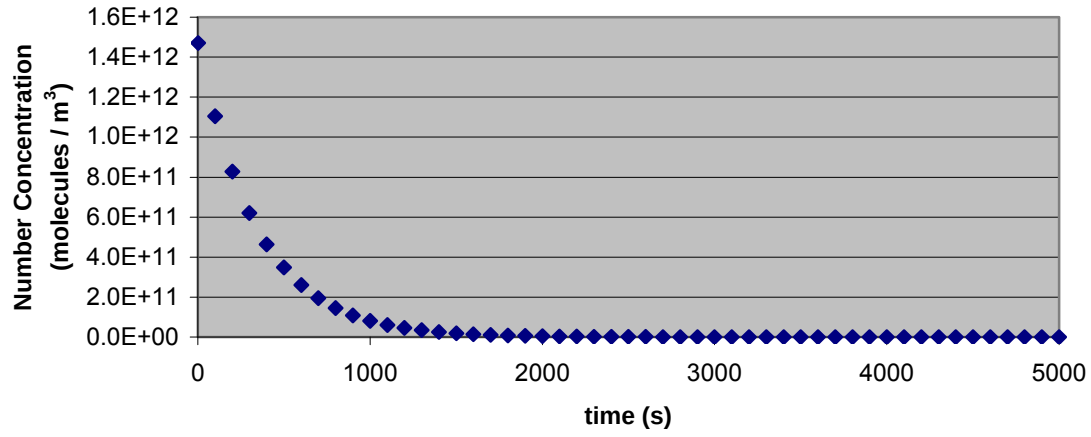

Figure 15. Concentration Decay. Number concentration in the aircraft cabin as a function of time.

If every air molecule was exchanged every three minutes, the number concentration of 5-μm ^{210}Po particles would need to be 1.4 x 10^{14} particles/m^3, since passengers would breathe the polonium for three minutes before it is recycled, as shown in Fig. 16. This would equate to an activity of 0.355 GBq per minute inhaled. Unfortunately, the air circulation system inside a Boeing 767-300 is not that simple.

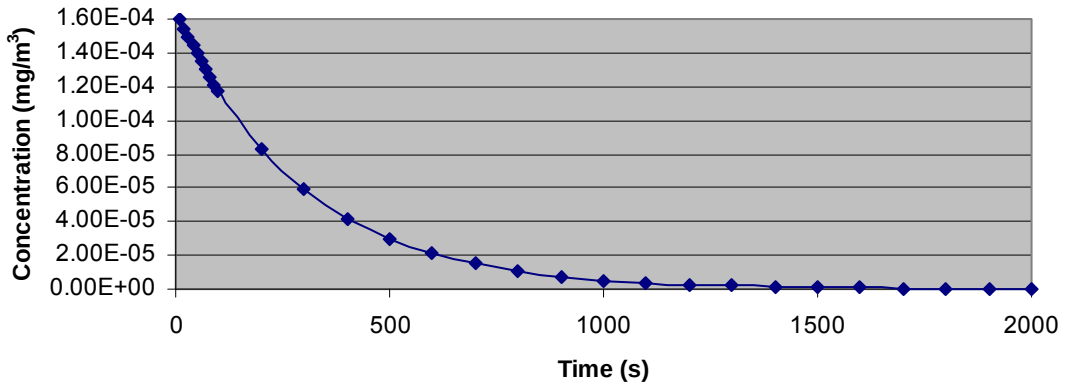

Figure 16. Theoretical Concentration Over Time for Stirred Settling. The theoretical mass concentration as a function of time (Eq. 3) based on an initial concentration of 1.66 x 10^{-4} mg/m^3 and a terminal settling velocity of .007 m/s.

The air velocities measured by Zhang *et. al.* (18) are significantly higher than the terminal velocity calculated using Eq. 12, suggesting that the cabin airflow is more complicated than just stirred settling. Airflow in aircraft cabins is governed by a combination of the air delivery and distribution system, air exhaust system and obstructions in the recirculation pattern, (e.g., seats and passengers). The air delivery and distribution system contributes the most to create two recirculation areas.

Table 4. Velocity of ^{210}Po at Each Seat. The calculated velocity of ^{210}Po using the terminal settling velocity and the ventilation effectiveness factor.

