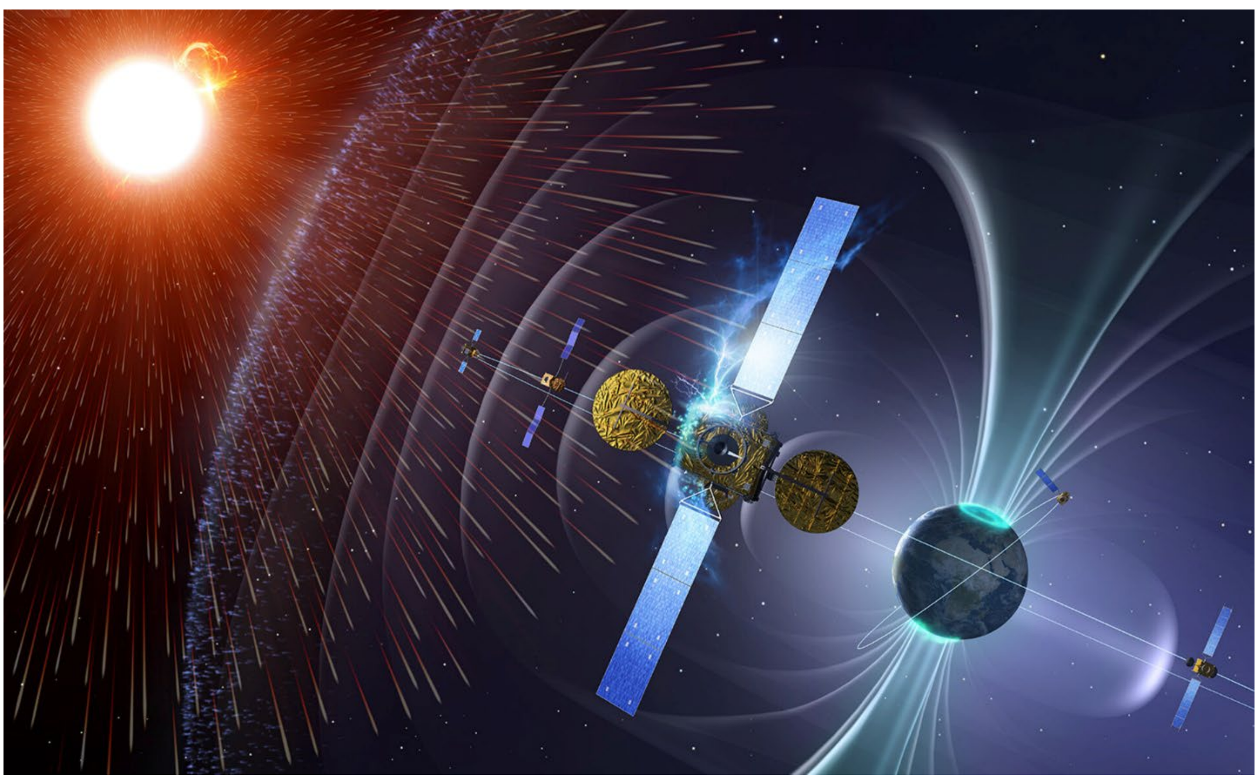
National Aeronautics and Space Administration

Math Problems Related to

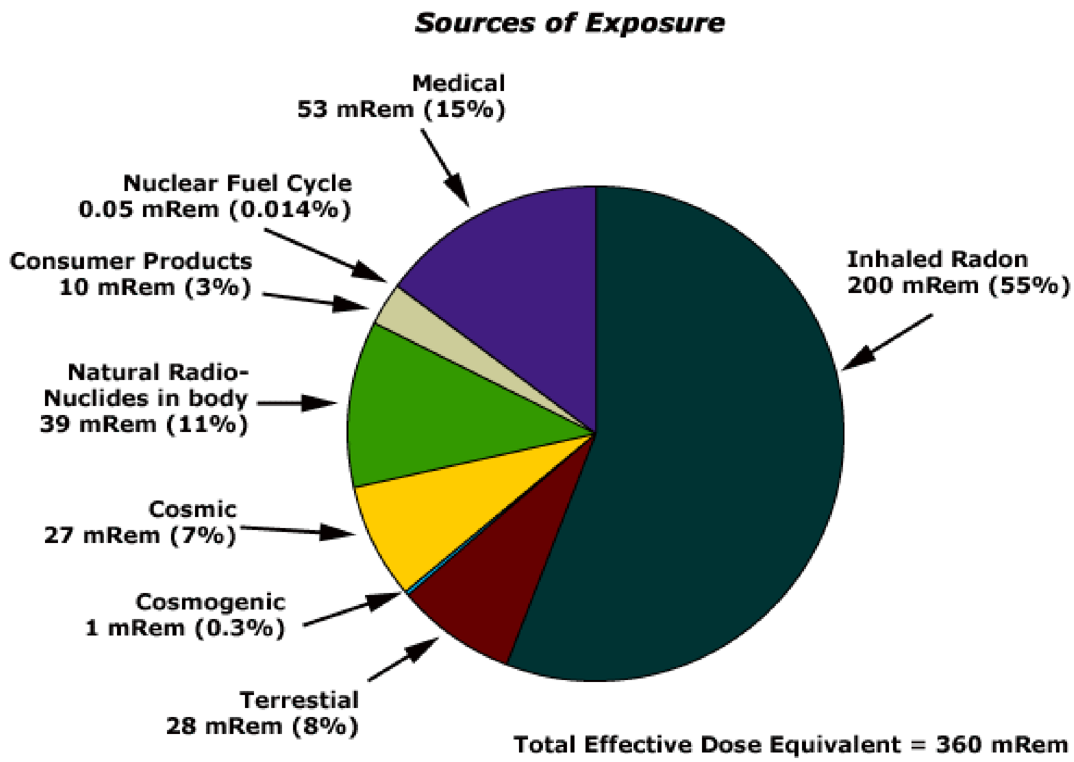
Radiation

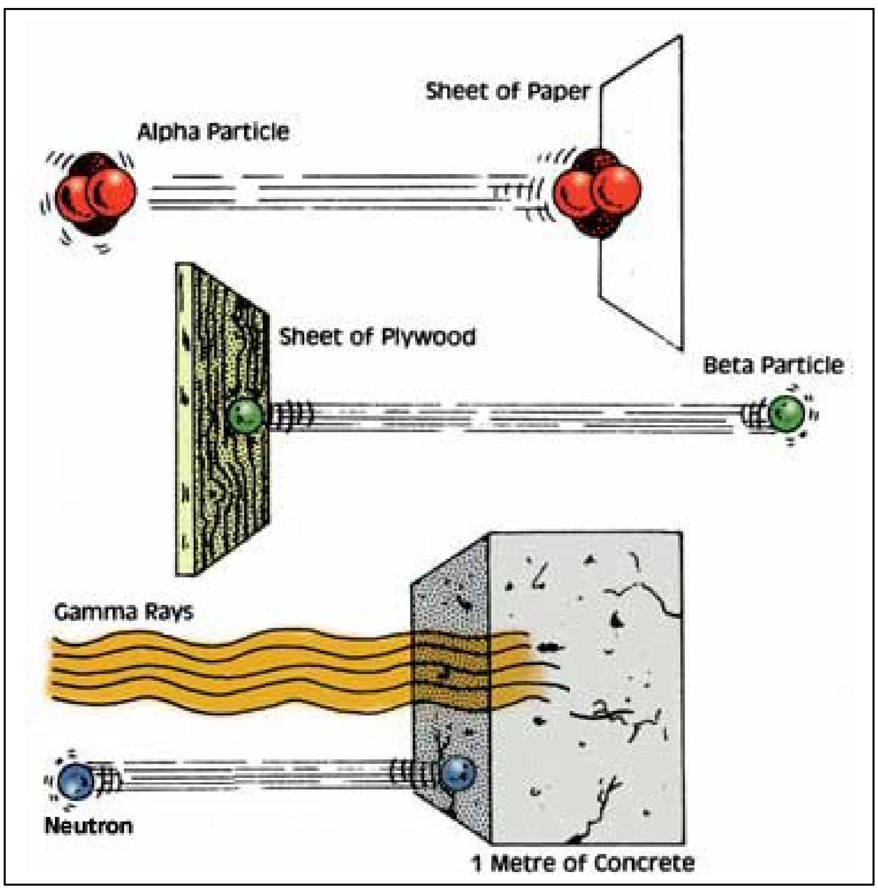


Introduction

This book provides an assortment of mathematics problems that deal with aspects of radiation exposure from electromagnetic sources such as x-rays and gamma rays, and particle sources such as electrons, protons, neutrons and other forms of matter. The book covers units of radiation measurement and conversions from one unit of measure to another, radiation shielding, and radiation exposure by astronauts as they travel to the moon and Mars.

Page	Level	Math Skill	Topic
1	Beginning	Arithmetic	An Introduction to Space Radiation
2	Beginning	Conversions	Radon Gas in the Basement
3	Beginning	Arithmetic	Airline Travel and Space Weather
4	Intermediate	Ratios	Unit Conversion Exercises
5	Intermediate	Conversions	Background Radiation and Lifestyles
6	Intermediate	Graphing, Conversions	A Study of Astronaut Radiation Dosages in Space
7	Intermediate	Formulas, Conversions, Rates	A Perspective on Radiation Dosages
8	Intermediate	Graphing, Conversions	A Hot Time on Mars
9	Intermediate	Formulas, Conversions	Calculating Total Radiation Dosages at Mars
10	Intermediate	Graphing, Conversions	Single Event Upsets in Aircraft Avionics
11	Intermediate	Conversions, Graphing, Equations	Radiation Dose and Distance
12	Intermediate	Conversions, Equations	Radiation Dose and Dose Rate
13	Intermediate	Data Analysis, Graphing	Solar Proton Events and Satellite Damage.
14	Advanced	Arithmetic	Are the Van Allen Belts Really Deadly?
15	Advanced	Equations	Some Puzzling Thoughts about Radiation!
16	Advanced	Algebra I	An Introduction to Radiation Shielding
17	Advanced	Algebra II	Atmospheric Shielding from Radiation- I
18	Advanced	Algebra I	Atmospheric Shielding from Radiation- II
19	Advanced	Calculus	Atmospheric Shielding from Radiation- III





Different types of radiation can be shielded by different materials

An Introduction to Space Radiation

Believe it or not, you are surrounded by radiation! As you are sitting here reading this article, electromagnetic radiation from sunlight, electric lights, power cables in the walls, and the local radio station are coursing through your body. Is it something to worry about? It all depends on how much you absorb, and in what forms.

There are two main types of radiation: electromagnetic radiation, and particle radiation. Both forms carry energy, which means that if you accumulate too much over time, either in the tissues of your body, or in sensitive electronic equipment, they can potentially do damage. A small amount of ultraviolet radiation can give you a nice tan. Too much can increase your risk for skin cancer. A small amount of radio radiation is enough to pick up a distant station on your radio, but too much in a microwave oven will cook you in ten seconds flat! A small amount of particle radiation in, say, the radium dial of a watch, is enough to make it glow in the dark harmlessly, but too much can destroy the DNA in your cells and lead to mutations…even death.

Scientists measure radiation dosages and exposure in terms of units called Rads and Rems (Grays and Seiverts are used in Europe). Rad means 'Radiation Equivalent Dose' and REM means 'Roentgen Equivalent Man'. One Rad is equal to 100 ergs of energy delivered to one gram of matter. The Rem compares the amount of absorbed energy to the amount of tissue damage it produces in a human.

$$\text{Rad} = \text{Rem} \times Q$$

Electromagnetic radiation, such as x-rays and gamma-rays, produce 'one unit' or tissue damage, so for this kind of radiation Q = 1, and so 1 Rad = 1 Rem. Most low-intensity forms of 'EM' radiation can be shielded by using clothing or skin creams. In high dosages, X-rays and gamma-rays require shielding to reduce their health effects, otherwise they can be lethal, or can even incinerate tissue. There are three different kinds of particle radiation, each produces its own level of tissue damage.

Alpha-particles are given-off by radioactive atoms. They are nuclei containing two protons and two neutrons: essentially helium nuclei. These particles, at high energy, can be very destructive to tissue as they leave tracks of ionization in cytoplasm and other cellular tissues. For these Q = 15-20.

Beta-particles are also given off by radioactive atoms. They consist of energetic electrons traveling at high-speed, and require several millimeters of aluminum or other shielding to stop most of them. For these, Q = 1.

Neutron particles are produced in nuclear reactions including fission and fusion. Because they carry no charge, they easily penetrate many substances. Q = 10.

Because of the differences in Q, different forms of radiation produce different levels of tissue damage. Beyond this, radiation also has different effects depending on how much you absorb over different amounts of time. Let's consider two extreme examples where your entire body is 'irradiated': A small dose over a long time, and a big does over a short time.

Weak and Long! On the ground, you receive about 0.4 Rem (e.g. 400 milliRem) of natural backround radiation and radiation from all forms of medical testing, what you eat, and where you live. Over the course of your lifetime, say 80 years, this adds up to 80 x 0.4 = 32 Rem of radiation. By far, the biggest contribution comes from radioactive radon gas in your home, which can amount to as much as 0.1 Rem, which yields a lifetime dose of 8 Rem. Some portion of this radiation exposure invariably contributes to the average cancer risk that each and every one of us experiences.

Medical Diagnostic Radiation:

0.002 Rems	Dental x-ray
0.010 Rems	Diagnostic chest X-ray
0.065 Rems	Pelvis/Hip x-ray
0.150 Rems	Barium enema for colonoscopy
0.300 Rems	Mammogram
0.440 Rems	Bone scan
2 to 10 Rem	CT scan of whole body

Strong and Intense! In cancer therapy, small parts of your body are irradiated to kill cancerous cells. This works because radiation transports energy into cellular tissue where it is absorbed, and cancerous cells are very sensitive to heat. Although patients report nausea and loss of hair, the benefits to destroying cancerous cells far outweighs the collateral effects. Typical dosages are about 200 Rems over a few square centimeters, or even 5,000 Rem over a single tumor area! For whole-body dosages, the effects are far worse!

50 - 100 Rems	No significant illness
100 - 200 Rems	Nausia ,vomiting. 10% fatal in 30 days.
200 - 300 Rems	Vomiting. 35% fatal in 30 days.
300 - 400 Rems	Vomiting, diarrhea. 50% fatal in 30 days.
400 - 500 Rems	Hair loss, fever, hemorrhaging in 3wks.
500 - 600 Rems	Internal bleeding. 60% die in 30 days.
600- 1,000 Rems	Intestinal damage. 100% lethal in 14 days.
5,000 Rems	Delerium, Coma: 100% fatal in 7 days.
8,000 Rems	Coma in seconds. Death in an hour.
10,000 Rems	Instant death.

Would you like to check your annual exposure? Visit the American Nuclear Society webpage and take their test at
http://www.ans.org/pi/resources/dosechart/

or use the one at the US Environmental Protection Agency
http://www.epa.gov/radiation/students/calculate.html

or the one at the Livermore National Radiation Laboratory
http://newnet.lanl.gov/main.htm

Questions to ponder, based on the text.

1- During an accident, a 70 kg person absorbed 1,000 Rem of x-ray radiation. How much energy, in ergs, did he gain? If 41,600,000 ergs is needed to raise the temperature of 1 gram of water by 1 degree C, how many degrees did the radiation raise the person's body if the human body is mostly water?

