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What Is RESRAD And Why Should You Care?

A Community Guide to Estimating Radiation Doses From Residual Radioactive Contamination

BY BRICE SMITH, PH.D.

Since World War II, large amounts of radioactive waste have been generated by both civilian and military uses of nuclear power. In areas contaminated with these wastes, one of the most important steps in protecting human health is to determine how these radionuclides may eventually reach people and thus cause them harm. The closely related question of what impact the contaminants may have on the larger ecosystem is outside the scope of the present article.

The first step in such an assessment is to determine how the site might be used in the future. The set of possible behaviors and activities is called an "exposure scenario." Often, the most appropriate scenario is a resident farmer who grows her or his own food on the contaminated site and collects her or his own water also from the contaminated site. Inherent in this approach is the need to ensure that the "farmer" is truly the most vulnerable member of the exposed population. A major motivation for the current work is to explore how doses to children can be calculated as part of an effort to protect those most at risk.

Once the exposure scenario is chosen, the second step is to predict how the radionuclides will move through the environment to where they could come into contact with humans. The final step is to then predict what the resulting dose would be. The total lifetime dose received by the individual (measured in rem) is calculated from a given amount of a radionuclide ingested or inhaled (measured in curies) multiplied by a dose conversion factor (DCF) or from a related calculation of the dose from external penetrating radiation. As would be expected, the DCFs for children are, in general, different from those of adults.

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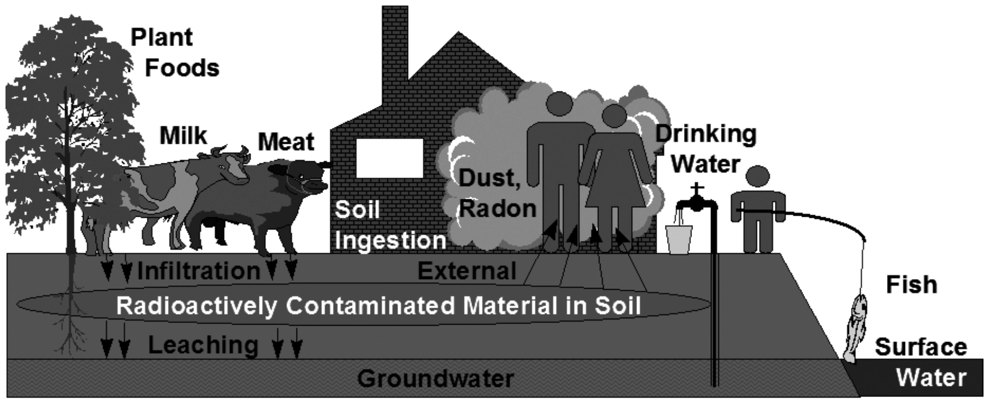

RESRAD Family of Codes and Argonne National Laboratory's Environmental Science Division

Figure 1: RESRAD is a computer program used to make regulatory decisions about residual radioactivity levels at nuclear sites (e.g., to help determine "how clean is clean enough"). Even though this official RESRAD image includes a child, the program cannot correctly calculate doses to children from exposure to external radiation nor can it calculate doses to breast-fed infants. The default settings of RESRAD are primarily those for a 20- to 30-year-old, 154 pound Reference Man.

INSIDE

STATEMENT OF PRINCIPLES

To Achieve a Carbon Free and Nuclear Free U.S. Energy System by 2050

We the undersigned believe that the United States can and should implement energy production, distribution, and use policies that will phase out the use of fossil fuels and nuclear power by the year 2050. A recent book, *Carbon-Free and Nuclear-Free: A Roadmap for U.S. Energy Policy,*[1] provides a detailed analysis that shows that this goal is technically and economically feasible. The Roadmap lays out how we can get from a 94 percent reliance on fossil fuels and nuclear energy (as of 2005) to none by mid-century.[2] Oil imports would be completely eliminated along the way.

Action to achieve such an energy system as soon as possible is necessary given the scale of the climate crisis, global conflicts over oil resources, and the serious risks of nuclear power. Achieving a near total elimination of CO_2 emissions in the United States is also implied by U.S. commitments under the United Nations Framework

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Given that calculations for dose assessments are complex, they are best done on a computer. It is in this light that we introduce the computer program, RESRAD, the focus of this article. RESRAD (short for RESidual RADioactivity) was developed by Argonne National Laboratory and first issued in 1989 to carry out the three steps described above.[1] After registering, the program may be downloaded for free from the Argonne website at **http://web.ead.anl.gov/resrad/register2.** RESRAD allows users to specify the features of their site and to predict the dose received by an individual at anytime over the next 100,000 years. The exposure pathways considered by RESRAD include (1) external radiation, (2) inhalation of radon or other gaseous radionuclides and contaminated dirt, (3) ingestion of contaminated plants, meat, aquatic foods, and soil, and (4) drinking contaminated water and milk. This article will present a brief introduction to the way RESRAD carries out these dose assessments. In addition, it will present a brief overview of how you may use RESRAD to modify dose assessments carried out by regulators or site operators in order to calculate the doses received by children and to explore the assumptions about your site that have been made. This will help you to ensure that the dose assessments upon which regulatory decisions are made are, in fact, adequately protective.

RESRAD allows users to specify the features of their site and to predict the dose received by an individual at anytime over the next 100,000 years.

While other tools are available, RESRAD is particularly important because it has been accepted for use by the government in making regulatory decisions and is freely available to the public. The most recent version (v. 6.4) was released on December 19, 2007, and is the focus of this article. Significantly, this is the first version of RESRAD to include the built-in ability to calculate doses to children.[2] Until this most recent version, RESRAD was only designed to calculate doses for the so-called Reference Man, a five foot seven inch, 154 pound male in his twenties.[3] Version 6.4, however, finally incorporates the child specific DCFs first published by the International Commission on Radiological Protection (ICRP) more than a decade ago. The age ranges considered by the ICRP are; from 0 to 1 years old (called "Infant" in RESRAD), from 1 to 2 years old ("Age 1"), more than 2 years to 7 years old ("Age 5"), more than 7 years to 12 years old ("Age 10"), more than 12 years to 17 years old ("Age 15"), and more than 17 years old ("Adult").[4]

Even with the latest version of the program, however, there are still some things RESRAD cannot do. First, RESRAD can only predict doses to individuals who actually enter the contaminated area, and not to neighbors of the site. Second, RESRAD cannot predict doses to the embryo/fetus or to a breast-fed infant, nor can it predict doses from swimming in contaminated water. Finally, RESRAD cannot correctly calculate doses to children from exposure to external radiation.[5]

How RESRAD Models a Site

It is an old adage that Garbage In equals Garbage Out, no matter how good your program is. By the same token, good input data can result in a reliable result, provided the software is working as intended. Thus, it is very important to understand how information is supplied to RESRAD by the user. In short, RESRAD models a site through the use of more than 150 variables describing everything from how much soil is contaminated to how much water a person will drink. These parameters each have

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a default value assigned by the developers at Argonne. The use of default values, however, should be closely scrutinized to make sure that important site-specific effects haven't been overlooked.