Seat	Avg Air Vel	Avg VEF	V_{TS} for ^{210}Po	^{210}Po Vel
	m/s		m/s	m/s
A	0.22	1.17	0.007	0.0082
B	0.12	1.29	0.007	0.0091
C	0.08	1.08	0.007	0.0076
D	0.18	1.37	0.007	0.0096
E	0.08	1.06	0.007	0.0074
F	0.18	1.24	0.007	0.0087
G	0.3	1.07	0.007	0.0075

The experiment used helium bubbles to determine the velocity of the air. Because the ventilation in an aircraft cabin is more efficient than just stirring air to remove particle concentrations (as shown in Fig. 14) (24), the velocities of the ^{210}Po particles would have to be greater than the terminal settling velocity, calculated using Eq. 12. The mean air velocity was measured using neutrally buoyant helium bubbles and not 5-μm ^{210}Po particles, which are heavier than helium bubbles. By applying the ventilation effectiveness factors to the measured air at each seat with the terminal settling velocity of ^{210}Po, the average velocity at each seat was calculated, as shown in Table 4. The results for seat G should be similar to those for seat A, but are different possibly from non-symmetrical measuring points at seats A and G (24). Neglecting seat G, the velocity at seats C and E have the slowest moving particles. Figure 17 is the result of applying the results in Table 3 with Eq. 11, with the line labeled "Theory" using the terminal velocity calculated in Eq. 12. The line labeled "Theory" showed the slowest reduction in the concentration while Seat D shows the fastest reduction in the concentration. This result is consistent also with the mean age of the air, where the particles with the highest mean age was located at seats C and E, while the lowest mean age was at seat D.