2 - Your probability of contracting cancer from the natural background radiation (0.3 Rem/year) depends on your lifetime exposure. From detailed statistics, a sudden 1 Rem increase in dosage causes an 0.08% increase in deaths during your lifetime, but the same dosage spread over a lifetime causes about 1/2 this cancer increase. By comparison, cancer studies show that a typical person has an 20% lifetime mortality rate from all sources of cancer. (see "Radiation and Risk", Ohio State University, http://www.physics.isu.edu/radinf/risk.htm).

a) Consider 10,000 people exposed to radiation. How many natural cancer deaths would you expect to find in such a sample?

b) How much does the natural background radiation contribute to this cancer death rate?

c) Whenever you take a survey of people, there is a built-in statistical uncertainty in how precisely you can make the measurement, which is found by comparing the sample size to the square-root of the number of samples. In polls, this is referred to as the 'margin of error'. For your answer to Problem 2a, what is the range of people that may die from cancer in this population?

d) Compared to your answer to Problem 2B, do you think you would be able to measure the lifetime deaths from natural background radiation exposure compared to the variation in cancer mortality in this population?

Answer Key

1- During an accident, a 70 kg person absorbed 1,000 Rem of x-ray radiation. How much energy, in ergs, did he gain? If 41,600,000 ergs is needed to raise the temperature of 1 gram of water by 1 degree C, how many degrees did the radiation raise the person's body if the human body is mostly water?

Q = 1 so 1 Rem = 1 Rad.

1000 Rem x 100 ergs/gram x 170 kg x 1000 gm/kg = 170,000,000,000 ergs.

1000 Rem x 100 ergs/Rem = 100,000 ergs
100,000 ergs/ (41,600,000 ergs/degree C) = 0.002 degrees C.

2 - Your probability of contracting cancer from the natural background radiation (0.3 Rem/year) depends on your lifetime exposure. From detailed statistics, a sudden 1 Rem increase in dosage causes an 0.08% increase in deaths during your lifetime, but the same dosage spread over a lifetime causes about 1/2 this cancer increase. By comparison, cancer studies show that a typical person has an 20% lifetime mortality rate from all sources of cancer. (see "Radiation and Risk", Ohio State University, http://www.physics.isu.edu/radinf/risk.htm).

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d) Compared to your answer to Problem 2B, do you think you would be able to measure the lifetime deaths from natural background radiation exposure compared to the variation in cancer mortality in this population?

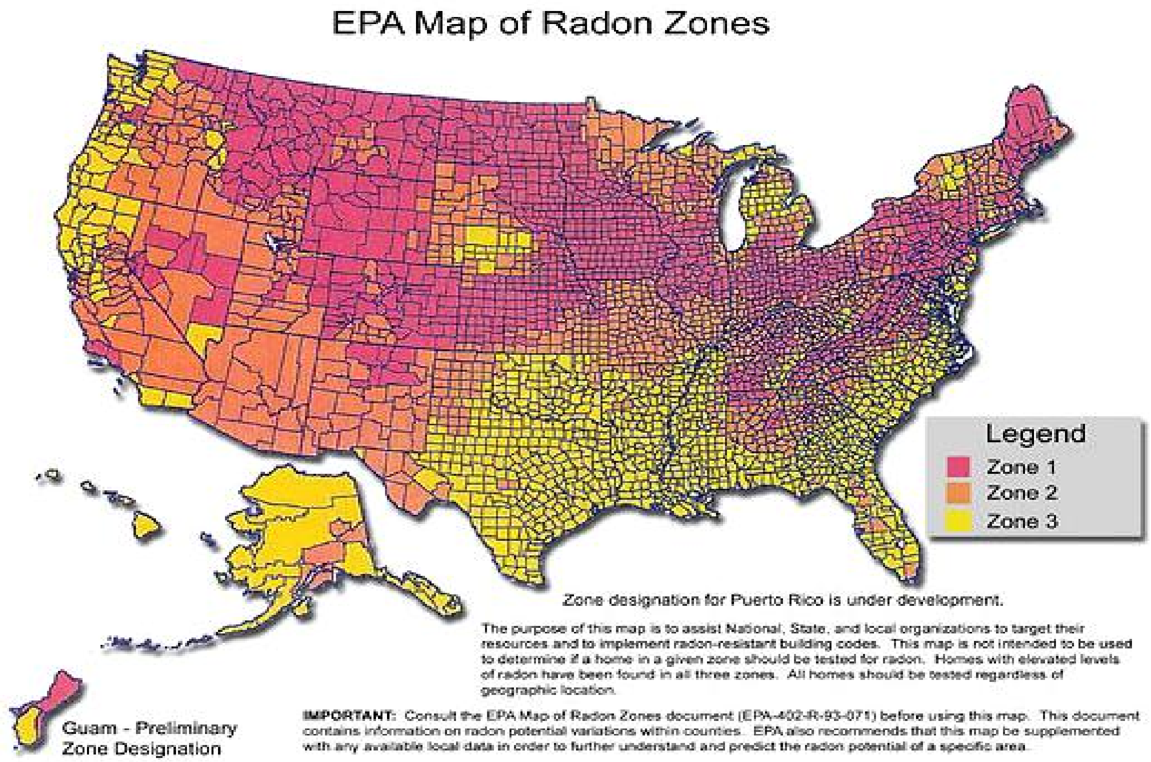
a) 10,000 x 0.2 = 2,000 deaths over a lifetime.

b) 0.3 Rem/yr x 75 years x 0.04% = 0.9% x 10,000 people = 90 people.

c) (10000)1/2 = 100 so the range is from (2000 - 100) to (2000 + 100) or 1900 to 2100 people.

d) Comparing the 90 deaths to the statistical uncertainty of 100 deaths in a sample of 10,000 people, you would not be able to detect the 90 deaths assigned to the natural background, against the variation of deaths you statistically expect from all other causes of cancer.

Radon Gas in the Basement: A Radiation Hazard



Most family rooms (dens) are located in the basements of homes across the country. This is also the place where radon gas can collect over time. When inhaled over time, radon gas adds to your lifetime natural background radiation exposure, and is a significant risk factor for various forms of lung and respiratory cancer. This is why in many states, home buyers must have prospective homes tested before purchase. The typical, annual radiation exposure from all non-radon forms of natural exposure is about 200 milliRem per year.

The above figure shows the four radon zones based on a study by the US Environmental Protection Agency (http://www.epa.gov/radon/zonemap.html). By the way, you can also find maps for individual states at this website. The four zones correspond to radiation dosages of Zone 1: 4 picoCuries/liter Zone 2: 3 picoCuries/liter Zone 3: 2 picoCuries/Liter. Note: 4 picoCuries/liter for a full-year exposure is equal to about 3 Rems.

Problem 1: A typical family may only spend 4 hours a day in the basement room. What fraction of a full year does this represent?

Problem 2: In Zone-1, a full years exposure equals 3 Rem. From your answer to Problem 1, what would you predict as the total annual dosage, in milliRems, for a member of this family if they were living in A) Zone-1? B) Zone-2? C) Zone-3?

Problem 3: If a typical lifetime is 80 years, what would be the total lifetime radiation dosage from radon in Rem for the family members in Problem 1 if they lived in A) Zone-1; B) Zone-2; C) Zone-3?

Answer Key:

Problem 1: A typical family may only spend 4 hours a day in the basement room. What fraction of a full year does this represent?

Answer: (4 / 24) = 1/6th of a year

Problem 2: In Zone-1, a full years exposure equals 3 Rem. From your answer to Problem 1, what would you predict as the total annual dosage, in milliRems, for a member of this family if they were living in:

A) Zone-1?
Answer: 3 Rem/year x 1/6 year = 1/2 Rem = 500 millirem

B) Zone-2?
Answer: 3/4 x 3 Rem/year x 1/6 year = 3/8 Rem = 375 milliRem

C) Zone-3?
Answer: 2/4 x 3 Rem/yr x 1/6 year = 1/4 Rem = 250 milliRem

Problem 3: If a typical lifetime is 80 years, what would be the total lifetime radiation dosdage from radon in Rem for the family members in Problem 1 if they lived in

A) Zone-1; Answer = 80 x 1/2 Rem = 40 Rem

B) Zone-2; Answer = 80 x 3/8 Rem = 30 Rem

C) Zone-3? Answer = 80 x 1/4 Rem = 20 Rem.

In 1999, Dr. Sten Odenwald wrote a book called 'The 23rd Cycle: Learning to live with a stormy star" that described all of the ways that severe space weather events, called solar storms, can affect our satellite technology, our electrical power, and even the health of astronauts and airline passengers and crew.

Read the excerpt from his book, and answer the following questions based on the information in the excerpt.

Question 1: What topic is this part of the book describing?

Question 2: Describe how a solar storm is involved with this topic?

Question 3: What does the article identify as a possible risk for passengers?

Here is a short list of your radiation exposure at ground level each year, in terms of a unit of radiation dosage called the milliRem.

Radon gas in your basement ....160 milliRems per year
The ground under your feet......................... 60
Nuclear reprocessing plants........................ 40
Cosmic rays at sea level............................. 38
Cosmic rays from high altitude city (Denver)....130
Medical imaging.. 30
Food and water... 25

Question 4: If you add up the different exposures in the list above, what is your total dosage each year if you were living at sea level? Living at high altitudes in Denver?

Question 5: According to the information in the article, how much extra radiation exposure would a passenger receive in a 10-hour flight at 35,000 feet?

Question 6: How much extra radiation will an airline crew member receive during 900 hours per year of flying?

Question 7: Do you think the radiation risk from solar storms is a significant one? Present the evidence that demonstrates the size of the health risk, and the evidence that suggests that the health risk is minimal.

Airline Travel and Solar Storms

Jet airliners fly at altitudes above 35,000 feet which is certainly not enough to get them into space, but it is more than enough to subject the pilots and stewardesses to some respectable doses when looked at over the course of their careers, and thousands of flights. A trip on a jet plane is often taken in a party-like atmosphere with passengers confident that, barring any unexpected accidents and food problems, they will return to Earth safely and with no lasting physical affects. But depending on what the Sun is doing, a solar storm can produce enough radiation to equal a significant fraction of a chest X-ray's dosage even at typical passenger altitudes of 35,000 feet. Airline pilots and flight attendants can spend over 900 hours in the air every year, which makes them a very big target for cosmic rays and anything else our Sun feels like adding to this mix. According to a report by the Department of Transportation, the highest dosages occur on international flights passing close to the poles where the Earth's magnetic field concentrates the particles responsible for the dosages.

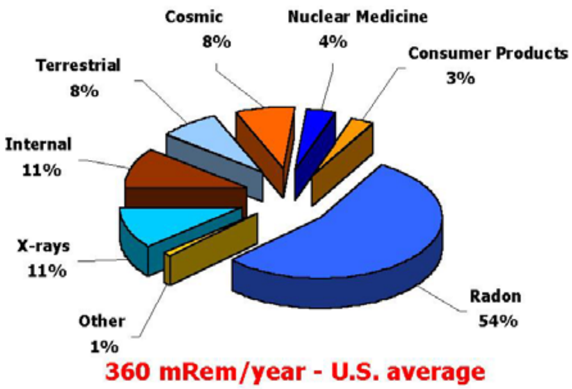
Although the dosage you receive on a single such flight per year is very small, about one milliRem per hour, frequent fliers that amass over 100,000 miles per year would accumulate nearly 500 millirems each year. Airline crews who spend 900 hours in the air would absorb even higher doses, especially on polar routes. For this population, their lifetime cancer rate would be 23 cancers per 100 people. By comparison, the typical cancer rate for ground dwellers is about 22 cancers per 100. But the impact does not end with the airline crew. The federally recommended limit for pregnant women is 500 millirems per year. Even at these levels, about four extra cases of mental retardation would appear on average per 100,000 women stewardesses if they are exposed between weeks 8 to 15 in the gestation cycle. This is a time when few women realize they are pregnant, and when critical stages in neural system formation are taking place in the fetus.

Matthew H. Finucane, air safety and health director of the Association of Flight Attendants in Washington DC, has claimed that these exposure rates are alarming, and demands that the FAA to do something about it. One solution is to monitor the cabin radiation exposure and establish OSHA guidelines for it. If possible, he also wants to set up a system to warn crews of unusually intense bursts of cosmic radiation, or solar storm activity during a flight. Meanwhile, the European Aviation Agency is contemplating going even further. They want to issue standard dosimetry badges to all airline personnel so that their annual exposures can be rigorously monitored. This is a very provocative step to take, because it could have a rather chilling effect on airline passengers. It might also raise questions at the ticket counter that have never been dealt with before*, 'Excuse me, can you give me a flight from Miami to Stockholm that will give me less than one chest X-ray extra dosage?'* How will the traveler process this new information, given our general nervousness over simple diagnostic X-rays?

Consider this: during September 29, 1989, for example, a powerful X-ray flare caused passengers on high-flying Concord airliners to receive dosages equal to two chest X-rays per hour. At the end of the flight, each passenger had silently received hundreds of additional millirems added to their regular background doses. Still, these occasional dosages the average person receives while flying, compared to the dosages we might accumulate once we land at another geographic location, are rather inconsequential over a lifetime. Compared to the quality of life that we gain in exchange for the minor radiation exposure we risk, most people will grudgingly admit the transaction is a bargain. Statisticians who work with insurance companies often think in terms of the number of days lost to your life expectancy from a variety of causes. On this scale, smoking 20 cigarettes a day costs you 2200 days; being overweight by 15% costs you 730 days; and an additional 300 millirem per year over the natural background dose (about 250 milliRem) reduces your life expectancy by 15 days. "

[Dr. Sten Odenwald, 'The 23rd Cycle' Columbia University Press, 2000]

Unit Conversion Exercises



To understand the effect that radiation has on biological systems, a number of different systems for measurement have arisen over the last 50 years. European scientists prefer to use Grays and Seiverts while American scientists still use Rads and Rems!

The chart to the left shows your typical radiation dosage on the ground and the factors that contribute to it.