Calculation times

RESRAD can project doses out to as much as 100,000 years from the present. However, the program will only go out as far as specified by the user. Generally, there is no scientific justification for artificially shortening the time over which dose projections are made. Thus, it is good practice to make at least one run with an upper time limit of 100,000 years. If times less than 100,000 years capture the true peak dose, then they may be used to help shorten the time RESRAD takes to complete its calculations.

Contaminants in the soil

In order to simplify its calculations, RESRAD makes a number of assumptions about the site. The first is that the site can be represented by a series of between two and eight soil layers of uniform thickness. These layers include: (1) zero or one layers of clean soil on top, (2) one layer of contaminated soil in which all radionuclides are uniformly distributed, (3) between zero and five layers of unsaturated (i.e., dry) soil below the contaminated zone, and (4) one saturated zone at the bottom (i.e., the water table into which a well could be drilled).

One important limitation of RESRAD is that only a single layer of soil can be contaminated. If multiple soil layers are contaminated at your site, then several different RESRAD runs will be needed. A second important limitation is that the contaminated zone is assumed to be uniformly contaminated. As such, it is important to ensure that the environmental sampling at your site is adequately representative. In cases where the distribution of contamination is not well known, it is often useful to conduct what is called a screening calculation. In a screening calculation, the most contaminated sample of soil is used to represent the entire contaminated zone in an effort to ensure that the actual dose is lower than what you predict in this analysis.

Distribution Coefficients (K_d)

RESRAD uses a simplified contaminant transport model described by a small number of constants. One of the most important of these is the so-called distribution coefficient (K_d). The distribution coefficient measures the strength with which a contaminant adsorbs onto soil by comparing its concentration in soil measured in picocuries per kilogram (pCi/kg) to its concentration in water measured in picocuries per liter (pCi/L). In other words:

K_d = concentration in soil (pCi/kg) / concentration in water (pCi/L)

Thus, a large value for K_d implies that the radionuclide is tightly bound to the soil and will migrate slowly, while a small value implies the opposite.

While this model is widely used, it cannot directly handle such real world problems as (1) reactive transport where contaminants react chemically with each other or with chemicals in the soil or groundwater, (2) chemical or physical changes to the radionuclides or soil caused by plants, animals, or microorganisms, (3) the complicated flow of water through cracks and fractures in rock, or (4) pathways, such as colloid-mediated transport, where the contaminants are carried along by tiny particles suspended in the water. Such phenomena must be handled outside of RESRAD.

Another drawback of this approach is that the value of K_d is highly dependent upon the chemical and physical properties of the soil. As such, the value of K_d for a given radionuclide can vary by thousands of times across a single site. Despite this potential for large variations, only one value for K_d can be specified in RESRAD for each layer of soil. Therefore, it is very important that site-specific analyses use representative, site-specific measurements for K_d. As such, it is often important to explore a range of possible K_d's based on measurements at your site to ensure that adequately conservative assumptions are being made.

Any site-specific RESRAD run that uses either default K_d values or the so-called geometric mean values summarized by Argonne in Table 32.1 of the RESRAD *Data Collection Handbook,* should be viewed with particular skepticism.[6] If these generic values are being used, you may want to explore the implications of raising and lowering the K_d values. If water dependent pathways are important at your site, then a lower K_d will typically result in earlier and higher doses than a larger K_d since the contaminants will migrate more rapidly. On the other hand, at sites where water independent pathways are important, a higher K_d value will typically result in higher doses since less of the radionuclides in the soil will be washed away over time.

Water infiltration

Another important variable determining how radionuclides migrate is the amount of water that flows through the soil. In RESRAD, the amount of water infiltration is specified by four parameters, including "Precipitation" and "Irrigation," which specify the total amount of water falling on the soil and the "Evapotranspiration coefficient" and "Runoff coefficient," which specify how much water is lost to evaporation and runoff. By default, RESRAD assumes that just 40 percent of the water falling on the ground manages to infiltrate the soil.

A complication in this respect arises because RESRAD allows only one layer of cover soil to be used. However, for many sites there may be multiple layers overlaying a contaminated region or the waste may be placed under an engineered cover such as a layer of concrete or compacted clay. While such situations cannot be handled directly by RESRAD, these sites can still be analyzed with the aid of tools like the Hydraulic Evaluation of Landfill Performance (HELP) program developed by the U.S. Army Corps of Engineers.[7] If no outside modeling with programs like HELP has been used to predict the rate of water infiltration at your site, these four parameters should be consistent with local meteorological conditions and agricultural practices.

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Erosion of the cover and contaminated zones

In addition to transport through water, RESRAD allows for the cover and contaminated soil to erode. How rapidly the soil might be removed will depend on the types of erosion at your site, the properties of the soil, the types of vegetation that will grow on top of it, the types of human activities at the site, and the types of animals that move on or through it. By default, RESRAD assumes an erosion rate of 0.001 meters per year. This is at the upper range of values considered by the Nuclear Regulatory Commission in supporting its low level waste classification rule and the observed long-term erosion rates in semi-arid climates.

Unlike transport through the water, however, once a piece of contaminated soil is eroded, RESRAD assumes that it is completely removed from the site and thus no longer of concern. This is due to the fact that only doses to those on top of the contamination are being considered and that, while the eroded contamination still exists, RESRAD assumes that it has been moved off site and thus is no longer able to contribute to the doses received by the people living on top of the contamination. One area in which the assumption that contaminants removed through erosion are no longer of concern is particularly questionable is where contaminants are transported via runoff into the surface water. For example, at Los Alamos National Laboratory, it is known that erosion during rain storms is one of the main mechanisms transporting contaminants like plutonium towards the Rio Grande. Such pathways must be handled outside of RESRAD.[8]

Exposure factors

In addition to changing the dose conversion factors, the most important parameters to change to determine doses to children are the so-called "exposure factors." This is because children will, in general, eat, breathe, and act differently than a 154 pound "Reference Man." While choosing appropriate values is a complicated task, and one that should take into account local customs and traditions, the EPA has published general recommendations for most exposure factors of interest. The following sections are based in large part on those recommendations.[9]

Occupancy of the site

As noted above, RESRAD only calculates doses for individuals who are directly on top of the contaminated soil. Since most people do not spend their entire day in one location, however, RESRAD allows you to specify the fraction spent indoors and outdoors on site with whatever fraction left over being spent off site. The default values used by RESRAD assume a residential scenario with 12 hours spent indoors on site, 6 hours spent outdoors on site, and the remaining 6 hours spent somewhere off site.

Table 1: Recommended values for use as a starting point in estimating average age-specific exposure factors for food and drink, based on recommendations from the U.S. Environmental Protection Agency. All values given on a per year basis for consistency with how RESRAD uses these exposure factors.[10]

Consumption Parameters	Infant	1-year -old	5-year -old	10-year -old	15-year -old	RESRAD Default
Fruit, vegetable and grain (kg/yr)	66	90	110	130	140	160
Leafy vegetable (kg/yr)	0.74	2.3	3.3	4.4	8.1	14
Meat and poultry (kg/yr)[(a)]	10	19	28	36	49	63
Fish (kg/yr)	n.a.	n.a.	28	39	52	5.4
Other seafood (kg/yr)	n.a.	n.a.	n.a.	n.a.	n.a.	0.9
Milk (L/yr)[(a, b)]	130	130	150	170	160	92
Drinking water (L/yr)[(c)]	69	80	190	250	290	510

(a) RESRAD assumes that all meat is beef and that all milk is cow's milk. If you consume other types of meats or get milk from something other than a cow, you will want to make sure that these changes have been properly taken into account.