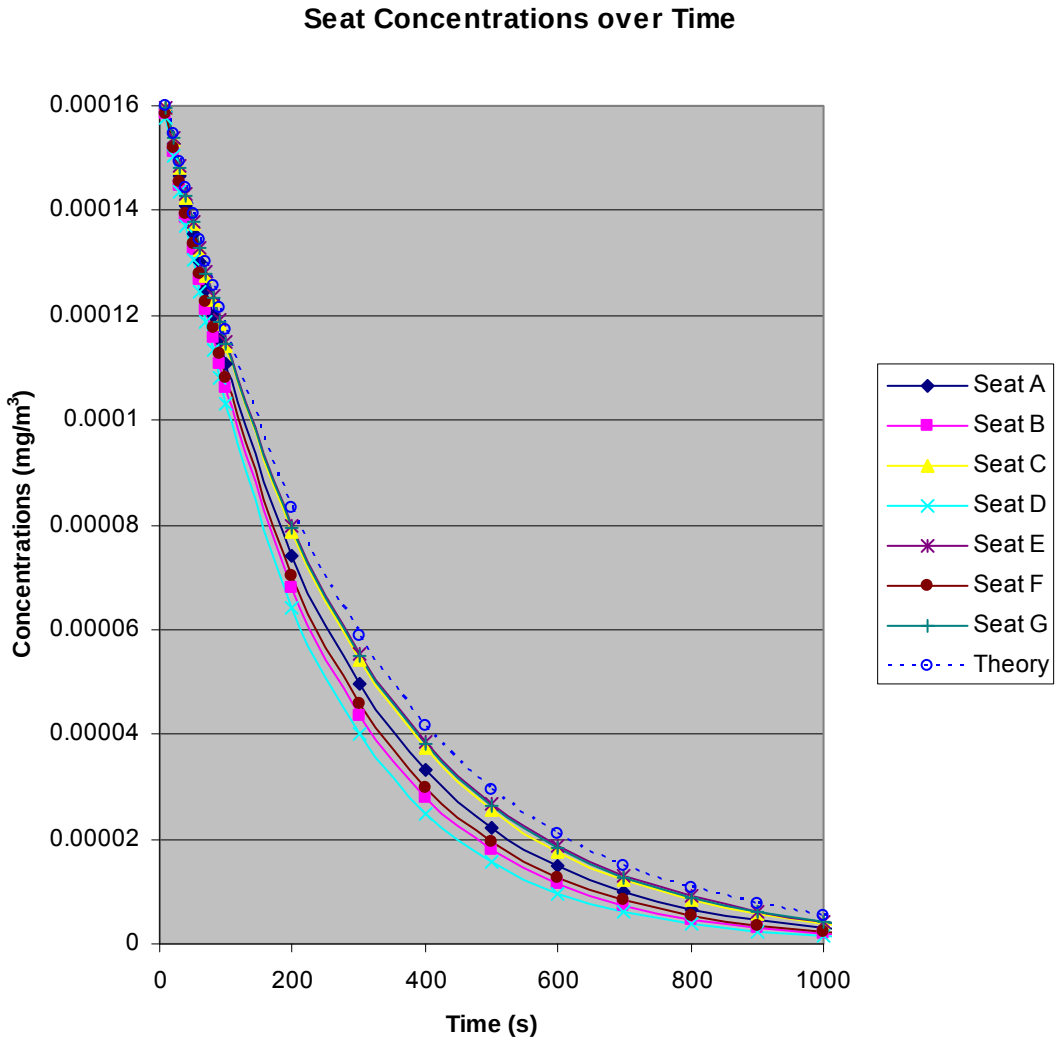

Figure 17. Seat Concentrations over Time. Mass concentration as a function of time (Eq. 3) based on an initial concentration of 1.66 x 10^{-4} mg/m^3 and the terminal settling velocity of .007 m/s multiplied by the Ventilation Effectiveness Factor (VEF). VEF for "Theory" is equivalent to stirred settling, which is unity.

3.2. Inhalation Concentrations

With an initial concentration of 1.66 x 10^{-4} mg/m^3 released into the airplane cabin, after 2000 seconds, passengers will have inhaled an activity between 11.6 and 15.0 MBq (Table 5). In order to achieve a concentration of 1.66 x 10^{-4} mg/m^3 in the entire aircraft, a total of 0.053 mg of ^{210}Po would need to be used. Since there is almost no exchange of air from one row to another, a lesser quantity of ^{210}Po would need to be released in the cabin to poison passengers within a row rather than all the passengers in the aircraft cabin. An economy class row would only need 0.001 mg of ^{210}Po, while business class would need 0.002mg of ^{210}Po to be released into a row to reach a concentration of 1.66 x 10^{-4} mg/m^3. After 6 hours, the average length of a trans-Atlantic

Table 5. Activity Inhaled at Each Seat after 2000 Seconds. Concentration received after 2000s with an initial concentration of 1.66 x 10^{-4} mg/m^3, a tidal volume of .5 L / breath and 12 breaths per minute.

Seat	Concentration Received	Volume breathed	Mass Inhaled	Activity Inhaled
	mg/m^3	m^3	mg	Bq
A	0.0412	0.2	0.0082	1.37 x 10^7
B	0.0371	0.2	0.0074	1.23 x 10^7
C	0.0445	0.2	0.0089	1.48 x 10^7
D	0.0350	0.2	0.0070	1.16 x 10^7
E	0.0454	0.2	0.0091	1.51 x 10^7
F	0.0387	0.2	0.0077	1.29 x 10^7
G	0.0450	0.2	0.0090	1.50 x 10^7
Theory	0.0480	0.2	0.0096	1.59 x 10^7

flight, the inhaled activity did not significantly increase because of the exponentially decreasing concentration in the cabin. With this inhaled activity, passengers would expect to survive between 150 – 500 days after the flight, as shown in Table 5. Through the ventilation effectiveness of the air circulation system on the aircraft, the amount of ^{210}Po breathed in by a passenger would decrease by as much as a percent difference of 27%.

Based on the inhaled activity, the activity received in the spleen, liver and kidneys will initially increase over the first 55 days after exposure then fall off gradually over the next 250 days. Figure 18 shows the activity in the critical organs over 300 days, where the maximum activity in the organs is 1.03×10^5 Bq 55 at days after exposure.

After 300 days, there were a total of 2.48×10^{12} transformations in the critical organs. Using Eqns. 1 and 2, the equivalent doses received in the kidney, liver and spleen after 300 days was 6.8 Gy, 1.1 Gy, and 11.7 Gy, respectively. The dose to the other tissues in the body, including the blood, was 0.03 Gy. Between 300 days and 50 years there were an additional 5.9×10^{10} transformations. The changes in the dose to the critical organs from increasing the time period are shown in Table 6. For the inhalation of 1Bq of activity, the dose to the red bone marrow (RBM) was 3.02×10^{-7} Sv/Bq. With a dose to the RBM of 4.35 Sv after an inhalation of 1.59×10^7 Bq over 300 days, the activity in the RBM was 10.08 MBq. From Table 3, the median survival time for man with an uptake of 3-26 MBq in the blood is 180 – 500 days.

