



In Class Exercises (ICE) - 4/23/01

On April 26 1986, the world's worst nuclear accident occurred in the #4 reactor at the Chernobyl power plant in the Ukraine. The accident spread biologically dangerous radioactive isotopes throughout the northern hemisphere. Potentially dangerous levels of fallout were detected in Washington State, New York City, Idaho, New Jersey, Alaska, Hawaii, Vermont, Wyoming, Nebraska, Virginia, Georgia, Tennessee, Maine and Oregon. Some of the radiation was detected in the ground, some in the air, and some in milk¹. The highest levels of radiation were detected in northern European countries², Scandinavian countries³ and the Baltic states⁴.

¹ These statements are based on measurements reported in the published scientific studies listed below. Except where otherwise noted, these studies are from: "Environmental Measurements Laboratory: A Compendium of the Environmental Measurements Laboratory's Research Projects Related to the Chernobyl Nuclear Accident." Report Number EML-460, Department of Energy, New York, 1986.

- Z. J. Juzdan, I. K. Helfer, K. M. Miller, W. Rivera, C. G. Sanderson and S. Silvestri. "Decomposition of radionuclides in the northern hemisphere following the Chernobyl accident."
- R. J. Larsen, C. G. Sanderson, W. Rivera, M. Zamichieli. "The characterizations of radionuclides in North American and Hawaiian surface air and deposition following the Chernobyl Accident."
- R. J. Larsen, P. L. Haagenson and N. M. Reiss. "Transport processes associated with the initial elevated concentrations of Chernobyl radioactivity in surface air in the United States." *Journal of Environmental Radioactivity*, **10**: 1-18, 1989.
- United States Environmental Protection Agency. "Environmental radiation data: Report 46. April 1986-June 1986." Report Number EPA 520/5-87-004. Environmental Protection Agency, Washington, DC, 1986.
- J. E. Dibb and D. L. Rice. "Chernobyl fallout in the Chesapeake Bay region." *Journal of Environmental Radiation*, **7**: 193-196, 1988.
- M. Dreicer and C. S. Klusek. "Transport of I-131 through the grass-cow-milk pathway at a northeast US dairy following the Chernobyl accident." *Journal of Environmental Radioactivity*, **7**: 201-207, 1988.
- M. Dreicer, I. K. Helfer and K. M. Miller. "Measurement of the Chernobyl fallout activity in grass and soil at Chester, New Jersey."
- H. W. Feely, I. K. Helfer, Z. R. Juzdan, C. S. Klusek, R. J. Larsen, R. Leifer and C. G. Sanderson. "Fallout in the New York metropolitan area following the Chernobyl accident." *Journal of Environmental Radioactivity*, **7**: 177-191, 1988.
- C. S. Klusek, C. G. Sanderson and W. Rivera. "Concentrations of I-131, Cs-134 and Cs-137 in milk in the New York metropolitan area following the Chernobyl reactor accident."
- K. M. Gebbie and R. D. Paris. "Chernobyl: Oregon's response." Radiation Control Section, Office of Environment and Health Systems, Health Division, Oregon Department of Human Resources. Portland, OR, 1986.
- E. A. Bondietti and J. N. Brantley. "Characteristics of Chernobyl radiation in Tennessee." *Nature*, **322**: 313-314, 1986.

² For example, see: K. Iriweck, B. Khademi, E. Henrich and R. Kronraff. "Pu-239(240), Sr-90, Ru-103 and Cs-137 concentrations in surface air over Austria due to dispersion of Chernobyl releases over Europe." *Journal of Environmental Radioactivity*, **20**: 133-148, 1993.



Figure 1: Sattelite photograph of Chernobyl power station, April 30 1986. The light area in the middle is the fire in the Number 4 reactor unit.