(b) Milk is one of the few foods where children may, on average, consume larger quantities than adults, and thus requires special attention for contaminants such as strontium-90 and iodine-131 that concentrate in milk.

(c) The default value for water consumption is significantly below the EPA recommendation of two liters per day (730 liters per year) for use in screening calculations.

Food and drink

RESRAD breaks down the amount of food or water a child consumes into seven categories; (1) "Fruit, vegetable and grain," (2) "Leafy vegetable," (3) "Meat and poultry," (4) "Fish," (5) "Other seafood," (6) "Milk," and (7) "Drinking water." By default, RESRAD assumes values more appropriate to adults, with an individual consuming roughly one and a half pounds (0.68 kilograms) of food per day and 1.65 liters of milk and water per day. Table 1 summarizes IEER's recommendations that may be used as a starting point for changing RESRAD parameters to predict doses to children.

Soil ingestion and pica

In addition to contaminated food and water, RESRAD also takes into account the consumption of contaminated soil. The default value for soil ingestion is 36.5 grams per year, the same as the EPA's recommendation for estimating the average amount of incidental soil ingestion for children. For screening calculations, the EPA recommends that a value four times higher (146 grams per year) be used for children.[11]

There may also be cases where children, intentionally consume significant quantities of dirt. This behavior is known as geophagia or soil pica. Typically, it is assumed that a child experiencing pica will consume between 5 and 10 grams of soil per day during that period.[12] Thus, for screening calculations, the ingestion of at least 30 to 40 grams of soil per year, occurring on a small number of days, should be considered in addition to the exposure from routine, inadvertent soil ingestion described above.[13]

Inhalation rates

Finally, RESRAD also considers the inhalation of gaseous radionuclides and contaminated dust. How much air an individual breathes depends strongly upon the type of activities he or she is doing. The EPA identifies five categories of activities including sleeping, sedentary, and light, moderate, and high intensity.[14] The mixture of these activities occurring at your site will vary depending upon the type of exposure scenario being considered.

As with other exposure factors, the volume of air inhaled by children will be different than for adults. The RESRAD default value for the inhalation rate is 8,400 cubic meters per year. For comparison, this would be roughly equivalent to the EPA's recommendation for continuous moderate to heavy activity by children or roughly twice the EPA's recommended value for use in long-term exposure scenarios for a five-year-old child.[15] While no upper percentile values were reported by the EPA, we note that given that the RESRAD default value is equivalent to children sustaining light activity 24 hours a day, it can reasonably be used to get a sense of the inhalation pathway in many screening calculations.

Introduction to Using RESRAD

The goal of this article is not to allow you to begin from scratch and develop your own RESRAD runs. It is instead intended to help you to better understand how RESRAD works and to help you modify the program at sites where RESRAD has already been used in support of regulatory decisions.[16] As such, we will now briefly touch upon how to begin setting up your own runs.

You will first need to identify which parameters must be changed in order to recreate the model proposed by the site operators. The easiest way to do this, and the only one discussed in this article, is to find the RESRAD output files often included in official reports. The file you need is called the summary report, and is given the file name "SUMMARY.REP." In setting up your own RESRAD run, it is the first three sections of this report that will be of greatest interest.

The first step in recreating the RESRAD run for your site is to find which pathways have been set to "active" and which have been "suppressed" from the summary report section "Summary of Pathway Selections." You can turn these pathways on and off in RESRAD under the "Set Pathways" button by clicking on the small square icon next to the pathway's name.[17] Once the pathways chosen by your site operator have been activated in your model, you can then begin to modify the other RESRAD parameters.

The value for each of RESRAD's 150 plus variables can be found in the summary report section entitled "Site-Specific Parameter Summary." If the "User Input" and "Default" columns in the summary report are the same, then the default value is being used, otherwise you will need to change this parameter to match the value chosen by the site operator.[18] These variable values can be changed by clicking on the "Modify Data" button on the left of the screen which brings up a series of 12 buttons in a new window.[19] (See Figure 2, page 7) When clicked, each of these 12 buttons will, in turn, launch a popup window that allows you to modify the associated parameters. In these popup windows, a yellow background indicates that the variable is still at its default value, while a white background denotes that the value has been changed by the user. To restore the default value, simply click on the variable and push F6. The locations of some important variables are summarized in Table 2. (see page 6)

After changing these parameters to match those selected by the site operator, it will be good to check your work by running RESRAD. To run RESRAD, click on the space shuttle icon on the top row of small buttons or select "Run RESRAD" from the "File" menu. When RESRAD has finished running, it will open your new summary report. This report should look the same as the one you started with from the site operator since you have now changed all of the parameters in RESRAD to match those used in the original summary report. The peak dose is reported on the first page of the "Contaminated Zone and Total Dose Summary" section under the title "Maximum TDOSE(t)."[20] You should check both its magnitude (i.e., the number of millirem per year)

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Table 2: Summary of important RESRAD variables and where they are located.

Variable Name	Menu Button
Nuclide concentration (pCi/g)	Soil Concentrations
Distribution coefficients (cm^3/g)	Soil Concentrations → Transport
Times for calculations (yr)	Calculation Times
Area of contaminated zone (m^2)	Contaminated Zone
Thickness of contaminated zone (m)	Contaminated Zone
Cover depth (m)	Cover/Hydrol.
Cover erosion rate (m/yr)	Cover/Hydrol.
Contaminated zone erosion rate (m/yr)	Cover/Hydrol.
Average annual wind speed (m/sec)	Cover/Hydrol.
Precipitation (m/yr)	Cover/Hydrol.
Irrigation (m/yr)	Cover/Hydrol.
Evapotranspiration coefficient (dimensionless)	Cover/Hydrol.
Runoff coefficient (dimensionless)	Cover/Hydrol.
Unsaturated zone thickness (m)	Unsaturated
Inhalation rate (m^3/yr)	Occupancy
Fraction of time spent indoors (dimensionless)	Occupancy
Fraction of time spent outdoors on site (dimensionless)	Occupancy
Fruit, vegetable and grain consumption (kg/yr)	Ingestion: Dietary
Leafy vegetable consumption (kg/yr)	Ingestion: Dietary
Milk consumption (L/yr)	Ingestion: Dietary
Meat and poultry consumption (kg/yr)	Ingestion: Dietary
Fish consumption (kg/yr)	Ingestion: Dietary
Other seafood consumption (kg/yr)	Ingestion: Dietary
Soil ingestion rate (g/yr)	Ingestion: Dietary
Drinking water intake (L/yr)	Ingestion: Dietary

and its timing (i.e., when the peak dose occurs). For the example included in Table 3, the peak dose is 899.6 millirem per year and it will occur at zero years (i.e., the peak dose is largest at the beginning and decreases over time). Your answer may be slightly different due to rounding errors, but if you find a significant difference, you will want to check your parameter values to ensure that they each match the values from the site operator.