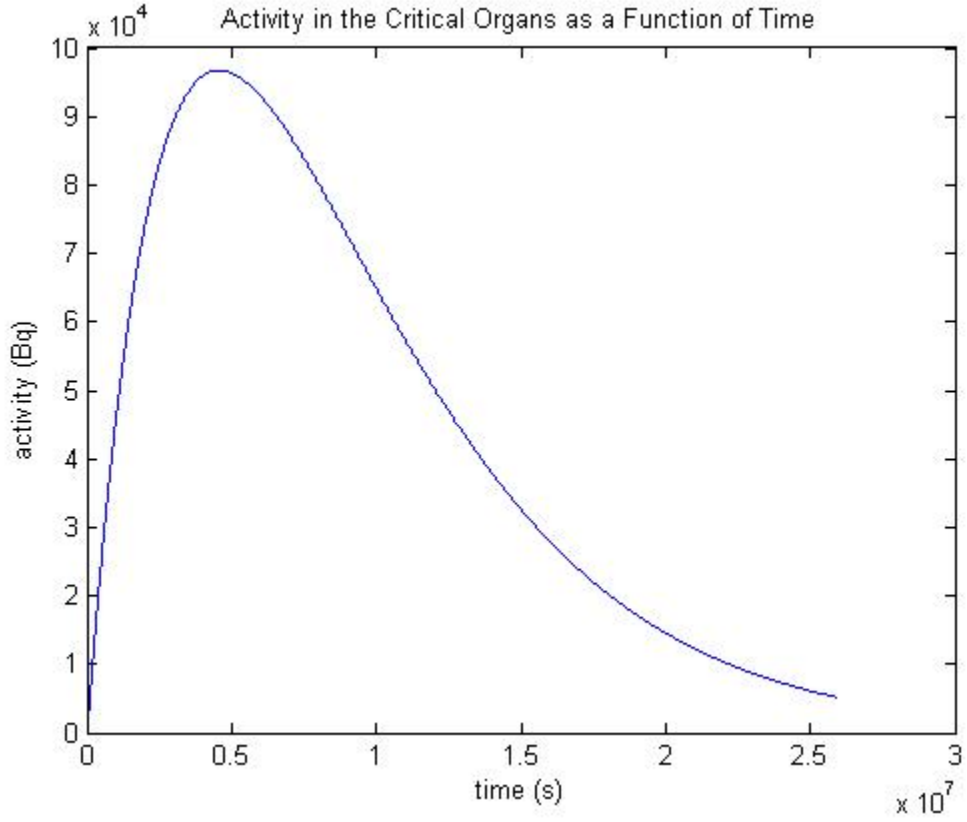

Figure 18. Activity in Organs over Time. Activity in the spleen, kidney and liver from a 2000 second inhalation of a type W ^{210}Po concentration of 1.66 x 10^{-4} mg/m^3 with an AMAD of 5 μm sized particles over a 300 day period.

Table 6. Transformations, SEE and Dose after 300 Days and 50 Years. The number of transformations, SEE and dose in sieverts and gray for the inhalation of ^{210}Po with an activity of 1.59×10^{7} Bq for a 300 day and a 50 year time period.

	Time Period	Transforms	SEE (MeV/trans/kg)	Conversion	Dose (Sv)	Dose (Gy)
Kidney	300 days	2.4810E+12	0.3419	1.60E-10	135.73	6.79
	50 years	2.5400E+12			138.96	6.95
Liver	300 days	2.4810E+12	0.0589		23.38	1.17
	50 years	2.5400E+12			23.93	1.20
Spleen	300 days	2.4810E+12	0.5889		233.77	11.69
	50 years	2.5400E+12			239.32	11.97
Other	300 days	1.7360E+13	0.0016		4.35	0.22
	50 years	1.7780E+13			4.45	0.22
RBM	300 days	3.8458E+11	0.0707		4.35	0.22
	50 years	3.9389E+11			4.45	0.22

Using the change in the inhaled dose as a result of the applying the ventilation effectiveness factor (Table 5), the dose in the critical organs is shown in Table 7. The difference between theory (stirred settling) and the seat with the most effective ventilation, D, is 3.9MBq uptake in the critical organs. According to the research completed by Harrison, *et. al.*, that can mean the difference between a 10-20% reduced life span to a median survival time of less than 500 days, as shown in Table 3 (14).