Basic Unit Conversions:

1 Curie = 37 billion disintegrations/sec	
1 Gray = 100 Rads	0.001 milli
1 Rad = 0.01 Joules/kg	0.000001 micro
1 Seivert = 100 Rems	1 lifetime = 70 years
1 Roentgen = 0.000258 Charges/kg	1 year = 8760 hours
1 microCoulomb/kg = 46 milliRem	1 Coulomb = 6.24 billion billion charges

Convert:

1. 360 milliRem per year to ………………………….microSeiverts per hour

2. 7.8 milliRem per day to ………………………….Rem per year

3. 1 Rad per day to ………………………………….Grays per year

4. 360 milliRem per year to …………………………..Rems per lifetime

5. 3.0 Roentgens to ………………………………. charges per gram

6. 5.6 Seiverts per year to …………………………..milliRem per day

7. 537.0 milliGrays per year to ………………..……..milliRads per hour

Unit Conversion Exercises

Answer Key

1 . 360 milliRem per year to ……………………………**0.41 microSeiverts per hour**
360 milliRem/yr x 1Rem/1000 milliRem x 1 year/8760 hours = 0.000041 Rem/hour
0.000041 Rem/hour x 1.0 Seiverts/100 Rem = 0.00000041 Seiverts/hour
0.00000041 Seiverts/hour x 1 microSeivert/0.000001Seivert = 0.41 microSeiverts/hour

2. 7.8 milliRem per day to ……………………….……**2.8 Rem per year**
7.8 milliRem/day x 365 days/year = 2847.0 milliRem/year
2847.0 milliRem/year x 1.0 Rem/1000milliRem = 2.8 Rem/year

3. 1 Rad per day to ……………………………………..…**3.65 Grays per year**
1 Rad/day x 365 days/year x 1 Gray/100 Rads = 3.65 Grays/year

4. 360 milliRem per year to ………………………………**25.2 Rems per lifetime**
360 milliRem/year x 70 years/lifetime x 1 Rem/1000 milliRem = 25.2 Rems/lifetime

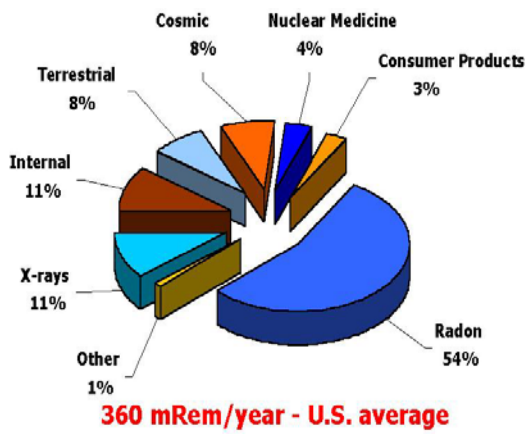
5. 3.0 Roentgens to …………………………..…**0.000000774 charges per gram**
3.0 Roentgens x 0.000258 charges/kg per Roentgen = 0.000774 charges/kg
0.000774 charges/kilogram x 1.0 kg/1000 gram = 0.000000774 charges/gram

6. 5.6 Seiverts per year to ………………………………**1530 milliRem per day**
5.6 Seiverts/year x 1.0 Year/365 days x 100 Rem/1.0 Seivert = 1.53 Rem/day
1.53 Rem/day x 1000 milliRem/Rem = 1530 milliRem/day

7. 537.0 milliGrays per year to …………………………**6.13 milliRads per hour**
537.0 milliGrays/year x 1.0 years/8760 hours x 100 Rads/1.0 Gray = 6.13 milliRads/hour

Note: There are many different conversion 'chains' that the students can offer. The challenge is to set up each ratio correctly with the right number in the numerator and denominator!

Background Radiation and Lifestyles



As we go about our daily lives, we are constantly surrounded by naturally-occurring sources of radiation. The accumulation of this radiation dosage every day throughout our lives leads to our total lifetime dosage. Depending on where we live, and our lifestyles, this lifetime dosage can make us susceptible to various forms of cancers. Generally, the lower your lifetime dose, the lower your risk for cancer.

In the following activity, you will calculate the total lifetime dosages (in Rems) for a person living in several different geographic locations with a variety of lifestyles.

1. Nancy was born in Denver where the cosmic rays (GCR) produce 120 milliRem/year and an additional 105 milliRem/year comes from the ground (Terr.). After 30 years, she moves to Baton Rouge, Louisiana where GCR = 35 milliRem/year and Terr. = 40 milliRem/year. At both locations, she buys the same kind of house and she receives 100 milliRem/year from radon gas in the basement. Assuming all other lifestyle sources contribute 50 milliRem/year during her entire life, and that she is now 65 years old, what has been her total radiation dosage to date in Rem?

2. Suppose that Nancy was also a cigarette smoker since she was 16 years old, but that she gave up smoking when she turned 52. How much additional lifetime radiation dosage in Rems did she receive from this habit during the time she lived in Denver and Baton Rouge if her one-pack-a-day habit exposed her to 15 milliRem/year?

3. Suppose that Nancy was also an airline pilot since she was 27 years old. She has been smoking since age 16. She flys 900 hours each year, with 90% of this time spent at cruising altitudes (35,000 feet) where the cosmic radiation dosage is 5 microSeiverts per hour. If 1 Seivert = 100 Rems, how much additional radiation has she received than in your answer to Question 2?

4. Suppose that after 30 years, instead of moving to Baton Rouge, Nancy moved from Denver to Kerala, India where the terrestrial radiation dosage (Terr.) is 380 milliRem/year, but gives up smoking. What will be her total dosage by age 65?

5. Instead of being an airline pilot, at age 35 she decides to become a non-smoking astronaut. From Denver, she moved to Baton Rouge for 5 years, and then finds a home in Houston near the NASA Johnson Spaceflight Center, which is the hub of manned spaceflight activities. At this location, GCR = 45 milliRem/year and Terr. = 30 milliRem/year. At age 39 she becomes the co-pilot for the Space Shuttle Atlantis on a 13-day trip, during which time her radiation dosage is 19 milliRem/day. If she takes three of these trips before age 65, what is her total dosage?

Answer Key:

1. Nancy was born in Denver where the cosmic rays (GCR) produce 120 milliRem/year and an additional 105 milliRem/year comes from the ground (Terr.). After 30 years, she moves to Baton Rouge, Louisiana where GCR = 35 milliRem/year and Terr. = 40 milliRem/year. At both locations, she buys the same kind of house and she receives 100 milliRem/year from radon gas in the basement. Assuming all other lifestyle sources contribute 50 milliRem/year during her entire life, and that she is now 65 years old, what has been her total radiation dosage to date in Rem?

Denver; (120 + 105 + 100 + 50)millirem/year x 30 years x 1 Rem/1000 milliRems = 11.25 Rem
Baton Rouge: (35 + 40 + 100 + 50) millirem/year x (65-30) years x 1 Rem/1000 milliRems = 7.88 Rem

Total = 11.25 Rems + 7.88 Rems = 19.1 Rems.

2. Suppose that Nancy was a cigarette smoker since she was 16 years old, but that she gave up smoking when she turned 52. How much additional lifetime radiation dosage in Rems did she receive from this habit during the time she lived in Denver and Baton Rouge if her one-pack-a-day habit exposed her to 15 milliRem/year?

Smoking = 15 milliRem/year x (52-16) years x 1.0 Rem / 1000 milliRems = 0.5 Rem
Geographic = 19.1 Rem
Total = 19.1 Rems + 0.5 Rems= 19.6 Rems

3. Suppose that Nancy was also an airline pilot since she was 27 years old, and retired at 45. She has been smoking since age 16. She flys 900 hours each year, with 90% of this time spent at cruising altitudes (35,000 feet) where the cosmic radiation dosage is 5 microSeiverts per hour. If 1 Seivert = 100 Rems, how much additional radiation has she received than in your answer to Question 2?

900 hours/year x (45-27) x 0.90 = 14,580 hours.
5 microSeiverts/hour x 100 Rems/1 Seivert = 500 microRems/hour
500 microRems/hour x 14,580 hours x 1 Rem/1000000microRem = 7.3 Rems
Total = 19.6 Rems + 7.3 Rems = 26.9 Rems

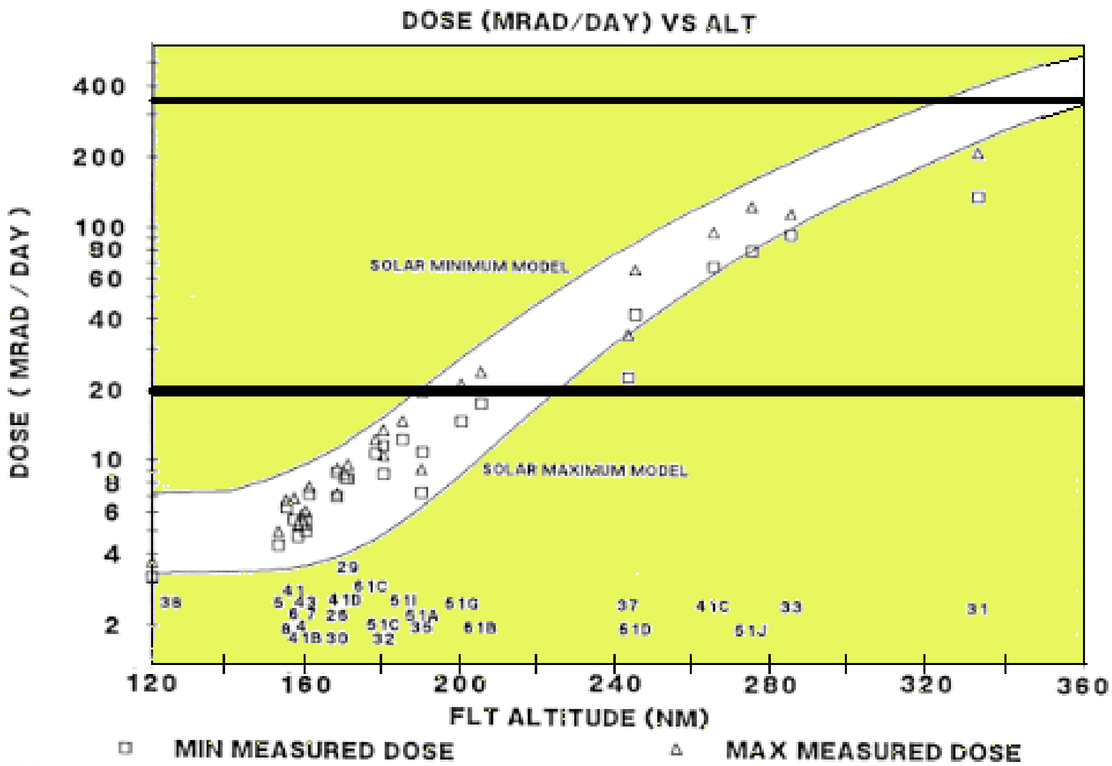
4. Suppose that after 30 years, instead of moving to Baron Rouge, Nancy moved from Denver to Kerala, India where the terrestrial radiation dosage (Terr.) is 380 milliRem/year, but gives up smoking. What will be her total dosage by age 65?

Denver = 11.3 Rems
Kerala = 380 milliRems/year x (65-30) years x 1.0 Rem/1000 milliRems = 13.3 Rems
Total = 11.3 Rems + 13.3 Rems = 24.6 Rems

5. Instead of being an airline pilot, at age 35 she decides to become a non-smoking astronaut. After 30 years in Denver, she moves to Baton Rouge for 5 years, then finds a home in Houston. At this location, GCR = 40 milliRem/year and Terr. = 30 milliRem/year. At age 39 she becomes the co-pilot for the Space Shuttle Atlantis on a 13-day trip, during which time her radiation dosage is 19 milliRem/day. If she takes three of these trips before age 65, what is her total dosage?

Denver: 11.3 Rems
Baton Rouge: 225 millirem/year x (35-30) years x 1 Rem/1000 milliRems = 1.1 Rem
Houston: 220 millirem/year x (65-35) years x 1 Rem/1000 milliRems = 6.6 Rem
Shuttle Flights: 3 x 13 days x 19 milliRem/day = 0.7 Rems
Total = 11.3 Rems + 1.1 Rems + 6.6 Rems + 0.7 Rems = 19.7 Rems

A Study of Astronaut Radiation Dosages



The typical radiation dosage on the ground is about 1.0 milliRad/day or 360 milliRad/year. This dosage is considered safe, and it is an unavoidable part of the natural background that we live and work within. In space, however, this normal background dosage is significantly exceeded. The figure above shows the radiation dosages encountered by Space Shuttle astronauts during various missions indicated by the numbers near the bottom of the graph. For example, at the far right, astronauts onboard Shuttle Mission STS-31 at an orbital altitude of 335 Nautical Miles (NM), experienced dosages between 150 to 200 milliRads per day.

Problem 1 - At about what altitude do most Space Shuttles orbit?

Problem 2 - What is the average daily dose at this altitude in milliRads/day?

Problem 3 - For a typical Shuttle mission of 10 days, what will be the astronaut's average dose?

Problem 4 - If the astronaut remained on the ground during this mission, how much of a dosage would he have acquired?

Problem 5 - How much radiation dosage did the STS-31 astronauts accumulate during their 118-hour mission to place the Hubble Space Telescope in orbit?

Answer Key:

The typical radiation dosage on the ground is about 1.0 milliRad/day or 360 milliRad/year. These dosages are considered safe, and part of the natural background that we live and work within. In space, however, this normal background dosage is significantly exceeded. The figure above shows the radiation dosages encountered by Space Shuttle astronauts during various missions indicated by the numbers near the bottom of the graph. For example, at the far right, astronauts onboard Shuttle Mission STS-31 at an orbital altitude of 335 Nautical Miles (NM), experienced dosages between 150 to 200 milliRads per day.

Problem 1 - At about what altitude do most Space Shuttles orbit?

Answer - The average of the cluster of points is near about 170 Nautical Miles.

Problem 2 - What is the average daily dose at this altitude in milliRads/day?

Answer - At 170 NM, the average dosage is about 9 milliRad/day

Problem 3 - For a typical Shuttle mission of 10 days, what will be the astronaut's average dose?

Answer - 10 days x 9 milliRad/day = 90 milliRads.

Problem 4 - If the astronaut remained on the ground during this mission, how much of a dosage would he have acquired?

Answer - 9 days x 1 milliRad/day = 9 milliRads.

Problem 5 - How much radiation dosage did the STS-31 astronauts accumulate during their 118-hour mission to place the Hubble Space Telescope in orbit? About how many years of ground dosage does this equal?

Answer - The radiation dosage at the orbit of STS-31 was about 200 milliRads/day.
The total dosage was
118 hours x (1 day / 24 hours) x 200 milliRads/day = 983 milliRads.

This equals about 983 milliRads/365 milliRads = 2.7 years of ground-level dosage

A Perspective on Radiation Dosages

Space travel is understandably a risky business. One of the most well-studied, and worrisome, hazards is the radiation environment. The sun produces streams of high-energy particles and flares, while the universe itself also rains particles down upon us from distant supernova explosions and other energetic phenomena. But how bad is space travel compared to just staying on Earth?

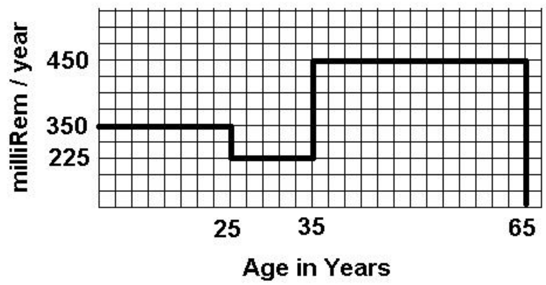
For the following problems, plot how the radiation environment changes for a person living in Denver, on the Space Station, on the Moon, and on a journey to Mars and back. Calculate the total radiation dosage by computing the area under the respective curves.

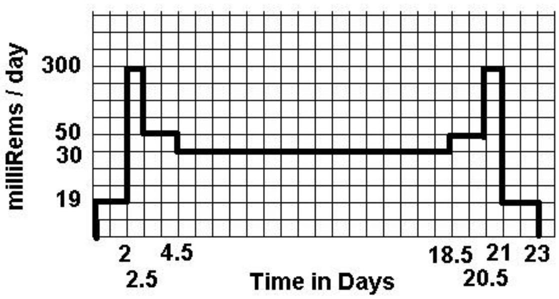
1. Nancy was born and raised in Denver where her radiation dosage was 350 milliRems/year. At age 25, she moved to Houston where her dosage was 225 milliRems/year, then moved to South Dakota 10 years later where her dosage was 450 milliRems/year until she retired at age 65. Create a plot showing 'YEAR' on the horizontal axis and 'Dosage' on the vertical axis. Prove that the product of the vertical axis units times the horizontal axis units is the total dose in milliRems. Plot Nancy's annual dosages and calculate her total dosage by age 65.