The Chernobyl accident occurred at the height of the Cold War. As such, Soviet officials may have been reluctant to announce the Chernobyl accident to the world, despite the fact that the accident had potentially global consequences. Swedish nuclear technicians detected the first signs of trouble at the Forsmark Nuclear Power Plant 60 miles north of Stockholm⁵. The Swedes detected abnormally high levels of radiation at approximately 9am on April 28 (2 days after the meltdown) and thought that their own reactor was leaking. After a frantic search revealed nothing wrong, the Swedes checked the prevailing wind patterns and questioned the Soviet government. Finally, at

9pm that night (after a full day of silence despite direct, desperate inquiries from Western nations), the newscaster on the official Soviet television station read the following statement (reproduced complete and verbatim here):

“An accident has taken place at the Chernobyl power station, and one of the reactors was damaged. Measures are being taken to eliminate the consequences of the accident. Those affected by it are being given assistance. A government commission has been set up.”

After that terse statement, the newscaster went on to discuss another news item.

Tens - possibly hundreds - of thousands⁶ of deaths in the former Soviet Union and Europe have been connected to radiation from the Chernobyl meltdown.

³ For example, see: A. Aarkrog. “Studies of Chernobyl debris in Denmark.” *Environment International*, **14**: 149-155, 1988.

⁴ For example, see: E. Realo, J. Jogi, R. Koch and K. Realo. “Studies on radiocesium in Estonian soils.” *Journal of Environmental Radioactivity*, **29**: 111-120, 1995.

⁵ Source: John Greenwald. “Deadly meltdown.” *TIME Magazine*, May 12, 1986.

⁶ The United Nations Office for the Coordination of Human Affairs reports that 7.1 million people in the Ukraine and neighboring countries have required special care for cancer and radiation sickness. The International Federation of the Red Cross has reported that cancer rates in these areas are 16 times higher than normal. European Union scientists estimate that more than 20,000 premature deaths in Europe may be directly attributed to Chernobyl radiation.



Figure 2: The Number 4 reactor unit at Chernobyl after the fire had been suppressed.

Scientists⁷ have estimated that world-wide, as many as 2.9 billion people may have been exposed to biologically dangerous radioactive materials ejected from the Chernobyl accident.

Astonishingly, the Chernobyl plant continued to operate for another 14 years until it was finally deactivated on December 15, 2000⁸. In 1986, workers encased the dangerously radioactive Number 4 reactor in a "Sarcophagus" of steel, lead, soil and concrete (see Figure 3). With the problem supposedly contained, the

remaining three reactors in the power plant continued to operate.

In this ICE, you will use satellite photographs of the plume of radioactive materials and radiation measurements made by labs and universities throughout Europe to calculate the amount of radioactive material ejected from the Number 4 reactor at Chernobyl during the first day of the accident - April 26, 1986.



Figure 3: The Number 4 reactor unit encased in a steel and concrete structure nicknamed the "Sarcophagus."

A unit of radioactivity that is commonly used throughout the world is the becquerel (named after the French radio-chemist), denoted Bq. One Bq is equivalent to one nuclear transformation per second.

When Western European countries first learned of the Chernobyl accident, a large number of nuclear facilities, government and university laboratories began to monitor levels of radioactivity. Some of the data that was collected is shown in Table 1. One equation that has been fitted to this data (see Figure 6) is:

$$A(x) = (6.334 \times 10^{14}) \cdot (0.999087)^x$$

where $A(x)$ is the activity in Bq per $(\text{km})^3$, and x is the distance from Chernobyl in kilometers. This equation was obtained from a regression analysis of the data contained in the following

publications:

⁷ See: L. R. Anspaugh, R. J. Catlin and M. Goldman. "The global impact of the Chernobyl reactor accident." *Nature*, **242**: 1516, 1988.

⁸ Source: www.newsmax.com

- P. H. Jensen. "The Chernobyl accident in 1986 - causes and consequences." Lecture delivered to the Institute of Physics and Astronomy, University of Aarhus, 30 November 1994.
- The International Chernobyl Project. "Surface contamination maps." International Atomic Energy Association: Vienna, 1991.