Table 7. Difference in Dose to Critical Organs from Ventilation Effectiveness. The effective dose to the critical organs from ^{210}Po inhalation as a result of the difference in the ventilation effectiveness at each seat.

Seat	Organ	Inhaled Activity	Transformations	Dose (Gy)	Uptake in Organs (MBq)
A	Kidney	1.37×10^{7}	2.14×10^{12}	5.85	12.41
	Liver			1.01	12.41
	Spleen			10.07	12.41
	Other		1.50×10^{13}	0.19	8.69
B	Kidney	1.23×10^{7}	1.92×10^{12}	5.25	11.14
	Liver			0.90	11.14
	Spleen			9.04	11.14
	Other		1.34×10^{13}	0.17	7.80
C	Kidney	1.48×10^{7}	2.31×10^{12}	6.32	13.41
	Liver			1.09	13.41
	Spleen			10.88	13.41
	Other		1.62×10^{13}	0.20	9.38
D	Kidney	1.16×10^{7}	1.81×10^{12}	4.95	10.51
	Liver			0.85	10.51
	Spleen			8.53	10.51
	Other		1.27×10^{13}	0.16	7.36
E	Kidney	1.51×10^{7}	2.36×10^{12}	6.44	13.68
	Liver			1.11	13.68
	Spleen			11.10	13.68
	Other		1.65×10^{13}	0.21	9.56
F	Kidney	1.29×10^{7}	$2.01\ 10^{12}$	5.51	11.69
	Liver			0.95	11.69
	Spleen			9.48	11.69
	Other		1.41×10^{13}	0.18	8.18
G	Kidney	1.50×10^{7}	2.34×10^{12}	6.40	13.59
	Liver			1.10	13.59
	Spleen			11.02	13.59
	Other		1.64×10^{13}	0.21	9.51
Theory	Kidney	1.59×10^{7}	2.48×10^{12}	6.79	14.41
	Liver			1.17	14.41
	Spleen			11.69	14.41
	Other		1.74×10^{13}	0.22	10.08

4. CONCLUSION

4.1. Summary

Po-210 is a very dangerous radionuclide when taken into the body. An uptake of only 26 MBq, which weighs only 15 μg, can cause death in 150 days. By placing a ^{210}Po aerosol in the environmental control system in a Boeing 767-300, the aerosol will circulate throughout the aircraft using the circulation pattern of the aircraft. The ventilation effectiveness in aircraft cabins is a critical factor for minimizing the exposure of passengers to airborne contaminants, such as a ^{210}Po aerosol. Better ventilation will reduce the amount of time that contaminants are circulated in the cabin, and thus inhaled, before exhausted out of the cabin. Different seats have different ventilation effectiveness; seats C and E having the worst circulation while seat D has the best circulation, although both are better than just stirred settling.

With an initial concentration of 1.66×10^{-4} mg/m^3 of ^{210}Po delivered instantaneously into the cabin of a Boeing 767-300 by the ventilation system, passengers seated in seat D will have inhaled an activity of 11.6 MBq while passengers seated in C and E will have inhaled an average of 15.0 MBq over 2000 seconds (33.3 min.). The concentration could be dispersed within one row causing more localized poisoning and require between 0.001 – 0.002 mg of ^{210}Po for economy or business class, respectively, or 0.053 mg of ^{210}Po for the entire cabin dispersed using the ventilation system. Without the circulation system, all passengers, regardless of seat location, would have inhaled an

activity of 15.9 MBq. Although the percent change between seat C with circulation and seat C without circulation is only 27%, the increase in survival rates is exponential. Mean survival time for an uptake of 3 – 26 MBq is 180 – 500 days.