You are now ready to begin calculating doses to children. The first step is to change the exposure factors as discussed in the exposure factors section above. This is one of the most important steps in making a dose projection, and great care should be taken when using any default or generic values. The next step is to select new dose conversion factors. To change the DCFs in RESRAD, click on the "Change Title" button at the far left of the screen. In the popup window that opens there will be a pull down menu entitled "Dose Factor Library" with a default value of "FGR 13 Morbidity." From the pull down list, select the appropriate library from those labeled ICRP 72 (Adult), (Age 1), (Age 5), (Age 10), (Age 15), and (Infant) which will automatically update the dose factors for all radionuclides.

You can now re-run RESRAD. In the illustrative example in Table 3, we have changed the amount of food and drink to reflect a 15-year-old child while leaving all other parameters at their default value. In that example, the peak dose, while still occurring at the same time, is found to be 2.3 times higher than that projected for Reference Man. After making all of the necessary changes to include children into your RESRAD run, you can also begin to change other assumptions made by the site operator such as the calculation times or distribution coefficients to ensure that no important effects have been overlooked.

In addition to the peak dose, the summary report provides a wealth of other information. A discussion of much of this information is beyond the scope of the present article, but we will note that RESRAD also shows how the peak dose is broken down among different exposure pathways. In the summary report, RESRAD breaks down the dose into seven water independent pathways and six water dependent pathways. While it is the total peak dose that will often be compared to regulatory limits, the drinking water doses at sites where this pathway is important should be separately compared to the 4 millirem per year standard used for most radionuclides by the EPA.[21] Despite RESRAD only giving the whole body dose when its DCF libraries are used, it is still important to compare its projections to the 4 millirem per year organ dose limit for drinking water to ensure that the most protective limit is being used at your site.

How you make use of your RESRAD results is entirely up to you. However, it is important to

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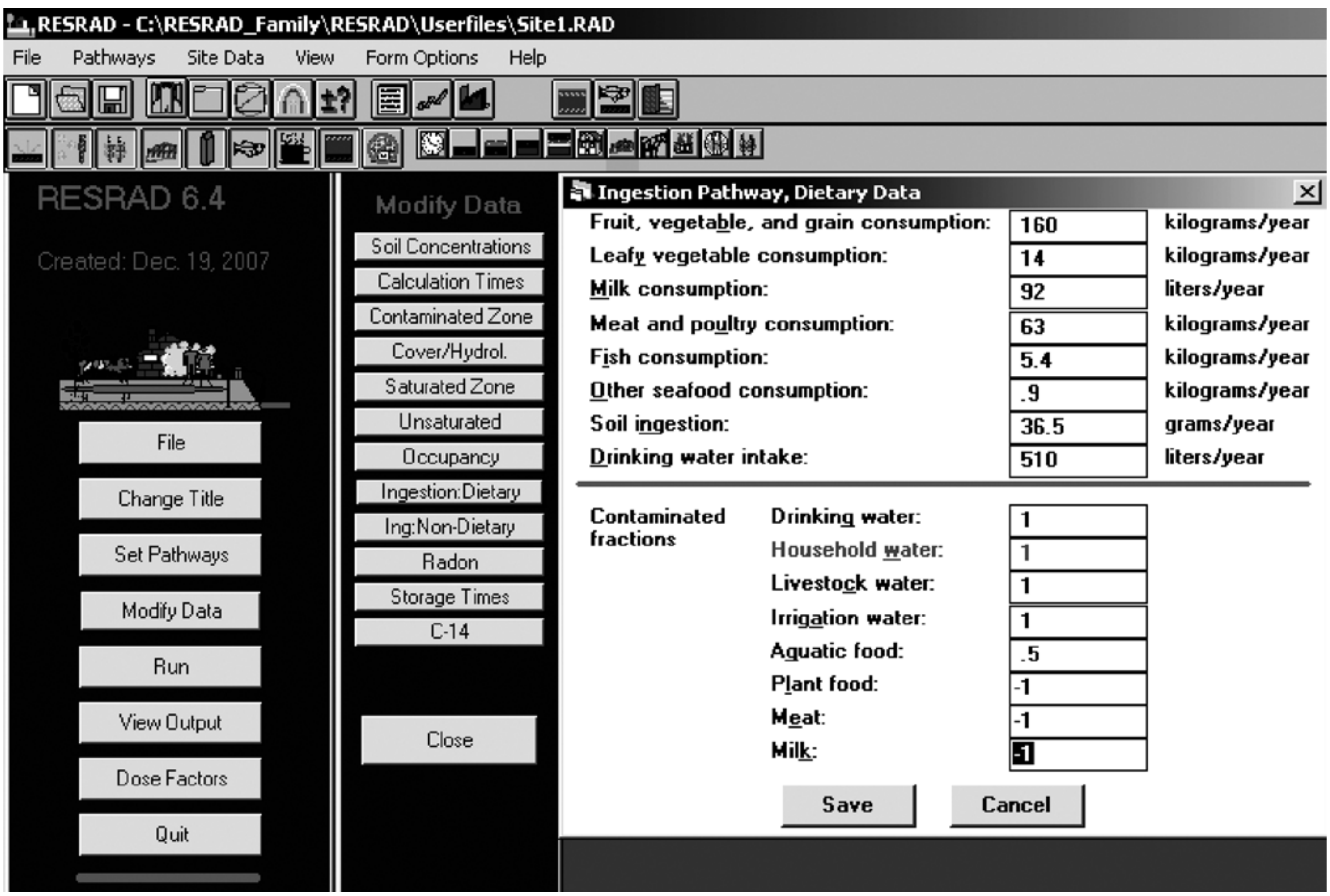
Table 3: Peak dose projections for a generic site contaminated with 100 pCi/g of strontium-90 (Sr-90) and 100 pCi/g of uranium-238 (U-238).

	Peak dose in mrem for Sr-90 and U-238	Time of peak dose for Sr-90 and U-238 combined	Peak dose in mrem for U-238 alone	Time of peak dose for U-238 alone
Default	384 (370 from Sr-90 and 14 from U-238)	0 years	63	1000 years
15-year-old child	899.6 (884.3 from Sr-90 and 15.3 from U-238)	0 years	56	1000 years

Notes:
The top line uses all default values while the second line makes adjustments to the exposure factors for a 15-year-old child.

At time t = 0, plants, meat, and milk, in that order, contribute most of the dose for Sr-90, while external radiation and inhalation are the main dose contributors for U-238. At time t = 1000 years, the peak dose is from U-238 only (Sr-90 has decayed away due to its short half-life) and mainly from drinking water due to its migration to the water pathway.



RESRAD Family of Codes and Argonne National Laboratory's Environmental Science Division

Figure 2: Screen capture of RESRAD's main window showing the Modify Data buttons and the data entry box for the ingestion pathway exposure factors.