Distance from site (km)	828	1096	904	1140	1616	2428
Radio-activity (Bq/(km) ³)	4.27*10 ¹⁴	2.44*10 ¹⁴	1.7*10 ¹⁴	1.42*10 ¹⁴	8.13*10 ¹³	8.13*10 ¹³

Table 1: Some of the data collected by European countries.

Figure 4⁹ shows the plume of radioactive material ejected from the Chernobyl reactor during the first 24 hours of the accident. At the time when this image was made, the plume was approximately 480 km long and 180 km wide. (The height of the plume during April 26, 1986 is not really known. Some speculations based on computer models are shown in Figure 5 on the next page.)



Figure 4: Plume of radioactive material ejected from the Chernobyl power plant. The image shows the plume 24 hours after the accident. At this time, the plume was 480 km long and 180 km wide at the widest point.

In this first part of the ICE, you will generate a mathematical description of this plume, and then use that mathematical description to set up an integral representing the total amount of radioactive material ejected from the plume.

Assume that after 24 hours, the plume was shaped like half of a cone. Use Figures 7 and 8 (shown on the next page) to:

- **Sketch the appearance of a cross-section of the plume when the distance from the power plant is constant.**
- **Find a formula that will give the cross-sectional area of the plume when you are a distance of x kilometers from Chernobyl.**

⁹ Source: OECD Nuclear Energy Agency. "Chernobyl ten years on. Radiological and health impact." Paris, France, 1995.

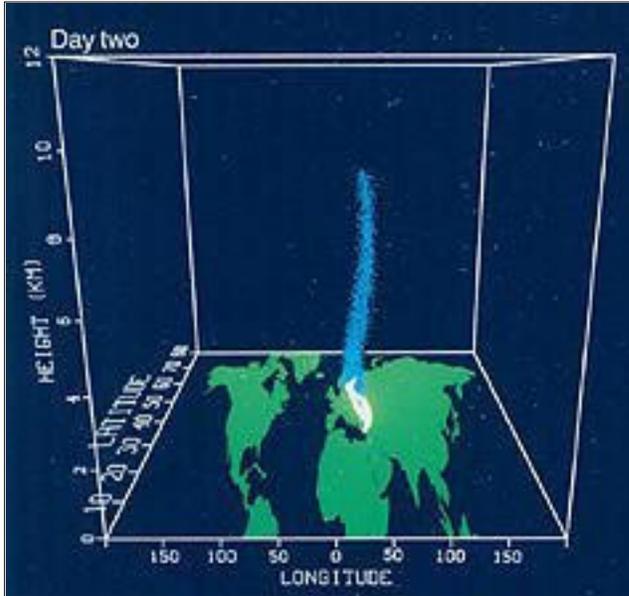


Figure 5: Three dimensional structure of the radioactive plume from Chernobyl. The image shown here is from a computer model of the Chernobyl accident and shows the plume reaching altitudes of up to 10km.

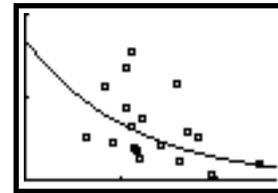


Figure 6: Data on levels of radiation following the Chernobyl accident.

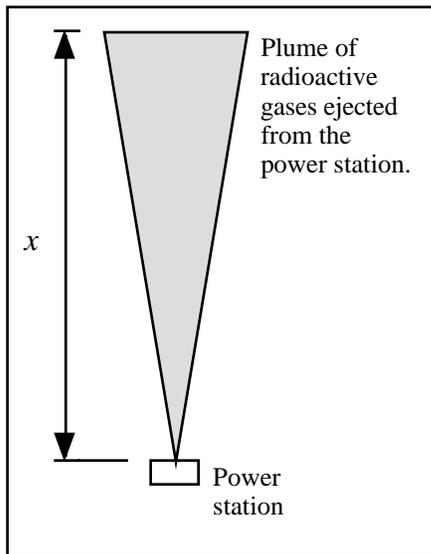


Figure 7: Schematic diagram showing power plant and cone shaped plume of radioactive gas.