Because alpha particles are not very penetrating and must be taken into the body, preventing ^{210}Po poisoning can be accomplished by using a simple paper filter mask. However, radiation cannot be easily detected without some type of radiation detector and since radiation sickness mimics food poisoning in the first couple days after exposure, passengers would not know immediately that they have been exposed to radiation. Thus, further research needs to be conducted in order to prevent the use of an aircraft as a possible radiation dispersal device.

4.2. Future Work

The research was conducted using the dosimetric model created in ICRP-30 as well as the metabolic data published in the Annex. Future work could be done using the ICRP-66 model or the biokinetic model developed by Leggett and Eckerman with more exact metabolic data. In addition, this research was conducted on only one type of aircraft and one radionuclide of one set size. Further work could explore the release of a different radionuclides, different circulation systems on various aircraft and different sized aerosol particles. Because ^{210}Po decays by emitting an alpha particle, further work could include the use of a radionuclide that decays via beta or gamma decay. Resuspension of particles and recirculation of particles could also be studied to

determine if either route would contribute a sizeable dose to the traveling passengers. To thwart an attempt at creating an undetectable radiation dispersal device, a radiation detector needs to be designed into the recirculation system that provides an immediate signal to the pilot so that he/she can address a potential life-threatening situation. Pilots could either drop down oxygen masks or have the flight attendants hand out respiratory filter masks to prevent passengers from breathing in lethal doses of radiation.