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Where is Reference Man?

The use of "Reference Man," a hypothetical 20- to 30-year-old "Caucasian" male, is pervasive in U.S. radiation protection regulations and guidelines. This is unacceptable because the vast majority of people fall outside the definition. The use of Reference Man often does not protect those most at risk, who are generally women and children.

The 2006 report on low-level ionizing radiation of the National Academies, commonly known as the BEIR VII report, concluded that for the same radiation dose, women have a greater chance of getting cancer and a greater chance of dying from cancer compared to men. The risk to children is even more pronounced.[1]

Reference Man \re-frn(t)s-man\

"Reference man is defined as being between 20-30 years of age, weighing 70 kg, is 170 cm in height, and lives in a climate with an average temperature of from 10° to 20°C. He is a Caucasian and is a Western European or North American in habitat and custom."

Source: International Commission on Radiological Protection. Report of the Task Group on Reference Man. [ICRP Publication] No. 23. Oxford: Pergamon Press, 1975. Adopted October 1974. Page 4.

Note:
70 kilograms ≈ 154 pounds
170 centimeters ≈ 5 feet 7 inches

The following table provides examples of where Reference Man is used in federal radiation protection standards. Reference Man is not used in all cases but it is used in, among others, some drinking water regulations, the standard computer program guiding the cleanup of radioactively contaminated sites, and guidance and compliance documents of the Environmental Protection Agency, Nuclear Regulatory Commission, and Department of Energy.

These findings are taken from the forthcoming IEER report by Arjun Makhijani, *The Use of Reference Man in Radiation Protection Standards and Guidance with Recommendations for Change* (anticipated release: December 2008).

IEER and the other organizations and individuals involved in the *Healthy from the Start* campaign are working to end the use of Reference Man. For more information on this important campaign, visit www.healthyfromthestart.org.

Regulatory Standards

Regulation or guidance	Description
Federal Guidance Report 11 (1988)	Guidance for internal dose calculations
Federal Guidance Report 12 (1993)	Guidance for external dose calculations
Federal Guidance Report 13 (1999, plus 2002 supplement)	Updated guidance for internal dose calculations
40 CFR 61, Subpart H	Regulation governing air emissions of radionuclides from DOE facilities (excluding radon)
40 CFR 141.66(c)	Regulation governing maximum contaminant level for gross alpha particle activity (excluding radon and uranium) in public drinking water systems
40 CFR 190	Regulation specifying radiation dose limits for the general public for nuclear fuel cycle operations
10 CFR 20	Regulation specifying occupational dose limits, dose limits to members of the public, and concentration limits for radioactive effluents released to the environment
DOE Order 5400.5 (1993)	Guidance for dose limits and calculations to members of the public from DOE operations
RESRAD computer code (latest version, 2007)	Computer program used by government and industry to estimate dose and risk from residual radioactivity

Notes, acronyms, and definitions:
ALARA: as low as reasonably achievable
CFR: Code of Federal Regulations
DOE: U.S. Department of Energy
Dose conversion factors: Numbers used to convert intakes of amounts of radionuclides to radiation dose (which is proportional to cancer risk)
EPA: U.S. Environmental Protection Agency

Endnote

1. Richard R. Monson (Chair) et al., *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII – Phase 2,* Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation, Board on Radiation Effects Research, National Research Council of the National Academies, National Academies Press, Washington, DC, 2006. On the Web at http://www.nap.edu/openbook.php?isbn=030909156X.

Using Reference Man (partial list)	
Implementing agency	**Role of Reference Man**
EPA	Dose conversion factors are based on Reference Man. Commonly used in compliance calculations.
EPA	Includes doses to ovaries and breasts but otherwise assumes Reference Man characteristics. Radiation dose to internal organs of children would be underestimated for energetic gamma radiation.
EPA	Specifies dose conversion factors at various ages, but averages values for males and females.
EPA	Air dispersion model generally used for estimating doses to the public (called CAP-88) uses only adult dose conversion factors and averages values for males and females.
EPA	Maximum Contaminant Level (MCL) for gross alpha was set in 1976 and is based on Reference Man and on obsolete publications from 1959 and 1963.
EPA	Dose calculations are done using Federal Guidance Reports (see above).
NRC	Worker dose limits are based entirely on Reference Man, except for declared pregnant workers. For the public, air concentration limits are derived from those for workers. There are several adjustment factors, among them a reduction by a factor of two "to adjust to occupational values (derived for adults) so that they are applicable to other age groups." This factor of two does not include gender differences. It is also not adequate for certain radionuclides. For example, the inhalation of a given amount of iodine-131 will result in a larger dose to the thyroid of a child during the first five years than the dose during the entire adult life. For external radiation this factor is dropped altogether. Fetal dose limit for declared pregnant workers is obsolete and needs to be reduced to that of the general public -- currently that would be a reduction from 500 millirem to 100 millirem.
DOE	Calculations of internal dose are based on FGR 11 but allow for the use of different models (e.g., one not based on Reference Man) <u>if</u> given special permission from DOE. External dose calculations are based on a model slightly more observant of male-female differences than FGR 12, but still lacking routine consideration of children.
Developed and maintained by DOE but used by NRC, EPA, and industry as well	Default dose conversion factor library remains that from FGR 11, which is based on Reference Man. Dose conversion factors for children included but not required to be used. Dose conversion factors for women not included.

External radiation dose: Dose received from a radiation source outside the body, e.g., x-ray machine or gamma-emitting radionuclides in soil.
NRC: U.S. Nuclear Regulatory Commission
RESRAD is not a regulation or guidance but rather a tool widely used by federal agencies and the commercial nuclear industry to calculate dose and risk for regulatory and other purposes.

Table compiled by Lisa Ledwidge based on Makhijani 2008 (forthcoming), to be posted at http://www.ieer.org/reports/referenceman.pdf.

consider that while the program does give reasonable results overall (provided the input data represent the environmental conditions specific to the site being modeled), we would recommend that you avoid putting too much significance on the precise values you derive, because there are significant uncertainties and variability in any set of parameter values being used. What is likely to be most important, and what you might consider stressing in any use of your own RESRAD calculations, is where you find significant differences with the site operator's results. These differences may arise directly from taking children into account by changing the exposure factors and dose conversion factors or they may arise from using different assumptions about site parameters like the distribution coefficient. In either case, your RESRAD calculations can be used to argue that the calculations of the site operator are not adequately protective. As such, being able to meet the regulators or site operators on their own ground, with their own model, can be a very powerful tool.