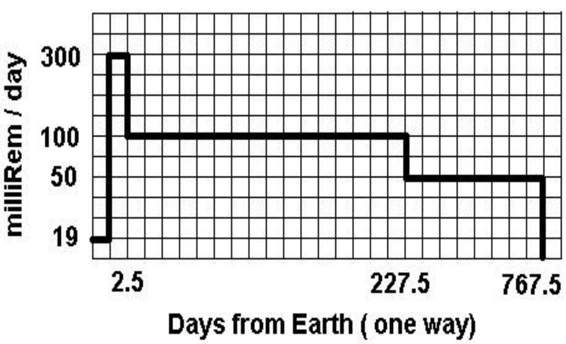
2. An astronaut travels to the Moon on NASA's Orion Crew Vehicle, and spends two weeks on the lunar surface before returning to Earth. The radiation dosage is 19 milliRem/day in Earth orbit for each of two days. The 1/2 day trip through the van Allen belts is 300 milliRem/day. The journey to the Moon takes two days at 50 milliRem/day. The stay on the lunar surface under shielded conditions is 30 milliRem/day. The astronaut returns to Earth retracing the previous conditions, followed by a 2-day stay at the International Space Station, where the dosage is 1.5 milliRem/hour. Plot her dosage history and calculate the total dosage in Rems.

3. An astronaut journeys to Mars. The radiation dosage is 19 milliRem/day at the International Space Station for each of two days. The 1/2 day trip through the van Allen belts was 300 milliRem/day. The crew spends 225 days traveling to Mars, during which time the dosages are 100 milliRems/day. On Mars, for a planned stay of 540 days, the dosage will be about 50 milliRem/day. This is followed by a similar 225-day return to earth, 1/2-day trip through the van Allen Belts, and a 2-day stay at the Space Station. Plot her dosage history and calculate the dosages.

Answer Key:







Problem 1:
<u>Denver to Houston to South Dakota:</u>
(350 mRem/yr x 25 yrs) + (225 mRem/yr x 10 yrs) + (450 mRem/yr x 30 yrs) = **24.8 Rem**

Problem 2:
<u>Roundtrip:</u>
(19 mRem/day x 2 days) + (300 mRem/day x 0.5 days) + (50 mRem/day x 2 days) + (30 mRem/day x 14 days) + (50 mRem/day x 2 days) + (300 mRem/day x 0.5 days) + (19 mRem/day x 2 days) = **1.1 Rem**

Problem 3:
<u>Earth to Mars:</u>
(19 mRem/day x 2 days) + (300 mRem/day x 0.5 days) + (100 mRem/day x 225 days) + (50 mRem/day x 540 days) = 49.7 Rem

<u>Return Trip</u> = **22.7 Rem**

<u>Total Trip =</u> 49.7 Rem + 22.7 Rem = 72.4 Rem

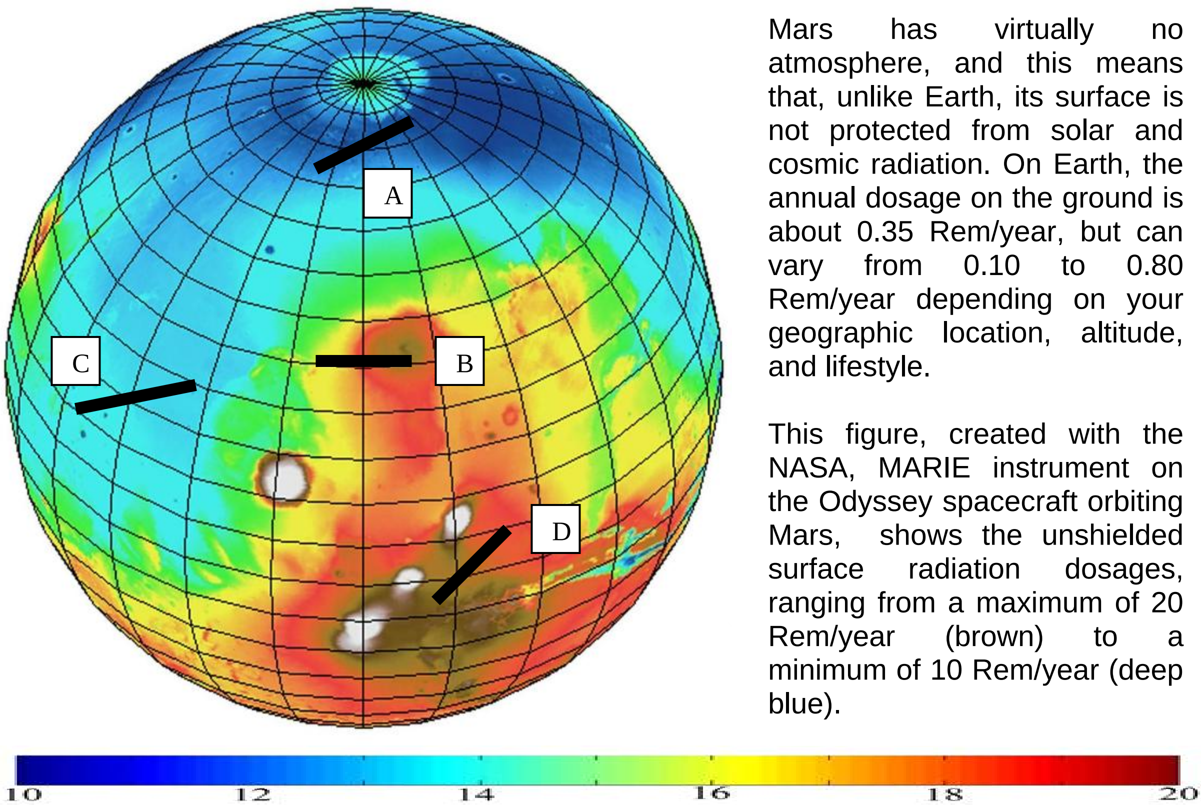
<u>Note to Teacher:</u>

The total lifetime radiation dosages for the trips in Problem 2 and 3 will be in ADDITION to the total dosages that the astronauts receive on the ground before and after the trip into space. For example, if an astronaut lives in Houston all his life (70 years) where the environmental and lifestyle dosage is 300 milliRems/year, the normal lifetime dosage will be 300 milliRems/year x 70 years = 21.0 Rems.

In Problem 3, an astronaut travels to Mars and back, taking (2.5 + 225 + 540 + 225 + 2.5)= 995 days or 2.7 years their total Mars dosage will be 72.4 Rem added to (70-2.7)x 300 milliRems/year = 20.2 Rems on the ground for a total lifetime dosage of 92.6 Rems!

Another way to look at this is to recognize that a trip to Mars will equal about 72.4 Rem/0.300 Rem = 241 years of normal background radiation living on Earth (in Houston)…but accumulated in only 2.7 years!

Having a Hot Time on Mars!



Mars has virtually no atmosphere, and this means that, unlike Earth, its surface is not protected from solar and cosmic radiation. On Earth, the annual dosage on the ground is about 0.35 Rem/year, but can vary from 0.10 to 0.80 Rem/year depending on your geographic location, altitude, and lifestyle.

This figure, created with the NASA, MARIE instrument on the Odyssey spacecraft orbiting Mars, shows the unshielded surface radiation dosages, ranging from a maximum of 20 Rem/year (brown) to a minimum of 10 Rem/year (deep blue).

Astronauts landing on Mars will want to minimize their total radiation exposure during the 540 days they will stay on the surface. The Apollo astronauts used spacesuits that provided 0.15 gm/cm^2 of shielding. The Lunar Excursion Module provided 0.2 gm/cm^2 of shielding, and the orbiting Command Module provided 2.4 gm/cm^2. The reduction in radiation exposure for each of these was about 1/4, 1/10 and 1/50 respectively. Assume that the Mars astronauts used improved spacesuit technology providing a reduction of 1/8, and that the Mars Excursion Vehicle provided a 1/20 radiation reduction.

The line segments on the Mars radiation map represent some imaginary, 1,000 km exploration tracks that ambitious astronauts might attempt with fast-moving rovers, and not a lot of food! Imagine a schedule where they would travel 100 kilometers each day. Suppose they spend 20 hours a day within a shielded rover, and they study their surroundings in spacesuits for 4 hours each day.

1) Convert 10 Rem/year into milliRem/day.

2) What is the astronauts radiation dosage per day in a region (brown) where the ambient background produces 20 Rem/year?

3) For each of the tracks on the map, plot a dosage history timeline for the 10 days of each journey. From the scaling relationship defined for one day in Problem 3, calculate the approximate total dosage to an astronaut in milliRems (mRems), given the exposure times and shielding information provided.

4) Which track has the highest total dosage in milliRems? The least total dosage? What is the annual dosage that is equivalent to these 20-day trips? How do these compare with the 350 milliRems they would receive if they remained on Earth?

Having a Hot Time on Mars!

1) Convert 10 Rem/year into milliRem/hour.

Answer: (10 Rem/yr) x (1 year/ 365 days) x (1 day/24 hr) = 1.1 milliRem/hour

2) What is the astronauts radiation dosage per day in a region (brown) where the background is 20 Rem/year?

Answer: From Problem 1, 20 Rem/year = 2.2 milliRem/hour.

20 hours x (1/20) x 1.1 milliRem/hr + 4 hours x (1/8) x 1.1 milliRem/hr = 1.1 + 0.55 = 1.65 milliRem/day

3) For each of the tracks on the map, plot a dosage history timeline for the 10 days of each journey. From the scaling relationship defined for one day in Problem 3, calculate the total dosage in milliRems to an astronaut, given the exposure times and shielding information provided. <u>The scaling relationship is that for each 20 Rems/year, the daily astronaut dosage is 0.66 milliRem/day (e.g. 0.66/20). The factor of 2 in the answers accounts for the round-trip.</u>

Track A dosage:

2x(12 Rems/yr x 10 days x (1.65 / 20)) = 2x(9.9) = 19.8 mRem.

Track B dosage:

2x(16 Rems/yr x 3.3days + 18 Rems/yr x 3.3days + 20 Rems/yr x 3.3days)(1.65/20) = 2x(14.8) = 29.6 mRem

Track C dosage:

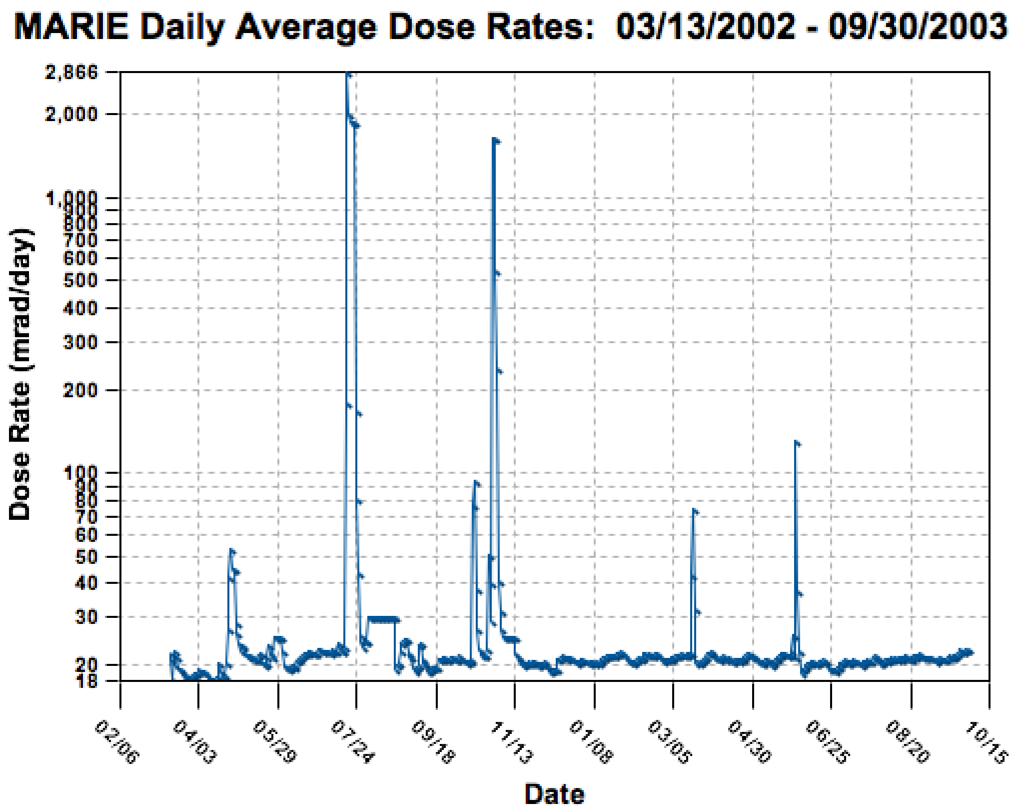
2x(12 Rems/yr x 5 days x (1.65/20) + 14 Rems/yr x 5 days x (1.65/20)) = 2x(5.0 + 5.8) = 21.6 mRem

Track D dosage:

2x(18 Rems/yr x 5 days x (1.65/20) + 20 Rems/yr x 5 days x (1.65/20)) = 2x(7.5 + 8.25) = 31.5 mRem

4) For this 20-day excursion, Track D has the highest dosage and Track A has the lowest. The equivalent annual dosage for the lowest-dosage track is 19.8 milliRem x 365 days/10 days = 722 milliRem, which is about twice the annual dosage they would receive if they remained on Earth. For the highest-dosage trip, the annualized dosage is 1,149 milliRems which is about 3 times the dosage on Earth.

Calculating Total Radiation Dosages at Mars



The NASA, Mars Radiation Environment Experiment (MARIE) measured the daily radiation dosages from a satellite orbiting Mars between March 13, 2002 and September 30, 2003 as shown in the figure above. The dose rate is given in units of milliRads per day. (1 Rad = 2 Rems for cosmic radiation.) The six tall 'spikes' are Solar Proton Events (SPEs) which are related to solar flares, while the rest of the plotted data (the wiggly line!) is the dosage caused by galactic cosmic rays (GCRs).

1. By finding the approximate area under the plotted data, calculate the total radiation dosage in Rems for the GCRs during the observation period between 4/03/2002 and 8/20/2003.

2. Assuming that each SPE event lasted 3 days, and that its plotted profile is a simple rectangle, calculate the total radiation dosage in Rems for the SPEs during the observation period.

3. What would be the total radiation dosage for an unshielded astronaut orbiting Mars under these conditions?

4. Are SPEs more important than GCRs as a source of radiation? Explain why or why not in terms of estimation uncertainties that were used.

Calculating Total Radiation Dosages at Mars

Teachers Note: Because students will be asked to determine the areas under a complicated curve using rectangles, please allow student answers to vary from the below estimates, by reasonable amounts! This may be a great time to emphasize that, sometimes, two scientists can get different answers to the same problem depending on how they do their calculation. Averaging together the student responses to each answer may be a good idea to improve accuracy!

1. By finding the approximate area under the plotted data, calculate the total radiation dosage in Rems for the GCRs during the observation period between 4/03/2002 and 8/20/2003.

From the graph, the average dosage rate is about 20 mRads/day. The time span is about 365 + 4x30 + 17 = 502 days. The area of a rectangle with a height of 20 milliRads/day and a width of 502 days is (20 milliRads/day) x (502 days) = 10040 milliRads. This can be converted to Rems by multiplying by (1 Rad/1000 milliRads) and by (2 Rem/1 Rad) to get **20 Rems.**

2. Assuming that each SPE event lasted 3 days, and that its plotted profile is a simple rectangle, calculate the total radiation dosage in Rems for the SPEs during the observation period.