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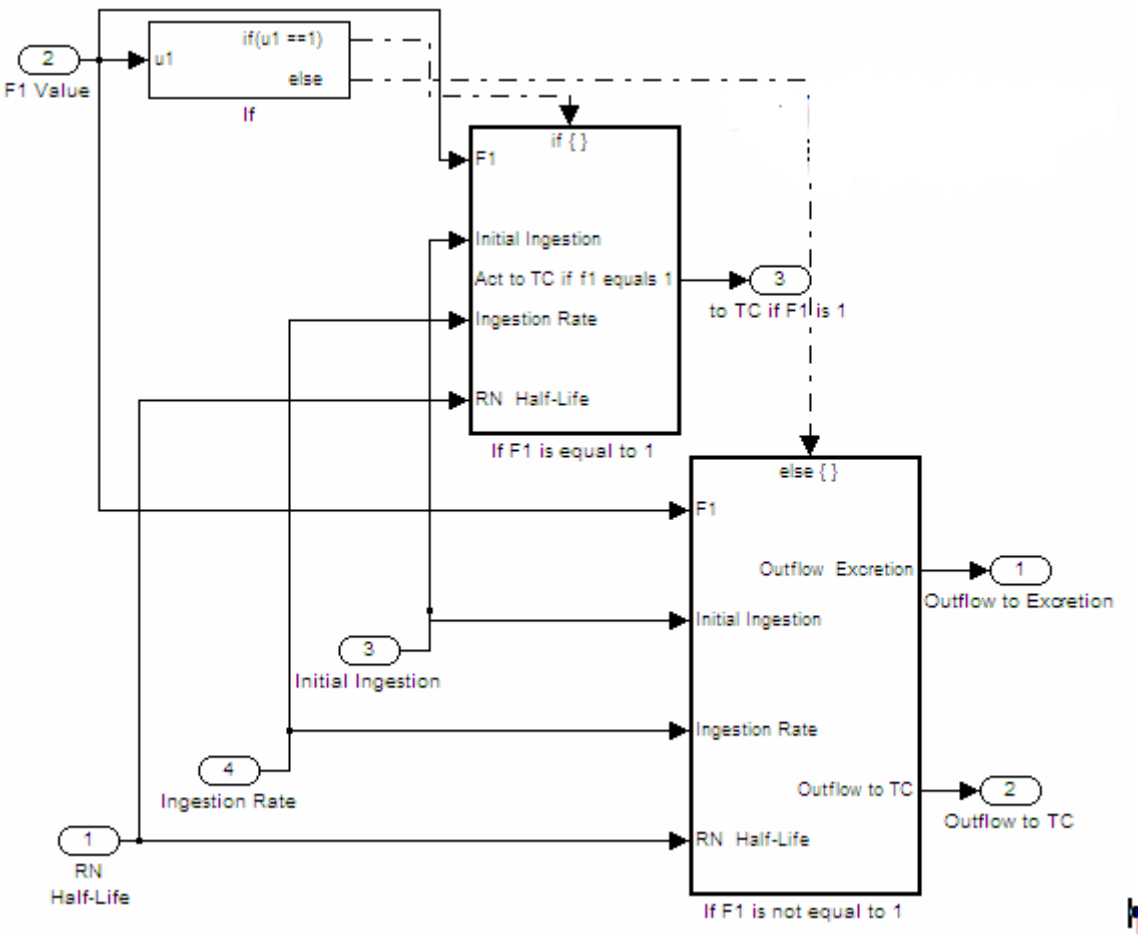
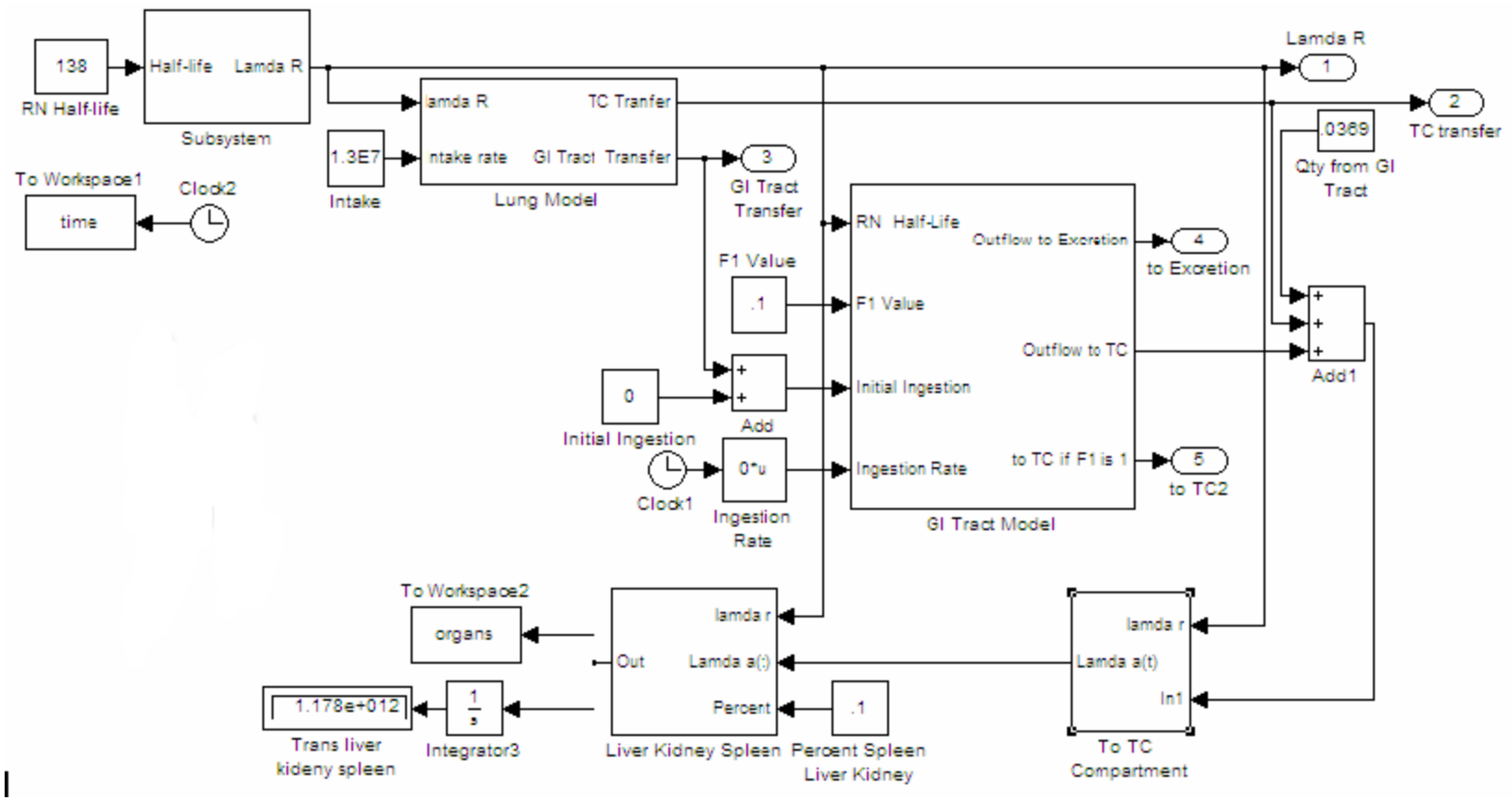
APPENDIX A