Endnotes

1. This article summarizes a forthcoming IEER guide on how to make use of the RESRAD program to calculate doses to children. Additional details and further discussion of how to run RESRAD will be included in this work. IEER's guide will be posted at http://www.ieer.org/reports/resrad.pdf.
2. IEER has advocated for these and other changes to the RESRAD model for several years. See, for example, two IEER reports: Arjun Makhijani, *Bad to the Bone: Analysis of the Federal Maximum Contaminant Levels for Plutonium-239 and Other Alpha-Emitting Transuranic Radionuclides in Drinking Water,* June 2005, at http://www.ieer.org/reports/badtothebone/fullrpt.pdf, pp. 25-26 and Arjun Makhijani, Brice Smith, and Michael C. Thorne, *Science for the Vulnerable: Setting Radiation and Multiple Exposure Environmental Health Standards to Protect Those Most at Risk,* October 19, 2006, at http://www.ieer.org/campaign/report.pdf, pp. 80-82.
3. International Commission on Radiological Protection, *Report of the Task Group on Reference Man,* [ICRP Publication] No. 23, Pergamon, Oxford, 1975, p. 4. Adopted October 1974.
4. International Commission on Radiological Protection, *Age-dependent Doses to the Members of the Public from Intake of Radionuclides: Part 5, Compilation of Ingestion and Inhalation Dose Coefficients,* ICRP Publication 72, Annals of the ICRP, 26 (1) 1996, Pergamon, Oxford, 1996, p. 11. Adopted September 1995.
5. In RESRAD, external doses are calculated for the average of an adult male and female. In 1999, the National Council on Radiation Protection and Measurement (NCRP), a U.S. organization, recommended that for children up to at least 12 years of age the external dose estimated for adults should be increased by 20 to 40 percent. (NCRP, *Recommended Screening Limits for Contaminated Surface Soil and Review of Factors Relevant to Site-Specific Studies,* NCRP Report No. 129, NCRP, Bethesda, MD, January 29, 1999, pp. 56-57). This correction must be done outside of RESRAD.
6. C. Yu et al., *Data Collection Handbook to Support Modeling Impacts of Radioactive Material in Soil,* Argonne National Laboratory, Argonne, IL, April 1993, at http://web.ead.anl.gov/resrad/documents/data_collection.pdf, p. 110-111. The geometric mean is a way of calculating the average of a given data set that gives less weight to very large or very small values.
7. See http://el.erdc.usace.army.mil/products.cfm?Topic=model&Type=landfill.
8. Brice Smith and Alexandra Amonette, *The Environmental Transport of Radium and Plutonium: A Review,* IEER, Takoma Park, MD, June 23, 2006, at http://www.ieer.org/reports/envtransport/fullrpt.pdf, p. 22-24.
9. See EPA 1997 (U.S. Environmental Protection Agency, National Center for Environmental Assessment, Office of Research and Development, *Exposure Factors Handbook, Volumes I to III,* EPA/600/P-95/002Fa, EPA, Washington, DC, August 1997, at http://rais.ornl.gov/homepage/EFH_Final_1997_EPA600P95002Fa.pdf.
10. The values for fruits, vegetables, grain, meat, poultry, and fish consumption taken from EPA 2008, Tables 8-22, 9-1, 10-1, 11-1, and 12-1 (U.S. Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment, *Child-Specific Exposure Factors Handbook,* EPA/600/R-06/096F, EPA, Washington, DC, September 2008, at http://oaspub.epa.gov/eims/eimscomm.getfile?p_download_id=478628). For leafy vegetable consumption we retained the percentages recommended by EPA for leafy versus non-leafy vegetable consumption from EPA 2008 Table 9-7. The EPA's recommendations were given on a per kilogram of body mass basis, so the data on average body mass was used to calculate the total amount of consumption per year for each age range. The drinking water and milk values were taken from FGR 13 (U.S. Environmental Protection Agency, *Cancer Risk Coefficients for Environmental Exposure to Radionuclides,* Federal Guidance Report No. 13, September 1999 (EPA 402-R-99-001) p. 139). No recommendations for other seafood for the general public were provided by the EPA in either FGR 13 or EPA 2008.
11. EPA 1997 p. 4-20 and Table 4-23.
12. EPA 1997 pp. 4-20 and 4-25 and Steven L. Simon, "Soil ingestion by humans: a review of history, data, and etiology with application to risk assessment of radioactively contaminated soil," *Health Physics,* v.74, no.6 (June 1998) 647-672. (p. 661).
13. Combining the intentional and unintentional ingestion gives approximately 176 to 186 grams per year.
14. EPA 2008 Table 6-2.
15. EPA 2008 Tables 6-1 and 6-2.
16. The forthcoming RESRAD guide from IEER will include more complete instructions and examples for how to use this model.
17. The nine exposure pathways are "External Gamma," "Inhalation," "Plant Ingestion," "Meat Ingestion," "Milk Ingestion," "Aquatic Foods," "Drinking Water," "Soil Ingestion," and "Radon."
18. Note that the summary report uses a form of scientific notation. For example a value of 17,000 would be reported as 1.700E+04 while a value of 0.00017 would be given as 1.700E-04.
19. The 12 modify data buttons are "Soil Concentrations," "Calculation Times," "Contaminated Zone," "Cover/Hydrol.," "Saturated Zone," "Unsaturated," "Occupancy," "Ingestion: Dietary," "Ingestion: Non-Dietary," "Radon," "Storage Times," and "C-14."
20. In the event that the peak dose occurs at one of the specified calculation times entered by the user, then there is no detailed "Contaminated Zone and Total Dose Summary" section and the peak dose summary is included in the "Total Dose Components" section. In either case the format of the information is the same.
21. *Code of Federal Regulations,* 40 CFR 141.66(d) 2007, links at http://www.access.gpo.gov/nara/cfr/waisidx_07/40cfr141_07.html.

IEER's full RESRAD guide will be posted at http://www.ieer.org/reports/resrad.pdf

Convention on Climate Change (UNFCCC) combined with the latest report of the Intergovernmental Panel on Climate Change (IPCC). The IPCC estimates that global CO_2 emissions should be reduced by 50 to 85 percent by 2050 relative to 2000 levels to limit temperature increases to less than 2 to 2.4 degrees Celsius, with the former reduction being given only a small chance of accomplishing the goal. If global emissions are allocated on a per capita basis, the U.S. would have to reduce CO_2 emissions by 92 to 96 percent by 2050 to have reasonable confidence that the temperature goal will be met. The United States has signed and ratified the UNFCCC, which went into effect in 1994.

A U.S. goal of zero-CO_2 emissions would greatly enhance the likelihood of serious negotiations with China, India, and other developing countries towards an agreement to reduce global CO_2 emissions by 50 to 85 percent. It would be the most practical way to recognize that the United States has contributed disproportionately to the build up of CO_2 in the atmosphere. It would show developing countries by example that economic well-being can be achieved using ecologically sound approaches. And it would establish U.S. leadership in an area where it has been sorely lacking.

A reliable electricity sector that is more secure than the present one can be created without nuclear power. The promoters of nuclear energy have used the threat of global warming to rekindle interest, but nuclear power entails risks of nuclear proliferation, severe accidents, and terrorist attacks. It would exacerbate the problem of nuclear waste, for which no reasonable solution is in sight. Overall, it shifts the burden of radiation and proliferation risks arising from current energy use to future generations.

Greatly increased energy efficiency throughout the country will make possible a more economical and faster transition to a renewable energy economy. Solar, wind, biofuels, and other renewable energy sources are ample and capable of supplying the energy requirements of a zero-CO_2 U.S. economy. But converting food, such as corn, into biofuel is not a suitable approach, because it is associated with increases in food prices, poor net energy output, and large greenhouse gas emissions. Biofuels must be derived from plants that trap solar energy efficiently and that can be grown on marginal lands. In addition, certain aquatic plants, including some types of algae, could simultaneously provide fuels as well as other environmental benefits.