Peak 1 = 53 milliRads/day x 3 days = 159 millirads
Peak 2 = 2866 millirads/day x 3 days = 8598 milliRads
Peak 3 = 90 milliRads/day x 3 days = 270 milliRads
Peak 4 = 1700 milliRads/day x 3 days = 5100 milliRads
Peak 5 = 70 milliRads/day x 3 days = 210 milliRads
Peak 6 = 140 milliRads/day x 3 days = 420 milliRads

The total dosage is 14,757 milliRads.
Convert this to Rems by multiplying by (1 Rad/1000 milliRads) x (2 Rem/1 Rad)
To get **30 Rems after rounding.**

3. What would be the total radiation dosage for an unshielded astronaut orbiting Mars under these conditions?
Answer: 20 Rems + 30 Rems = **50 Rems** for a 502-day visit.

4. Are SPEs more important than GCRs as a source of radiation? Explain why or why not.

Answer: Solar Proton Events may be slightly more important than Galactic Cosmic Radiation for astronauts orbiting Mars.

The biggest uncertainty is in the SPE dose estimate. We had to approximate the duration of each SPE by a rectangular box with a duration of exactly three days, although the plot clearly showed that the durations varied from SPE to SPE. If the average dose rate for each SPE were used, rather than the peak, and a shorter duration of 1-day were also employed, the estimate for the SPE total dosage would be significantly lower, perhaps by as much as a factor of 5, from the above estimates, which would make the GCR contribution, by far, the largest.

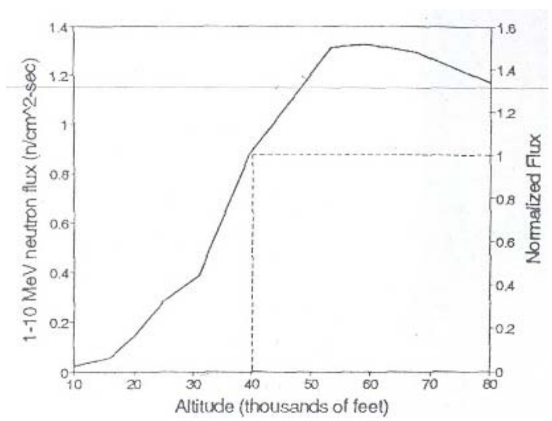
Single Event Upsets in Aircraft Avionics

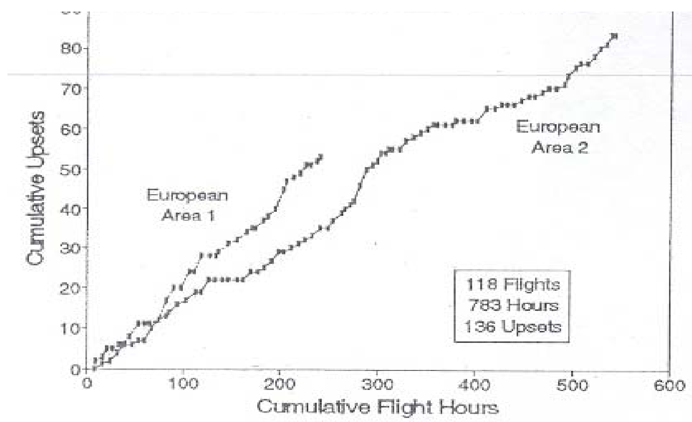
In 2001, the NASA Altair, Unmanned Air Vehicle (UAV) flew its first flight at an altitude of 100,000 feet. Designed by NASA-Dryden engineers and scientists, it is designed to fly for up to 48 hours to complete a variety of science research studies of Earth. For more details about this Dryden program, visit

http://www.nasa.gov/centers/dryden/news/FactSheets

Because of the complexity of the computer systems (called avionics) onboard, and the very high altitudes being flown, special attention had to be paid to cosmic ray showers. These particles, mostly neutrons, pass through the walls of the aircraft and can affect computer circuitry. For unmanned aircraft, the slightest computer glitch can spell the end of an $8 million aircraft. This exercise explores some of the issues behind computer glitches at aircraft altitudes.

Between the high-radiation environment of space, and the comparative safety of the ground, lies the atmosphere. Most human activity in the military and commercial flight industry takes place between ground-level and 100,000 feet. As cosmic rays collide with atmospheric atoms, they liberate showers of particles deep into the lower atmosphere. The most penetrating of these are the charge-free neutrons. The two figures below show the neutron flux versus altitude, and data taken from aircraft flying at 29,000 feet. The data were taken from a research paper by Taber and Normand (1993), and published in the *IEEE Transactions on Nuclear Science*, vol. 40, No. 2, pp 120.





The left-hand curve gives the number of neutrons that pass through each square centimeter of surface every second (the neutron flux). The right-hand plot gives the cumulative number of memory upsets at an altitude of 30,000 feet after a given number of hours in the air.

1. What is the neutron flux at 30,000 feet? At 60,000 feet?

2. How many memory upsets were registered after 400 hours of flight?

3. If the aircraft carried 1560 memory modules (called SRAMS), each with 64,000 bytes of memory, how many bytes of memory were carried? How many binary 'bits' of memory were carried? (1 byte = 8 bits)

4. If each upset involved one bit having the wrong data value due to a neutron impact, how many bit upsets were registered per day?

5. If the area of each memory unit is 7.5×10^{-9} cm^2 ,what is the total area of all the memory modules?

6. How many neutrons passed through this area in one second?

7. During the 400 hours of flight, how many neutrons passed through the memory modules?

8. What is the probability that one neutron will cause an upset?

9. How long do you have to wait for an upset to occur at 30,000 feet? At 60,000 feet? At 100,000 feet?

Answer Key:

The left-hand curve gives the number of neutrons that pass through each square centimeter of surface every second (the neutron flux). The right-hand plot gives the cumulative number of memory upsets at an altitude of 30,000 feet after a given number of hours in the air.

1. What is the neutron flux at 30,000 feet?
From the graph: 0.35 neutrons/cm2/sec

2. How many memory upsets were registered after 400 hours of flight?
From the graph: 60 upsets

3. If the aircraft carried 1560 memory modules (called SRAMS), each with 64,000 bytes of memory, how many bytes of memory were carried? How many binary 'bits' of memory were carried? (1 byte=8 bits)
1560*64000 = 99.8 megabytes x 8 bits/byte = 798,000,000 bits

4. If each upset involved one bit having the wrong data value due to a neutron impact, how many bit upsets were registered per day? 60/(400/24) = 3.6 bits/day for a population of 798,000,000 bits

5. If the area of each memory unit is 7.5 x 10^{-9} cm^2 ,what is the total area of the memory modules?
7.9 x 10^{-9} x 798,000,000 = 6.3 cm^2.

6. How many neutrons passed through this total memory area in one second?
From the answers to Problem 1 and 5:
0.35 neutrons/cm^2/sec x 6.3 cm^2 = 2.2 neutrons/second.

7. During the 400 hours of flight, how many neutrons passed through the memory modules?
2.2 neutrons/sec x 400 hours x 3600 seconds/hr = 3.2 million neutrons.

8. What is the probability that one neutron will cause an upset?
From Problem 2 and 7: 60 upsets /3.2 million neutrons= 1 chance in 53,300.

9. How long do you have to wait for an upset to occur at 30,000 feet?
The time it takes 53,300 neutrons to pass through the memory at 2.2 neutrons per second. 53,300/2.2 = 6.7 hours. Or you can get it by 400/60 = 6.7 hours.

At 60,000 feet, the neutron flux is 1.3/0.35 = 3.7 times higher than at 30,000 feet, so you would have to wait 6.7/3.7 = 1.8 hours.

At 100,000 feet, which is the cruising altitude of the Altair UAV, the graph suggests a neutron flux of about 1.0 neutrons/cm^2/sec, so the flux is 1.0/0.35 = 2.9 times stronger at 100,000 feet than at 30,00 feet, and the time between upsets would be about 6.7/2.9 = 2.3 hours.

If the UAV were equipped with this much memory (about 100 megabytes) and was airborne for 48 hours, it would experience 48/2.3 = 21 memory upsets! This is why the computer systems on the UAV have to be radiation-hardened and the software designed to fix radiation errors when they occur.

This iconic photo was taken at the Shibuya train station in Toyko on March 15, a few days after the Japan 2011 earthquake, which caused severe damage to the Fukushima Nuclear Plant in northern Japan located 250 km from Tokyo. The monitor indicates a reading of 0.6 microSeiverts per hour. The normal background dose rate is about 0.4 microSeiverts per hour.*(Courtesy Associated Press/Kyodo News)*

The devastating Japan 2011 earthquake damaged the nuclear reactors in Fukushima, which emitted clouds of radioactive gas and dust into the atmosphere. News reports indicated the radiation levels at many different locations and times through out the following week. Because radioactivity decays with time and distance, it is difficult to compare the many measurements to know if the dosages are declining as expected. The following table of measurements was collected from a variety of news reports:

Date	Distance (km)	Location	Dose Rate (microSeiverts/hr)
March 15	1 km	Fukushima #2 plant	8,200
March 15	20 km	Namai	330
March 16	30 km	Iwaki City	150
March 16	50 km	Koriyama City	2.7
March 16	70 km	Kitaibaraki City	1.2
March 16	160 km	Maebiashi City	4.0
March 15	250 km	Tokyo	0.9 maximum

Problem 1 - Graph the base-10 log of the radiation dose rate versus the base-10 log of distance from the Fukushima nuclear plant.

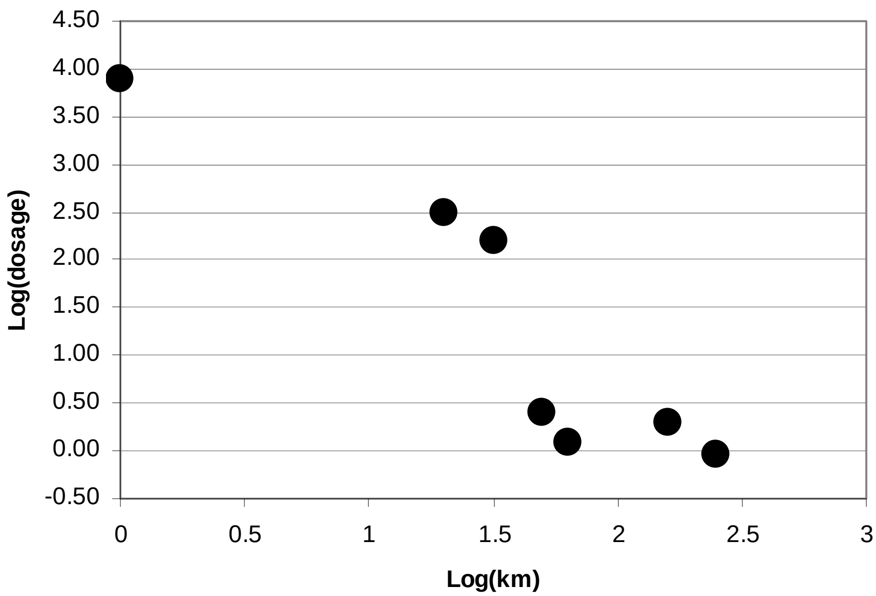
Problem 2 - On the Log-Log graph you just created, what is the approximate slope of the line that fits the data best? Show that an 'inverse-square law' has a slope of -2 on this graph.

Problem 3 - Using the graph, what would you predict for the dose rates near the city of Tamura, located 40 km from the nuclear reactors, and a position located at 10-kilometers, which is inside the limit to the evacuation zone?

Problem 1 - Graph the base-10 log of the radiation dose rate versus the base-10 log of distance from the Fukushima nuclear plant.

Distance	Dose Rate	Log(km)	Log(D)
1 km	8,200	0	3.9
20 km	330	1.3	2.5
30 km	150	1.5	2.2
50 km	2.7	1.7	0.4
70 km	1.2	1.8	0.08
160 km	4.0	2.2	0.3
250 km	0.9	2.4	-0.05

The graph of the Log(Dose Rate) and Log(distance) is as follows:

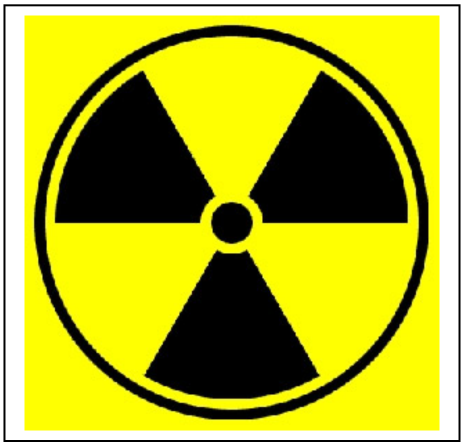


Problem 2 - On the Log-Log graph, what is the approximate slope of the line that fits the data best? Show that an 'inverse-square law' has a slope of -2 on this graph.
Answer: Using the first (0.0, 3.8) and last (2.4, -0.05) points, Slope = (-0.05 – 3.8)/(2.4 – 0.0), slope = -3.85/2.4); **Dose rate slope = -1.6**. An inverse square law is written as $y = x^{-2}$ Taking the log of both sides we get log(y) = -2 log(x). So the slope of an inverse-square law on a log-log graph would be exactly -2.0

Problem 3 – Using the graph, what would you predict for the radiation dose rates near the city of Tamura (d= 40 km), and a position located at 10-kilometers, which is inside the 20-kilometer limit to the evacuation zone?

Answer: Log(40km) = 1.6, so for x = 1.6, we can estimate from the graph that y = 1.4, and so Log(dosage) = +1.5 so that dosage = $10^{+1.5}$ = **32 microSeiverts/hour**. At a distance of 10-km, X = log(10) = 1.0 and so y = 2.0 and the dosage would be **1,000 microSeiverts/hour.**

Radiation Dose and Dose Rate



Radiation is measured in two units. The first is a measure of the rate at which you are being exposed to a source of radioactivity, while the second is a measure of how much radiation you have accumulated over time. Radiation dose is measured in units of microSeiverts while dose rate is measured in terms of dose per unit time such as microSeiverts per hour or milliSeiverts per year.

Hasty reports about the devastating Japan 2011 nuclear power plant radiation leakages have occasionally confused these two concepts. When you consider the analogy of filling up a 1-liter kettle of water from the water tap, it is easy to keep the distinction between dose and dose rate clear. The volume of water in the kettle (the dose) depends on the rate of water flow (the dosage rate) times the filling time.

Problem 1 - The natural radiation background at sea level is about 0.4 microSeiverts/hour. In terms of milliSeiverts, what is your total radiation dose after A) 1 year? B) a 70-year lifetime?

Problem 2 - At the typical cruising altitude of a passenger jet, about 10,000 meters (33,000 feet), the dose rate is about 5 microSeiverts/hour. During its years of operation, the French Concorde jet traveled at altitudes of 18,000 meters (54,000 feet) where the cosmic radiation dose rate was about 15 microSeiverts/hour. If a flight from Paris to New York takes 8 hours by ordinary jet and 3.5 hours by Concorde, what are the total radiation doses for a passenger in each case?