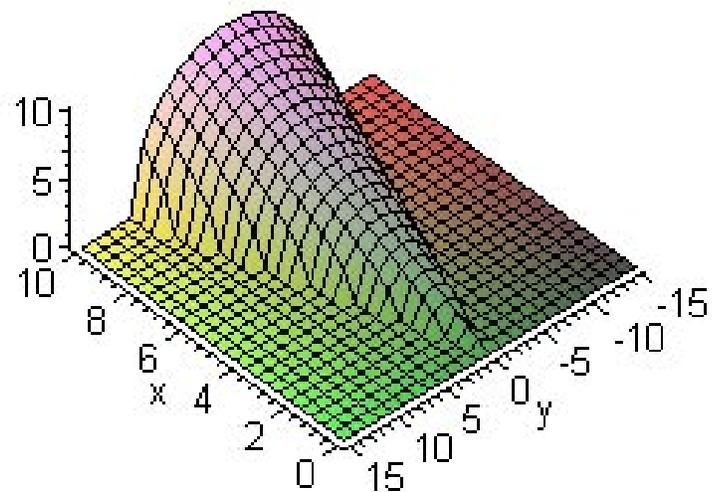


Figure 8: A computer model of the plume of radioactive gas released from Chernobyl. In this model, the power station is located at coordinates (0,0), the flat part of the graph represents the ground, and the cone is the plume of radioactive gas.

- **Use the three dimensional diagram that you drew and the function $A(x)$ to create a definite integral that will give the total amount of radioactivity (in Bq) contained in the plume on April 26, 1986.**

- **Verify that an anti-derivative of $f(x) = x^2 \cdot b^x$ is given by the formula:**

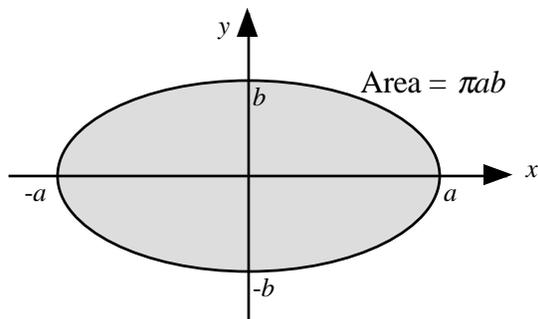
$$F(x) = \frac{x^2 \cdot b^x}{\ln(b)} + \frac{2 \cdot b^x}{[\ln(b)]^3} - \frac{2x \cdot b^x}{[\ln(b)]^2} + C$$

- **Evaluate the definite integral to find the amount of radioactivity in the plume. Official estimates¹⁰ give an estimate of $4.4 \cdot 10^{17}$ Bq. How does this compare with your estimate? What does Figure 5 tell you about the mathematical representation of the plume that you developed?**

¹⁰ Source: OECD Nuclear Energy Agency. "Chernobyl ten years on. Radiological and health impact." Paris, France, 1995.

In the next part of the ICE, you will use the information contained in Figure 5 to refine your mathematical representation of the plume of radioactive material and recalculate the amount of radioactivity in the plume.

- The assumption that the plume was shaped like a cone meant that the cross-sections of the plume were shaped like half-circles. Based on Figure 5, what seems like a more plausible cross-sectional shape for the plume?***
- Use the diagram given below to find a formula for the area of a cross-section of the plume at a distance of x kilometers from Chernobyl.***



- Set up a definite integral that will represent the total amount of radioactivity in the plume using your revised mathematical model for the shape of the plume.***
- Evaluate the definite integral. Does your new figure for the amount of radioactivity agree with the estimates provided by the NEA?***