Subsidies for problematic energy sources, notably fossil fuels, nuclear power, and food-based biofuels, should be ended. For example, neither loan guarantees nor production tax credits should be provided to new nuclear power plants.

New coal-fired power plants without carbon capture and storage (also called "sequestration") should be banned. While there is some experience with CO_2 storage, it is not yet a proven technology for climate protection, which requires isolation of CO_2 from the atmosphere for hundreds, if not thousands, of years. Storage technology should preferably be developed and tested using emissions from existing rather than new sources of CO_2. Carbon capture and storage technology may be needed to remove CO_2 that has already been emitted to the atmosphere.

The U.S. government will need to invest tens of billions of dollars per year in the transition to a carbon-free, nuclear-free economy. The funds will directly support renewable energy and efficiency projects, assist state and local governments, and finance worker and community transition. The money can be raised in a variety of ways, including taxes and the sale of emissions allowances; it should be dedicated to help achieve the transition to a renewable energy economy.

Whatever set of policies is adopted, there should be no free emission allowances. Such giveaways are inequitable and regressive. There should be no international offsets or trade in CO_2 allowances, especially with countries that have not set stringent limits on CO_2 emissions. Further, importing biofuels from developing countries could create land pressures that could harm the poor and may even increase greenhouse gas emissions directly or indirectly, for instance, by increasing destruction of tropical forests and peat bogs. U.S. policies must ensure that the goal of reliably ending CO_2 emissions by mid-century is translated into laws, regulations, and intermediate targets that are verifiable and enforceable all along the way.

Scientists, including leaders of the IPCC, have been warning that there is little time left to begin to shift from increasing to decreasing greenhouse gas emissions, of which CO_2 emissions are the most important. The United States has delayed too long, partly using the argument that China and India and other major emitters also need to participate in achieving global reductions. We agree that they do; but we note that U.S. leadership, in both immediate action and long-term commitments, is a sine qua non for securing serious commitments from developing countries, which have until recently contributed little to the problem.

Finally, the establishment of a goal of achieving a carbon-free and nuclear-free U.S. energy sector by mid-century can have a transformative effect on the global political climate, which is a prerequisite for protecting the planetary physical climate. The ecological, health, and security benefits of realizing that goal will be immense. We are committed to establishing that goal, creating policies designed to achieve the goal, and dedicating the resources to implement those policies.

You can find the list of signatories and add your organization at http://www.ieer.org/carbonfree/signon.php.

Endnotes

1 *Carbon-Free and Nuclear-Free: A Roadmap for U.S. Energy Policy* by Arjun Makhijani, Ph.D., is published jointly by RDR Press and IEER Press, 2007. It can be downloaded free at http://www.ieer.org/carbonfree/CarbonFreeNuclearFree.pdf. The Roadmap is described in Chapter 8.

2 Another recent book, *Winning Our Energy Independence: An Energy Insider Shows How,* by S. David Freeman, Gibbs Smith, Layton, Utah, 2007, also advocates a fully renewable, non-nuclear U.S. energy system.

DEAR ARJUN

What is carbon storage and do you think we should do it?

Confused in Columbus

Dear Confused:

Long, long ago, before gold became money, Frenchmen used to hide lumps of coal under their beds. This is because there used to be panics about "peak wood" every couple of decades, when crystal balls showed images of bare land where forests once flourished. Soon, the amount of coal became too large and the beds became uncomfortable; Frenchmen began to store coal in their cellars. It was called *stockage de charbon,* or carbon storage.

Stockage de charbon went completely out of style after World War I, when the French thought they could get their hands on Middle Eastern oil. But they only got Syria and Lebanon. The British made off with the rest (more or less).

Now, carbon storage (also often referred to as sequestration) is coming back into fashion because we have emitted too much carbon dioxide (CO_2) into the atmosphere by burning coal, oil, and natural gas. It is thought that CO_2 resulting from fossil fuel burning could be captured ("carbon capture") at the plant and stored in a deep geologic formation. Some also advocate removing CO_2 from the atmosphere and storing it, in order to reduce atmospheric CO_2 concentrations and the risk that climate change will turn into an ecological, economic, and social disaster.

Let me list the methods that have been proposed:

1. Capture of CO_2 from coal, oil, or natural gas burning power plants after combustion, and injection of the gas into underground geologic formations on land or under the ocean floor. This is called carbon capture and storage (CCS). CO_2 capture is made less difficult in the case of coal if coal gasification technology is used (Integrated Gasification and Combined Cycle or IGCC technology), rather than just burning the coal to make steam in a boiler ("pulverized coal" technology, which could be called PC, but is not, since it is very politically incorrect). The same technology can also be used if biomass is burned as a fuel, for instance, to generate electricity.

2. CO_2 can also be captured by using the exhaust gases from fossil-fuel-fired power plants to grow microalgae, which, when harvested, can be used directly as fuel, or converted into liquid and gaseous fuels. Solar energy (land) and water are other needed inputs to grow the microalgae. In this case, the CO_2 is captured but not stored. It would be used to make new fuels and reduce oil and natural gas consumption, which would decrease CO_2 emissions.

3. Algae and other aquatic plants, like water hyacinths, duckweed, and cattails, as well as other biomass can be slowly pyrolized (heated in the absence of air) and converted partly to a synthetic gas and partly to solid carbon. Pyrolysis of this sort is a kind of modern charcoal making process. The solid carbon can be put in a shallow subsurface layer of the soil in order to enrich it, much as was traditionally done, for instance in pre-Columbian Peru.

We will consider the first and third in the list above here, since the second does not involve long-term carbon storage, but should be developed and implemented to reduce CO_2 emissions).

1. CCS technology

The oil industry has long injected CO_2 into oil fields in order to enhance oil recovery. The injected CO_2 tends to stay in the geologic formations. So, there is considerable experience with carbon storage. However, amounts of CO_2 generated mainly in electricity production are orders or magnitude larger. The requirements of geologic storage for the purposes of climate change are also more stringent. If the CO_2 slowly leaks out over decades or centuries, the purpose of climate protection would be defeated (even setting aside the possibility of a sudden release event). Hence, while carbon storage may be workable in principle, it has not yet been rigorously proven with climate protection criteria in mind. There are no regulatory criteria as yet for siting geologic CO_2 repositories and for health and environmental protection that would be required as they are developed.

It will take at least a decade and more likely two in order to get to the point where CCS is a usable technology for avoiding CO_2 emissions. But the climate crisis is happening now and we must begin to reduce CO_2 emissions globally in the immediate future (next few years). I do advocate that CCS be developed as a back-up for two reasons:

- We may need it in case some of the more advanced technologies described in my book, *Carbon-Free and Nuclear-Free* (CFNF), do not decline in cost, as now anticipated.
- It could be used with biomass combustion to remove CO_2 that has already been emitted. In that case, CCS technology would be used to capture and inject the CO_2 in geologic formations.