Problem 3 - The Japan 2011 earthquake damaged several nuclear reactors, causing radiation leakage across northern Japan. On March 22, 2011 typical radiation levels across most of Japan are now below 50 microSeiverts/hour. The typical annual radiation dose from all forms of natural sources, medical tests, and food consumption is about 0.4 milliSeiverts. How many days will it take for a Japanese citizen to reach this annual dose level?

Problem 1 - The natural radiation background at sea level is about 0.4 microSeiverts/hour. In terms of milliSeiverts, what is your total dose after A) 1 year? B) a 70-year lifetime? Answer: A) 0.4 microSeiverts/hour x (24 hours/1 day) x (365 days/1 year) = 3500 microSeiverts. Converting this to milliServerts: 3500 microSeiverts x (1 milliSeivert/1000 microSeiverts) = **3.5 milliSeiverts**. B) In a 70-year lifetime ,your total dose will be 70 years x 3.5 milliSeiverts/year = **245 milliSeiverts**.

Problem 2 - At the typical cruising altitude of a passenger jet, about 10,000 meters (33,000 feet), the dose rate is about 5 microSeiverts/hour. During its years of operation, the French Concorde jet traveled at altitudes of 18,000 meters (54,000 feet) where the cosmic radiation dose rate was about 15 microSeiverts/hour. If a flight from Paris to New York takes 8 hours by ordinary jet and 3.5 hours by Concorde, what are the total doses for a passenger in each case?

Answer: Ordinary jet: 5 microSeiverts/hour x 8 hours = **40 microSeiverts**.
Concorde: 15 microSeiverts/hour x 3.5 hours = **53 microSeiverts**.

Problem 3 - The Japan 2011 earthquake damaged several nuclear reactors, causing radiation leakage across northern Japan. On March 22, 2011 typical radiation levels across most of Japan are now below 10 microSeiverts/hour. The typical annual radiation dose from all forms of natural sources, medical tests, and food consumption is about 0.4 milliSeiverts. How many days will it take for a Japanese citizen to reach this annual dose level?

Answer: Time = Amount / Rate

$$Time = \frac{0.4 milliSeiverts}{10 microSeiverts / hr}$$

$$Time = \frac{400 microSeiverts}{10 microSeiverts / hr}$$ so Time = 40 hours.

This means that in one year they will accumulate over 88 milliSeiverts of radiation dose, which is 88/0.4 = 220 times the normal annual dosage.

Fortunately, the dose rates are declining each day as the radioactive isotopes decay, and are also diluted through wind action. The actual accumulated dose may only be 10% of this in most regions of the country. This is still, however, 20 times the natural pre-contamination dose rate. Other communities where the dose rates are higher than 10 microSeiverts/hr will have to be decontaminated by soil removal and other time-consuming and expensive methods.

Solar Proton Events can cause satellite damage and produce harmful radiation dosages for astronauts working and traveling in space. The table below lists all the SPEs between 1997 and 2004 with intensities greater than 300 pico-Flux Units (pFU). Study this table and answer the questions that follow.

Date	SPE Intensity	Solar Flare Brightness
Nov 7, 2004	495	200.0
Jul 25, 2004	2,086	10.0
Nov 4. 2003	353	2800.0
Nov 2, 2003	1,570	
Oct 28, 2003	29,500	1700.0
Oct 26, 2003	466	100.0
Nov 9, 2002	404	40.0
Aug 24, 2002	317	300.0
May 22, 2002	820	5.0
April 21, 2002	2,520	100.0
Dec 26, 2001	779	70.0
Nov 22, 2001	18,900	90.0
Nov 4, 2001	31,700	100.0
Oct 1, 2001	2,360	90.0
Sep 24, 2001	12,900	200.0
Apr 18, 2001	951	2.0
Apr 10, 2001	355	200.0
Apr 2, 2001	1,110	2000.0
Nov 24, 2000	942	200.0
Nov 8, 2000	14,800	70.0
Sep 12, 2000	320	10.0
July 14, 2000	24,000	500.0
Nov 14, 1998	310	1.0
Sep 30, 1998	1,200	20.0
Aug 24, 1998	670	100.0
May 6, 1998	210	200.0
April 20, 1998	1,700	10.0
Nov 6, 1997	490	900.0

Question 1: What is the range of the SPE intensities recorded for the period from 1997 to 2004?

Question 2: What is the frequency of SPE events for each year?

Question 3: Is there a relationship between the SPE intensity and the solar flare brightness?

Question 4: Do the brightest solar flares produce the most intense SPEs? Give examples that demonstrate your answer.

Question 5: The sunspot cycle had the largest number of sunspots during 2000. What is unusual about the frequency of SPEs and 'sunspot maximum'?

Question 6: Are there more SPEs during certain months of the year?

Applying what you have learned.

Satellites lose 2% of their electrical power for every SPE brighter than 15,000 pFUs. If a satellite was launched in 1997, how much power loss will it have suffered by the end of 2004?

If the satellite systems require 4500 watts to operate, how could the designers have insured that the satellite received all the power it needed by the end of 2004?

Once in a while. the sun lets loose with a powerful burst of energy similar to a solar flare, but potentially far more lethal. Solar Proton Events (SPEs) are streams of protons that are accelerated to high energies near the solar surface, lasting from hours to as much as a day or two. As these protons arrive at Earth, they can scour solar panels on satellites costing them several years worth of power. When the particles slam into metal in satellites or in spacecraft, they can produce secondary nuclear particles and electrons that can damage delicate circuitry, or even endanger astronaut health. This activity will have students examine a list of the SPEs since 1996 from the archive at http://image.gsfc.nasa.gov/poetry/weekly/SEPsince1976.htm which was produced by scientists at the National Geophysical Data Center. Students will analyze the table and answer questions on its statistical content.

Question 1: What is the range of the SPE intensities recorded for the period from 1997 to 2005? **Answer:** The range is [210, 31700]

Question 2: What is the frequency of SPE events for each year? **Answer:** 1997 = 1, 1998 = 5, 1999 = 0, 2000 = 4, 2001 = 8, 2002 = 4, 2003 = 4, 2004 = 2, which can be bar-graphed.

Question 3: Is there a relationship between the SPE intensity and the solar flare brightness? **Answer:** No. The most intense SPEs can have solar flares that span nearly the entire brightness range for flares.

Question 4: Do the brightest solar flares produce the most intense SPEs? Give examples that demonstrate your answer. **Answer:** No. See, for example November 4, 2003 and Nove,ber 4, 2001.

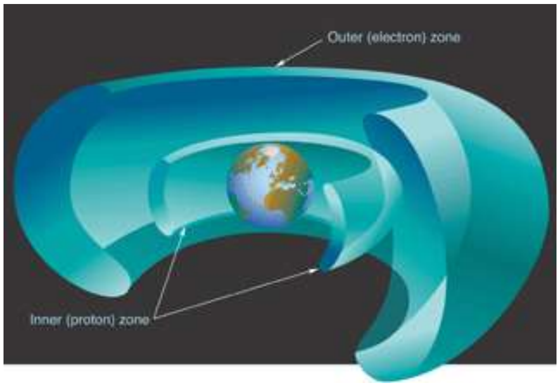
Question 5: The sunspot cycle had the largest number of sunspots during 2000. What is unusual about the frequency of SPEs and 'sunspot maximum'? **Answer:** There are far more SPEs after sunspot maximum than before sunspot maximum.

Question 6: Are there more SPEs during certain months of the year? **Answer:** Yes. November and April have more SPEs!

If a satellite was launched in 1997, how much power loss will it have suffered by 2005? **Answer:** There were 5 SPEs during this time that were brighter than 15,000 pFUs so the satellites lose 5 x 2% = 10% of their electrical power between 1997-2005.

If the satellite systems require at least 4500 watts to operate, how could the designers have insured that the satellite received all the power it needed by 2005? **Answer:** Just make the solar panels 10% larger to they produce 4900 watts at launch. By the end of 2004, the power will have declined 10% to 4500 watts which is still enough power to keep the equipment operating!

The Deadly Van Allen Belts?

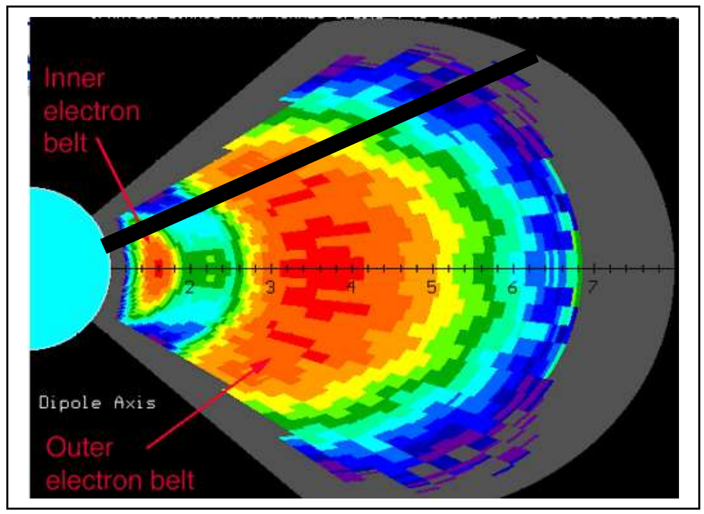


In 1958, Dr. James Van Allen discovered a collection of high-energy particle clouds within 40,000 km of Earth. Arranged like two nested donuts, the inner belt is mainly energetic protons, while the outer belts contain both protons and electrons. These belts have long been known as 'bad news' for satellites and astronauts, with potentially deadly consequences if you spend too much time within them. The figure below, produced by scientists from the NASA, CRRES satellite, shows the radiation dosages at various locations within the belts.

Blue = 0.0001 Rads/sec Green= 0.001 Rads/sec Yellow= 0.005 Rads/sec Orange= 0.01 Rads/sec and Red= 0.05 Rads/sec.

The numbers along the horizontal axis give the distance from Earth in multiples of the Earth radius (1 Re=6378 km). The Inner van Allen Belt is located at about 1.6 Re. The Outer van Allen Belt is located at about 4.0 Re. At a distance of 2.2 Re, there is a 'gap' region in between these belts. Satellites such as the Global Positioning System (GPS) orbit in this gap region where radiation effects are minimum.

The International Space Station and Space Shuttle, on this scale, orbit very near the edge of the blue 'Earth disk' in the figure, so are well below the Van Allen Belts.



Apollo astronauts, and astronauts in the upcoming visits to the Moon, will have to travel through some of these belt regions because the orbit of the Moon lies along the fastest line-of-travel from Earth. On the scale of the above figure, the distance to the Moon is 60 Re.

1. The speed of the spacecraft will be about 25,000 km/hour. If the spacecraft travels along the indicated path (black bar), how long, in minutes, will it spend in the Blue, Green, Yellow, Orange and Red regions?

2. Given the indicated radiation dosages in Rads/sec for each zone, what will be the dosages that the astronauts receive in each zone?

3. What will be the total radiation dosage in Rads for the transit through the belts?

4. Some people believe that the Apollo moon landings were a hoax because astronauts would have been instantly killed in the radiation belts. According to the US Occupation Safety and Health Agency (OSHA) a lethal radiation dosage is 300 Rads in one hour. What is your answer to the 'moon landing hoax' believers?

Note: According to radiation dosimeters carried by Apollo astronauts, their total dosage for the entire trip to the moon and return was not more than 2 Rads over 6 days.

Answer Key:

Apollo astronauts, and astronauts in the upcoming visits to the Moon, will have to travel through some of these belt regions because the orbit of the Moon lies along the fastest line-of-travel from Earth. On the scale of the above figure, the distance to the Moon is 60 Re.

1. The speed of the spacecraft will be about 25,000 km/hour. If the spacecraft travels along the indicated path, how long, in minutes, will it spend in the Blue, Green, Yellow, Orange and Red regions?
Note: transit estimates may vary depending on how accurately students measure figure.

Blue: 1.8 Re x (6378 km/Re) x (1 hour/25,000 km) x (60 minutes/1 hour) =	27.6 minutes
Yellow: (1.4 x 6378) /25,000 x 60 =	21.4 minutes
Orange: (1.0 x 6378) / 25,000 x 60 =	15.3 minutes
Green: (0.25 x 6378)/25,000 x 60 =	3.8 minutes
Red:	0 minutes
Total transit time……………………… 68.1 minutes	

2. Given the indicated radiation dosages in Rads/sec for each zone, what will be the dosages that the astronauts receive in each zone?

Blue: = 27.6 minutes x (60 sec/ 1 minute) x (0.0001 Rads/sec) =	0.17 Rads
Yellow = 21.4 minutes x 60 sec/minute x 0.005 rads/sec =	6.42 Rads
Orange = 15.3 minutes x (60 sec/minute) x 0.01 rads/sec =	9.18 Rads
Green = 3.8 minutes x (60 sec/minute) x 0.001 rads/sec =	0.23 Rads

3. What will be the total radiation dosage in Rads for the transit through the belts?
0.17 + 6.42 + 9.18 + 0.23 = 16.0 Rads

4. Some people believe that the Apollo moon landings were a hoax because astronauts would have been instantly killed in the radiation belts. According to the US Occupation Safety and Health Agency (OSHA) a lethal radiation dosage is 300 Rads in one hour. What is your answer to the 'moon landing hoax' believers?

Note: According to radiation dosimeters carried by Apollo astronauts, their total dosage for the entire trip to the moon and return was not more than 2 Rads over 6 days.

The total dosage for the trip is only 16 Rads in 68.1 minutes. Because 68.1 minutes is equal to 1.13 hours, his is equal to a dosage of 16 Rads / 1.13 hours = 14.0 Rads in one hour, which is well below the 300 Rads in one hour that is considered to be lethal. Also, this radiation exposure would be for an astronaut outside the spacecraft during the transit through the belts. The radiation shielding inside the spacecraft cuts down the 14 Rads/hour exposure so that it is completely harmless.

Some Puzzling Thoughts about Space Radiation

We have all heard, since grade school, that **1**___________ affects living systems by causing cell mutations. The particles such as fast-moving ions or **2**____________ strike particular locations in the **3**_________ of a cell, causing the cell to malfunction, or **4**______________ and pass-on a **5**______________ to its progeny. Sometimes the mutations are not beneficial to an organism, or to the evolution of its species. When this happens you can get **6**________________.

Cancer risks are generally related to the total amount of lifetime radiation exposure. The studies of **7**________________ survivors, however, still show that there is much we have to learn about just how radiation delivers its harmful impact. Very large **8**______________ over a short period of time seem not to have quite the deleterious affect that, say, a small dosage delivered steadily over many years does.

The National Academy of Sciences has looked into this issue rather carefully over the years to find a relationship between **9**________________ cancer risks and low-level radiation exposure. What they concluded was that you get up to 100 cancers per 100,000 people for every 1000 **10**_____________ of additional dosage per year above the natural **11**_______________ rate. If a dosage of 1000 millirems extra radiation per year, adds 100 extra deaths per 100,000, then as little as one extra millirem per annum could cause cancer in one person per **12**_______________. Although it's just a **13**_________________ estimate, if you happen to be that 'one person' you will be understandably **14**_________________. No scientific study, by the way, has shown that radiation has such a **15**________________impact at all levels below 100 millirem, but that's what the **16**_________________ application of arithmetic shows.