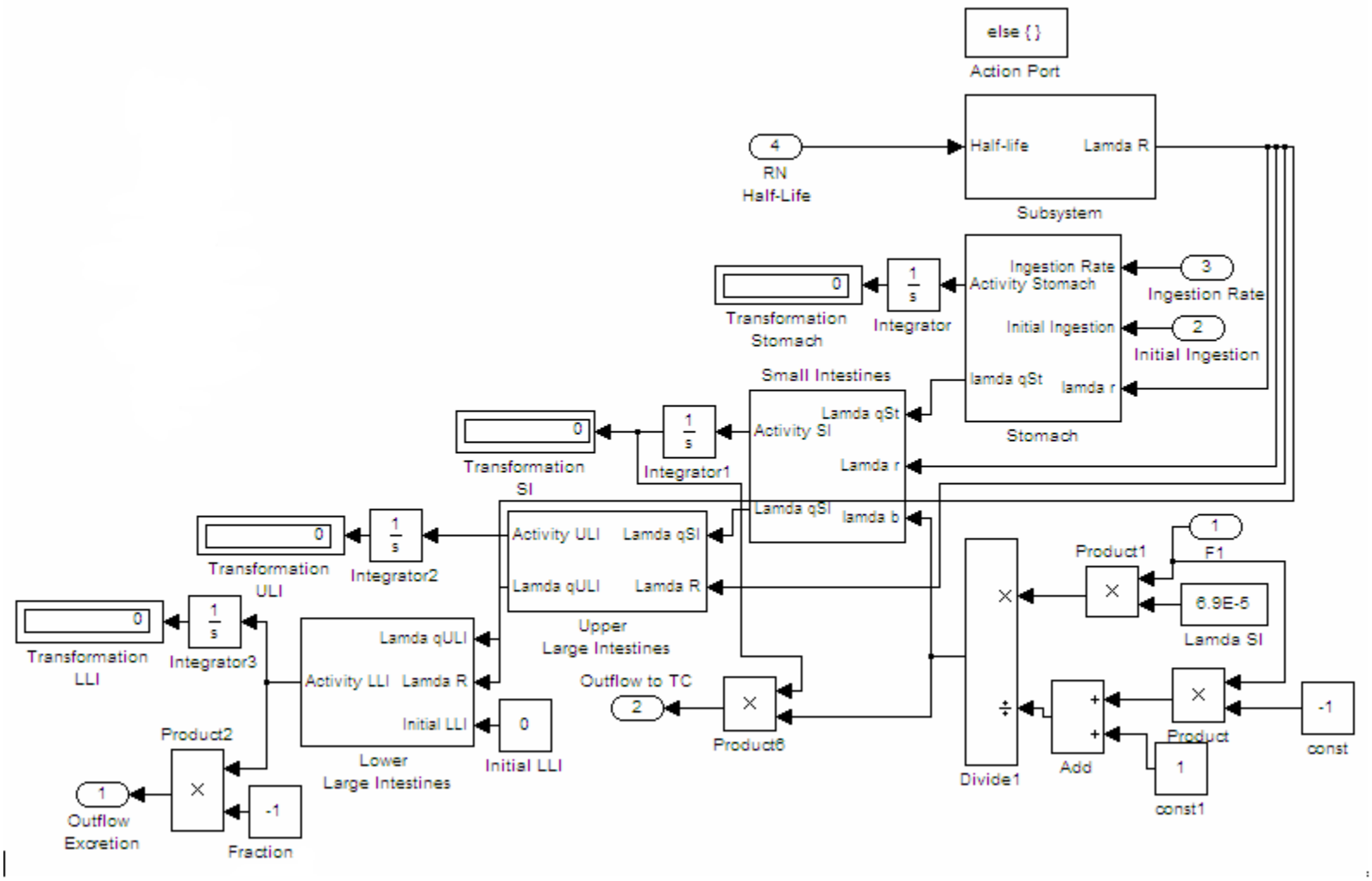
GI Tract Model Part 1 as per ICRP-30



Inhalation Intake Model as per ICRP-30



GI Tract Model Part 2 as per ICRP-30



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