Government safety regulations now require that people who work with radiation, such as **17**__________, nuclear medicine technologists, or nuclear power plant operators, are given a maximum permissible dose limit of 500 millirems per year above the prevailing **18**_____________ background rate. For you and me doing ordinary work in the office, factory or store, the acceptable maximum dose is 1000 milliRems/year above the 350 milliRem you get each year from natural sources. As a comparison, if you lived within 20 miles of the **19**__________ nuclear power **20**_____________ at the time of its **21**_________ meltdown, your annual dose would have been about 1500 milliRem/year during the first year, declining slowly as the radioactive **22**_____________ in the environment decay

(Excerpted from 'The 23rd Cycle", Sten Odenwald, Columbia University Press)

Solve for X in each equation, and select the correct word from the pair of solutions for X, to fill-in the indicated blanks from 1 to 22 in the essay above.

1) $x^2 - 2x - 3 = 0$
2) $x^2 + 4x - 5 = 0$
3) $x^2 - 3x + 2 = 0$
4) $x^2 - x - 12 = 0$
5) $2x^2 - 12x + 10 = 0$
6) $x^2 - 2x - 24 = 0$
7) $x^2 + 5x + 6 = 0$
8) $x^2 - 9 = 0$
9) $2x^2 + 4x - 30 = 0$
10) $3x^2 + 3x - 6 = 0$
11) $x^2 - 6x - 16 = 0$
12) $x^2 - 3x - 88 = 0$
13) $x^2 - 4x - 21 = 0$
14) $x^2 - x - 30 = 0$
15) $x^2 - 9x - 36 = 0$
16) $x^2 - 16x + 63 = 0$
17) $x^2 + 16x + 63 = 0$
18) $x^2 + 14x + 48 = 0$
19) $x^2 + 19x + 90 = 0$
20) $x^2 + 8x - 33 = 0$
21) $x^2 - 100 = 0$
22) $x^2 - 8x = 0$

<u>Word bank - factor list</u>

-11	plant	-4	cancer	3	lifetime	10	1986
-10	2005	-3	dosages	4	survive	11	hundred
-9	Chernobyl	-2	Hiroshima	5	mutation	12	linear
-8	million	-1	radiation	6	upset		
-7	dentists	0	isotopes	7	statistical		
-6	natural	1	milliRems	8	background		
-5	neutrons	2	DNA	9	blind		

Here are the correct words added:

We have all heard, since grade school, that **1-radiation** affects living systems by causing cell mutations. The particles such as fast-moving ions or **2-neutrons** strike particular locations in the **3-DNA** of a cell, causing the cell to malfunction, or **4-survive** and pass-on a **5-mutation** to its progeny. Sometimes the mutations are not beneficial to an organism, or to the evolution of its species. When this happens you can get **6-cancer**.

Cancer risks are generally related to the total amount of lifetime radiation exposure. The studies of **7-Hiroshima** survivors, however, still show that there is much we have to learn about just how radiation delivers its harmful impact. Very large **8-dosages** over a short period of time seem not to have quite the deleterious affect that, say, a small dosage delivered steadily over many years does.

The National Academy of Sciences has looked into this issue rather carefully over the years to find a relationship between **9-lifetime** cancer risks and low-level radiation exposure. What they concluded was that you get up to 100 cancers per 100,000 people for every 1000 **10-millirems** of additional dosage per year above the natural **11**-**background** rate. If a dosage of 1000 millirems extra radiation per year, adds 100 extra deaths per 100,000, then as little as one extra millirem per annum could cause cancer in one person per **12-million**. Although it's just a **13-statistical** estimate, if you happen to be that 'one person' you will be understandably **14-upset**. No scientific study, by the way, has shown that radiation has such a **15-linear** impact at all levels below 100 millirem, but that's what the **16-blind** application of arithmetic shows.

Government safety regulations now require that people who work with radiation, such as **17-dentists**, nuclear medicine technologists, or nuclear power plant operators, are given a maximum permissible dose limit of 500 millirems per year above the prevailing **18-natural** background rate. For you and me doing ordinary work in the office, factory or store, the acceptable maximum dose is 1000 milliRems/year above the 350 milliRem you get each year from natural sources. As a comparison, if you lived within 20 miles of the **19-Chernobyl** nuclear power **20-plant** at the time of its **21-1986** meltdown, your annual dose would have been about 1500 milliRem/year during the first year, declining slowly as the radioactive **22-isotopes** in the environment decay away.

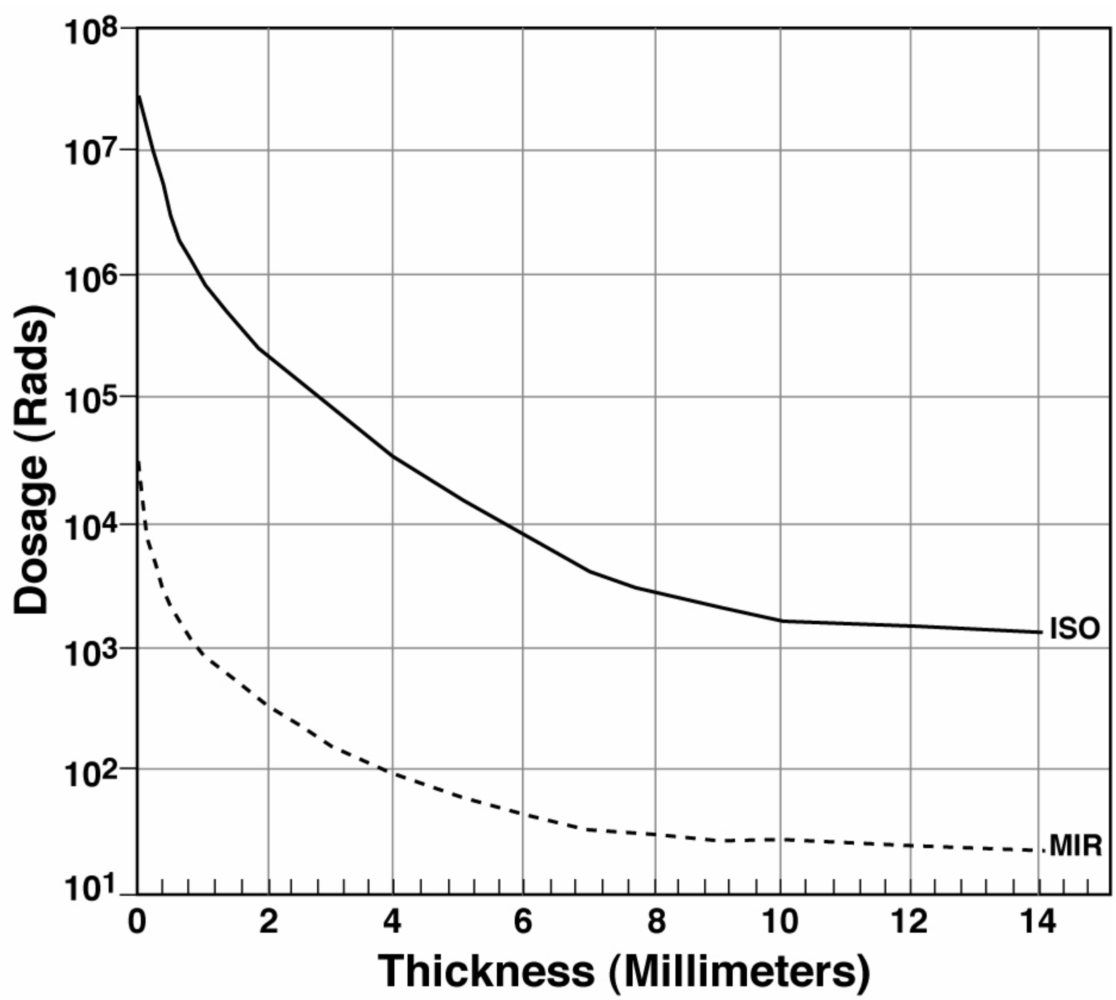
(Excerpted from 'The 23rd Cycle", Sten Odenwald, Columbia University Press)

1)	(x - 3) (x + 1)	3, **-1**	radiation	12)	(x + 8) (x - 11)	**-8**, 11	million
2)	(x + 5) (x - 1)	**-5**, 1	neutrons	13)	(x - 7) (x+3)	**7**, -3	statistical
3)	(x - 2) (x - 1)	**2**, 1	DNA	14)	(x - 6) (x + 5)	-5, **6**	upset
4)	(x - 4) (x + 3)	**4** ,-3	survive	15)	(x - 12) (x + 3)	**12**, -3	linear
5)	(2x - 2) (x - 5)	1 , **5**	mutation	16)	(x - 7) (x - 9)	7, **9**	blind
6)	(x - 6) (x + 4)	6, **-4**	cancer	17)	(x + 7) (x + 9)	**-7**, -9	dentists
7)	(x + 2) (x + 3)	**-2**, -3	Hiroshima	18)	(x + 6) (x + 8)	**-6**, -8	natural
8)	(x + 3) (x - 3)	**-3**, 3	dosages	19)	(x + 10) (x + 9)	-10, **-9**	Chernobyl
9)	(2x - 6) (x + 5)	**3**, -5	lifetime	20)	(x + 11) (x - 3)	**-11**, 3	plant
10)	(3x + 6) (x - 1)	2, **1**	milliRems	21)	(x + 10) (x - 10)	-10, **10**	1986
11)	(x - 8) (x + 2)	**8**, -2	background	22)	x (x - 8)	**0**, 8	isotopes

<u>Word bank - factor list</u>

-11	plant	12	linear
-10	2005	11	hundred
-9	Chernobyl	10	1986
-8	million	9	blind
-7	dentists	8	background
-6	natural	7	statistical
-5	neutrons	6	upset
-4	cancer	5	mutation
-3	dosages	4	survive
-2	Hiroshima	3	lifetime
-1	radiation	2	DNA
0	isotopes	1	milliRems

Introduction to Radiation Shielding



Satellites are designed to withstand many forms of radiation in the harsh environment of space. The above graph shows how the total life time radiation dosage inside a spacecraft changes as the amount of aluminum shielding increases. The data comes from the former MIR space station and the research satellite ISO. The sensitive instruments and electronic systems operate inside the satellite shell and are protected from harmful dosages of radiation by the shielding provided by the spacecraft walls.

Problem 1: You want to design a new satellite to replace the ISO satellite and to last 8 years in orbit, but it can only continue to work normally if it accumulates no more that 75,000 Rads of radiation during that time. Using the curve for ISO, how thick do the satellite walls have to be to insure this?

Problem 2: The International Space Station has the same orbit as the MIR. An astronaut will spend about 100 hours in space to assemble the station. If the equivalent shielding of her spacesuit is 1.0 mm of aluminum, how large of a dosage will she receive during this time? How does it compare to the 0.4 Rads she would receive if she stayed on the ground?

Problem 3: A cubical satellite has sides 1 meter across, and the density of the aluminum is 2.7 g/cc. How much mass, in kilograms, will the satellite have with 4 mm-thick walls? 12 mm-thick walls? If the launch cost is $15,000 per kilogram, how much extra will it cost to launch the heavier, and better-shielded, satellite?

Answer Key:

Problem 1: You want to design a new satellite to replace the ISO satellite and to last 8 years in orbit, but it can only continue to work normally if it accumulates no more that 75,000 Rads of radiation during that time. Using the curve for ISO, how thick do the satellite walls have to be to insure this?

Answer: The annual dosage would be 75,000 rads/8 years = 9,375 rads/year. From the ISO curve, this level of radiation would occur with about 5.5 millimeters of aluminum shielding.

Problem 2: The International Space Station has the same orbit as the MIR. An astronaut will spend about 100 hours in space to assemble the station. If the equivalent shielding of her spacesuit is 0.5 mm of aluminum, how large of a dosage will she receive during this time? How does it compare to the 0.4 Rads she would receive if she stayed on the ground?

Answer: The graph shows that for 0.5 millimeters equivalent spacesuit thickness and a MIR orbit, the annual dosage is 800 Rads. But she will only spend 100 hours in space. There are 8760 hours in a year, so her actual dosage would be about 800 Rads/yr x (100 hrs/8760 hrs/yr) = 9.1 Rads. This is about 9.1/0.4 = 23 times the dosage she would get on the ground in one year..or equal to 23 years worth of dosage on the ground.

Problem 3: A cubical satellite has sides 1 meter across, and the density of the aluminum is 2.7 grame per cubic centimeter. How much mass, in kilograms, will the satellite have with 4 mm-thick walls? 12 mm-thick walls? If the launch cost is $15,000 per kilogram, how much extra will it cost to launch the heavier, and better-shielded, satellite?

Answer: A) A cube consists of six sides. Each side has a volume of 1 meter x 1 meter x 4 millimeters, which in centimeters is = 100 x 100 x 0.4 = 4000 cubic centimeters. The density of aluminum is 2.7 grams/cubic centimeter, so the mass of one side of the cube will be 2.7 x 4000 = 10,800 grams or 10.8 kilograms. The entire satellite will have a mass of 6 x 10.8 kilograms or 64.8 kilograms.

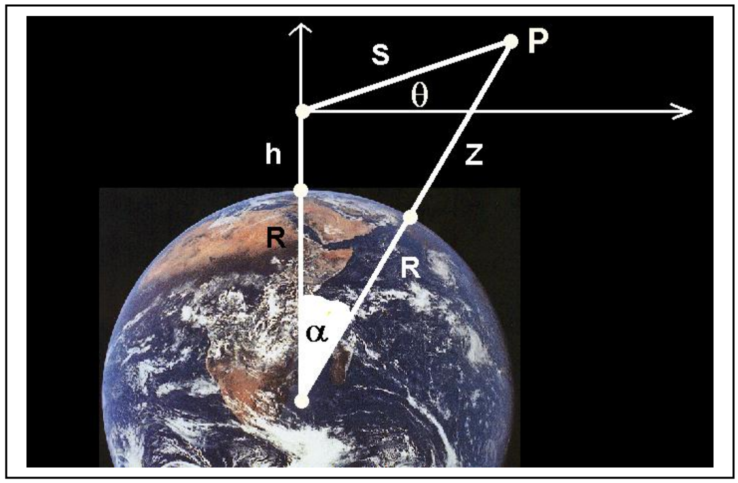
B) With 12-millimeter walls, the mass will be 100x100x1.2 x 2.7/1000 = 32.4 kilograms.
C) The extra launch cost would be (32.4 - 10.8)x $15,000/kg = $324,000

Atmospheric Shielding from Radiation I

The least expensive form of radiation shielding is a planetary atmosphere, but just how efficient is it? The walls of the International Space Station and the Space Shuttle provide substantial astronaut protection from space radiation, and have an equivalent thickness of 10 grams/cm^2 of aluminum, which has a density of 2.7 grams/cm^3. Compare this shielding to the spacesuits worn by Apollo astronauts of only 0.1 grams/cm^2. The atmosphere of Earth is a column of air with density of 0.0012 grams/cm^3, that is 100 kilometers tall. How much shielding does this provide at different altitudes above the ground?

In this three-part problem, we will begin the first step in constructing a mathematical model of the shielding from a planetary atmosphere. A similar calculation was published by Drs. Lisa Simonsen and John Nealy in February, 1993 in the article *"Mars Surface Radiation Exposure for Solar Maximum Conditions and 1989 Solar Proton Events"*, (NASA Technical Paper 3300)

The figure below right gives the necessary geometry and variable definitions.



The figure shows a radiation sampling point located 'h' above Earth's surface, and radiation from a source at point P, which is located at a distance 'S' from the sampling point. The distance from Earth's surface to point P is given by 'z'. Also, as seen from the sampling point, the vertical arrowed ray points to a point straight overhead, and the horizontal arrowed ray points to the horizon. The angle 'θ' is the elevation angle of the radiation source from the sampling point. So, a scientist would place a radiation detector at the sampling point located above Earth's surface, point the instrument at the radiation source at point P, and make a measurement of the amount of radiation coming from that particular direction in the sky.

Problem 1: From the information given in the figure, calculate the distance, S, in terms of h, R, z, and θ.

Problem 2: What is the form of S(R, h, z, θ) when;

A) If h is very much smaller than R? (h approaches zero)
B) $\theta = 90^o$?
C) If z is very much smaller than R? (z approaches zero)

Problem 1: From the information given in the figure, calculate the distance, S, in terms of h, R, z, and θ.
First, take three deep breaths, and play with the figure a bit. After some fascinating trial-and-error attempts, the simplest thing to realize is that the Law of Cosines can be used. There is only one of the three forms of this Law that do not involve the undesired angle, β , namely:

$$(R + Z)^2 = S^2 + (R + h)^2 - 2 (R + h) S \cos(\theta + 90^o)$$

Where we can use the angle addition theorem, cos (A + B) = Cos(A)cos(B) - sin(A)sin(B) to simplify it:

$$(R + Z)^2 = S^2 + (R + h)^2 + 2 (R + h) S \sin(\theta)$$

At first, it doesn't look like this pile of junk is useful because S doesn't appear by itself on one side of the equals sign. But by re-arranging, you see that it is really an equation with an interesting form:

$S^2 + [2(R+h) \sin(\theta)] + \left[(R + h)^2 - (R + Z)^2 \right] = 0$ which is a quadratic equation in which the coefficients are

$A = 1$ $B = 2(R+h) \sin(\theta)$ and $C = (R + h)^2 - (R + Z)^2$

We use the quadratic equation to solve for the positive root, because the negative root has no physical meaning. With a 'little' algebra we get:

Answer --- > $S(R,h,z,\theta) = \left((R + h)^2 \sin^2\theta + 2 R (z - h) + z^2 - h^2 \right)^{1/2} - (R + h) \sin \theta$

Problem 2: What is the form of S(R, h, z, θ) when;

A) $h << R$? Answer: Let $h = 0$

$$S(R,h,z,\theta) = \left(R^2 \sin^2\theta + 2 R z + z^2 \right)^{1/2} - R \sin \theta$$

B) $\theta = 90^o$? Answer:

$$S(R,h,z,\theta) = \left((R + h)^2 + 2 R (z - h) + z^2 - h^2 \right)^{1/2} - (R + h)$$

We can simplify this as

$$S(R,h,z,\theta) = \left((R + h)^2 + 2 R (z - h) + z^2 - h^2 \right)^{1/2} - (R + h)$$

$$S(R,h,z,\theta) = \left(R^2 + 2Rh + h^2 + 2Rz - 2Rh + z^2 - h^2 \right)^{1/2} - (R + h)$$

$$S(R,h,z,\theta) = \left(R^2 + 2Rz + z^2 \right)^{1/2} - R - h$$

$$S(R,h,z,\theta) = (R + z) - R - h$$

Answer --- > $S (R,h,z,\theta) = z - h$

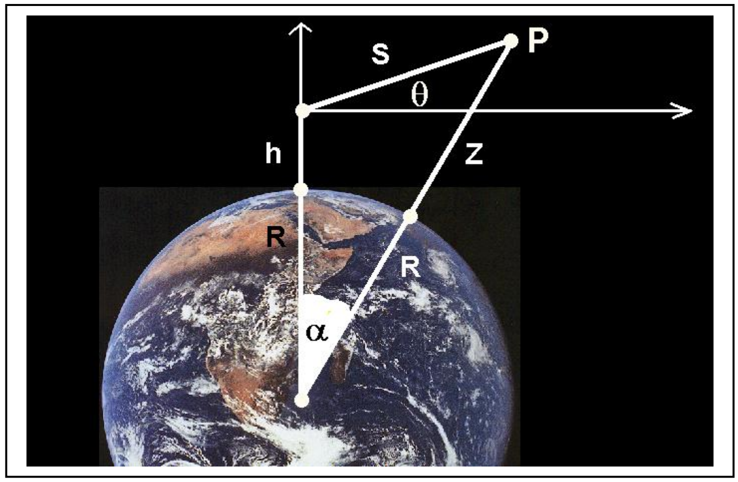
C) $z << h$? Answer: Set $z = 0$ then

$$S(R,h,z,\theta) = \left((R + h)^2 \sin^2\theta + 2 R h - h^2 \right)^{1/2} - (R + h) \sin \theta$$

Atmospheric Shielding from Radiation II

The least expensive form of radiation shielding is a planetary atmosphere, but just how efficient is it? The walls of the International Space Station and the Space Shuttle provide substantial astronaut protection from space radiation, and have an equivalent thickness of 10 grams/cm^2 of aluminum, which has a density of 2.7 gm/cm^3. Compare this shielding to the spacesuits worn by Apollo astronauts of only 0.1 gm/cm^2. The atmosphere of Earth is a column of air with density of 0.0012 gm/cm^3, that is 100 kilometers tall. How much shielding does this provide at different altitudes above the ground?

In the previous problem 'Atmospheric Shielding from Radiation I' we defined a function that gives the length of the path from the radiation source to the measurement point located h above Earth's surface. To find the amount of shielding provided by the atmosphere, we have to multiply this length, by the density of the atmosphere along the path S. In this problem, we will assume that the atmosphere has a constant density of 0.0012 grams/cm^3, and see what the total shielding is along several specific directions defined by θ.



The formula for S is given by:

$$S(R,h,z,\theta) = \left((R + h)^2 \sin^2\theta + 2 R (z - h) + z^2 - h^2 \right)^{1/2} - (R + h) \sin \theta$$

Assume R = 6,378 kilometers.

Problem 1: What is the form of the function that gives the shielding for a direction A) straight overhead ($\theta = 90^0$) and B) at the horizon ($\theta = 0^0$), for a station at sea-level (h=0 kilometers)?

Problem 2: More than 90% of the atmosphere is present below an altitude of about 2 kilometers. If this is approximated as being uniform in height, what is the total shielding towards the zenith (overhead) and the horizon, if z = 2 kilometers?

Problem 3: The atmosphere of Mars is about 100 times less dense, and mostly resides below 1 kilometer in altitude. Re-calculate the answers to Problem 2, and compare the radiation dosage difference at the surface of each planet.

The formula for S is given by:

$$S(R,h,z,\theta) = \left((R + h)^2 \sin^2\theta \ + \ 2 R (z - h) + \ z^2 - \ h^2 \right)^{1/2} \ - \ (R + h) \sin\theta$$

Shielding $D(R,h,z,\theta) = 0.0012 \times S(R,h,z,\theta)$ in units of gm/cm^2 for S given in cm.

Problem 1: What is the form of the function that gives the shielding for A) a direction straight overhead ($\theta = 90^o$), and B) at the horizon ($\theta = 0^o$), for a station at sea-level (h=0 kilometers)?

Answer: A) $D = 0.0012 \times Z$ where Z is in centimeters.

B) $D(R,h,z,\theta) = 0.0012 \left(z^2 + 2 R z \right)^{1/2}$ where R and z are in centimeters.

Problem 2: More than 90% of the atmosphere is present below an altitude of about 2 kilometers. If this is approximated as being uniform in height, what is the total shielding towards the zenith (overhead) and the horizon, if z = 2 kilometers?

Answer:

A) $D = 0.0012 \ gm/cm^3 \times 200{,}000 \ cm = 240 \ gm/cm^2$ for radiation entering from straight overhead.

B) Because $z << R$, $z^2 <<< 2Rz$ so

$$D = 0.0012 \times (2 R z)^{1/2}$$

$$= 0.0012 \times (2 \times (2 \times 10^5) \times (6.278 \times 10^6))^{1/2}$$

$$= 0.0012 \times 1.59 \times 10^6$$

$= 1916 \ gm/cm^2$ for radiation entering from the horizon direction

Problem 3: The atmosphere of Mars is about 10 times less dense. Re-calculate the answers to Problem 2, and compare the radiation dosage difference at the surface of each planet.

Answer: For mars, R = 3,374 km, density = $0.00012 \ gm/cm^3$ then from Problem 2:

A) $D = 0.00012 \ gm/cm^3 \times 100{,}000 \ cm = 12 \ gm/cm^2$

B) $D = 0.00012 \times (2 R z)^{1/2}$

$= 0.00012 \times (2 \times (1 \times 10^5) \times (3.374 \times 10^6))^{1/2}$

$= 0.00012 \ gm/cm^3 \times 8.2 \times 10^5 \ cm$

$= 98 \ gm/cm^2$

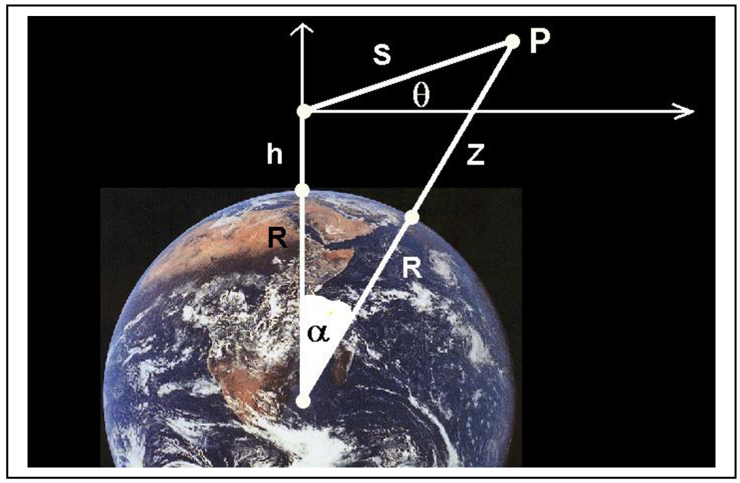
The minimum radiation shielding comes from directions above your head that pass through the least amount of atmosphere. The amount of radiation shielding at the surface of Mars is $(240 \ gm/cm^2) /(12 \ gm/cm^2)$= 20 times less than on Earth. That means that radiation dosages at the surface of Mars would be about 20 times higher than on Earth's surface. Instead of 27 mRems/year, which is typical of the cosmic ray background on Earth's surface, you would receive about 27 x 20 = 560 mRems/year on Mars. Compare this with 370 mRems/year as the average human dosage on Earth from all sources.

In the next problem 'Atmospheric Shielding from Radiation III' we will calculate this shielding more exactly.

Atmospheric Shielding from Radiation III

The least expensive form of radiation shielding is a planetary atmosphere, but just how efficient is it? The walls of the International Space Station and the Space Shuttle provide substantial astronaut protection from space radiation, and have an equivalent thickness of 10 grams/cm^2 of aluminum, which has a density of 2.7 gm/cm^3. Compare this shielding to the spacesuits worn by Apollo astronauts of only 0.1 gm/cm^2. The atmosphere of Earth is a column of air with density of 0.0012 gm/cm^3, that is 100 kilometers tall. How much shielding does this provide at different altitudes above the ground?

In the previous problem 'Atmospheric Shielding from Radiation II' we estimated the atmospheric shielding of Earth and Mars and compared the potential radiation dosages on the planetary surface. In this problem, we will create a more accurate estimate by using a realistic model for the atmospheres of these planets. Assume R (Earth) = 6,378 kilometers, R (Mars = 3,374 km)



The formula for S is given by $S(R,h,z,\theta) = \left((R + h)^2 \sin^2\theta + 2 R (z - h) + z^2 - h^2 \right)^{1/2} - (R + h) \sin \theta$

Problem 1: What is the form of the function S for h=0 ?

The density of a planetary atmosphere is defined by the exponential function $N(z) = N(0)\, e^{(-Z/H)}$ where H is the scale-height of the gas. For the composition of Earth's atmosphere, temperature, and surface gravity, H = 8.5 km. For Mars, H = 11.1 km. The sea-level density for Earth, N(0) = 0.0012 gm/cm^3, while for Mars, N(0) = 0.00020 g/cm^3. The amount of surface shielding for radiation arriving from a direction, θ, is given by evaluating the integral below:

$$D = \int_0^{+\text{inf.}} N(z)\,ds$$

Problem 2:

A) Determine the form for S for the case of θ = 90 which gives the minimum planetary shielding at the surface for radiation entering from directly overhead.

B) Evaluate the integral for Earth and for Mars.

C) Assuming that the radiation environments of Mars and Earth are otherwise similar, about how many times more would your radiation dosage be on the surface of Mars compared to Earth?

D) How does the atmospheric shielding of Earth compare to the shielding provided by the International Space Station or the Space Shuttle?

The formula for S is given by $S(R,h,z,\theta) = \left((R + h)^2 \sin^2\theta + 2 R (z - h) + z^2 - h^2 \right)^{1/2} - (R + h) \sin \theta$

Problem 1: What is the form of the function S for h=0 ?

$$S(R, z,\theta) = \left(R^2 \sin^2\theta + 2 R z + z^2 \right)^{1/2} - R \sin \theta$$

Problem 2: The density of a planetary atmosphere is defined by the exponential function $N(z) = N(0)\, e^{(-Z/H)}$ where H is the scale-height of the gas. For the composition of Earth's atmosphere, temperature, and surface gravity, H = 8.5 km. For Mars, H = 11.1 km. The sea-level density for Earth, N(0) = 0.0012 gm/cm^3 , while for Mars, N(0) = 0.00020 g/cm^3.

A) From the definition of S in Problem 1, determine the form for S for the case of θ = 90 which gives the minimum planetary shielding at the surface for radiation entering from directly overhead.

Answer: sin(90) = 1 so $S = \left(R^2 + 2 R z + z^2 \right)^{1/2} - R$ $S = (R+z) - R$ so **S = z !!!**

B) Evaluate the integral for Earth and for Mars.

From A) s = z so by substituting s for z, the integral becomes ………

$$\boxed{D = \int_0^{+inf.} N(0)\, e^{-(z/H)}\, dz}$$

Using the variable substitution x = z/H , you can put the integrand in a standard form………

$$\boxed{D = N(0)\, H \int_0^{+inf.} e^{-x}\, dx}$$

Evaluating the integral…..

$$\boxed{D = N(0)\, H \left(e^{-0} - e^{-(infinity)} \right)}$$

The answer is that **D = N(0) H**

For Earth: D = 1.2 kg/m^3 x 8.5 km = 1,020 gm/cm^2

For Mars: D = 0.020 kg/m^3 x 11.1 km = 22 gm/cm^2

C) Assuming that the radiation environments of Mars and Earth are otherwise similar, about how many times more would your radiation dosage be on the surface of Mars compared to Earth?

Answer: Note: This means that, because your maximum radiation dosage comes from radiation reaching you from the vertical direction (less shielding), on Mars, you will be receiving about 1,020 gm/cm^2 / 22 gm/cm^2 or 46 times as much radiation on the ground as you would get on Earth. On Earth, your annual cosmic ray dosage is about 27 mRem /year, so on Mars the dosage could be 46 x 0.027 Rem/year = 1.2 Rem/year.

D) How does the atmospheric shielding of Earth compare to the shielding provided by the International Space Station or the Space Shuttle?

Answer: The ISS shielding is about 10 gm/cm^2, but the atmospheric shielding on the ground for Earth is 1,020 gm/cm^2 which is100 times greater!