In this context, it is essential that new coal-fired power plants without CCS be banned. I also prefer that CCS technology should be developed and demonstrated using existing sources of CO_2, or by building biomass IGCC plants. The latter can be used as one baseload component of a distributed electricity grid (see CFNF). For the next 10 to 15 years, capture of CO_2 from fossil-fuel fired electricity generation plants should focus on CO_2 capture in microalgae and converting the algae into fuel. This will help reduce CO_2 emissions and oil imports simultaneously.

2. Slow pyrolysis

Converting biomass by slow pyrolysis to synthetic gas (primarily hydrogen and carbon monoxide) and charcoal (also called char) is a promising approach to carbon sequestration and making biofuels. The synthetic gas is used as a fuel. The charcoal would serve as a means of carbon storage in solid form. Deep geologic formations would not be needed. The charcoal would be buried at

Elsen L. Karstad, Chardust Ltd.

One form of carbon sequestration: charcoal made from coffee husks, by Chardust Ltd., of Nairobi, Kenya. See www.chardust.com.

shallow depths, where it can be monitored. It would help water retention and enhances soil quality.

Burying charcoal has been used in the past to enhance soil quality. Black soil, known as terra preta de indio, or Amazonian Black Earths, were probably created in the Brazilian Amazon in pre-Columbian times in this way:

> "Terra Preta de Indio" (Amazonian Dark Earths; earlier also called "Terra Preta do Indio" or Indian Black Earth) is the local name for certain dark earths in the Brazilian Amazon region. These dark earths occur, however, in several countries in South America and probably beyond. They were most likely created by pre-Columbian Indians from 500 to 2500 years B.P. [Before the Present] and abandoned after the invasion of Europeans. However, many questions are still unanswered with respect to their origin, distribution, and properties. [1]

It contains many times the amount of carbon per unit of soil weight compared to ordinary soil – 15 percent by weight compared to 2 to 3 percent by weight. The black carbon in the soil has persisted for centuries. Besides black carbon, Black Amazonian Earths have other features, such as high phosphorous content, that make them fertile.

The existence of these high-carbon soils that were created centuries or millennia ago has raised the possibility that burying charcoal made by slow pyrolysis could be used similarly to sequester carbon and to enhance soil fertility.

Johannes Lehmann of Cornell University has made the following observations about the potential and some of the research that remains to be done:

> Furthermore, the organic matter in the dark earths is persistent since we find these elevated carbon contents even hundreds of years after they were abandoned. The reason for the high stability of the soil carbon is currently under discussion. So-called black carbon was identified as a probable reason for the high stability. Further research is necessary to quantify the recalcitrance of the soil carbon over long periods of time and to evaluate techniques for creating such soils through application of black carbon…[2]

The other questions that need to be resolved are:

1. What types of soils can retain the carbon for centuries without significant oxidation? In other words, how widespread can this technique become, if it is suitable?

2. How much charcoal can be put into an acre of land?

3. Will putting charcoal made by the proposed methods function in the same way as the Amazonian Black Earths?

4. What kinds of technologies and regulations would be needed to verify storage over the long-term, especially given a tendency to loss of institutional memory?

One of the most important problems is the amount of land area it would take. For instance, if the yield of charcoal is 5 metric tons per acre, it would require about 800,000 square kilometers (about 310,000 square miles, a little more than Texas) of land to grow the biomass needed to create one billion tons of the charcoal per year. Evidently, the amount of carbon charcoal per acre would need to be much higher for this for this approach to work. For instance, it could be used with aquatic biomass, which has much higher yields. But such biomass should preferentially be used in the short- and medium-term to create liquid fuels to displace imported oil.

All that said, the approach of burying charcoal in soil seems to be very worthwhile from a number of different points of view and should be developed. When the questions associated with it are more clearly answered it may well join efficiency, solar, and wind as a major component of addressing the problem of climate stabilization.

Conclusions

1. CCS technology should be developed, but it is not likely to be ready for one to two decades. Given the urgency of significantly reducing CO_2 emissions well before that period, energy policy should not rely on the use of coal and carbon capture but rather be based entirely on renewable fuels and efficiency.

2. Slow pyrolysis technology development as well as extensive field projects and related analysis should be undertaken to determine the viability of sequestration via burying charcoal in soil. The implications for global land use and for biofuels production need to be carefully examined, especially in view of the unfolding problems with biofuels from food and the less than thoughtful ways in which they are being produced.

Endnotes

1. Johannes Lehmann, *Terra Preta de Indio: Soil Biogeochemistry* (no date), Cornell University, at http://www.css.cornell.edu/faculty/lehmann/terra_preta/TerraPretahome.htm. I am indebted to James Amonette for calling this method of carbon sequestration to my attention.
2. ibid.

Calculating CO_2 emissions from nuclear power (uranium enrichment via gas centrifuge)

In this Atomic Puzzler – the last in the series of four about calculating carbon dioxide (CO_2) emissions from fossil fuel plants and nuclear plants – you will calculate a portion of the indirect CO_2 emissions from a light-water reactor. While there are indirect emissions associated with the mining, milling, and transportation of the fuel and the construction of the power plant, we will focus on the enrichment of the uranium, which is unique to the nuclear fuel cycle and traditionally one of the largest sources of indirect emissions for nuclear power in the United States.

There are two dominant types of commercial enrichment technology in use today. In the last issue, we calculated indirect CO_2 emissions from the operation of a ***gaseous diffusion*** enrichment plant. This Puzzler is about calculating indirect CO_2 emissions from a ***gas centrifuge*** plant, such as the one Louisiana Energy Services is building in southeastern New Mexico. Gas centrifuge is the most common technology in the world for enriching uranium.

In the next issue, we will summarize the Puzzler series and compare side by side the CO_2 emissions from nuclear power to those from coal and natural gas fired plants.

Note: Enrichment services are measured in units known as the kilogram Separative Work Units (kgSWUs) pronounced "swooze."

1. A typical light water reactor requires approximately 110 metric ton Separative Work Units (MTSWUs) per year of enrichment services in order to supply its fuel. Modern gas centrifuge plants consume approximately 55 kilowatt-hours of electricity per kilogram SWU. How many kilowatt-hours of electrical energy are required to enrich the fuel for one year's worth of the operation at a nuclear power plant? *Hint: 1,000 kilograms = 1 metric ton.*

2. We will assume that the electricity consumed by the proposed gas centrifuge enrichment plant in southeast New Mexico would be supplied by electricity generated in Texas and New Mexico. In 2005, the electricity generated in these two states was 46 percent from coal, 41 percent from natural gas, and 9.8 percent nuclear. The remainder came from renewables and other resources. In earlier Atomic Puzzlers, we found that coal fired plants emit 982 grams of CO_2 per kilowatt-hour and natural gas fired plants emit 403 grams of CO_2 per kilowatt-hour. How many grams of CO_2 would be emitted to supply the enrichment services to fuel a nuclear reactor for one year? *Hint: Use the number of kilowatt-hours from question one and the given percentage of that electricity which would be supplied by coal and natural gas while ignoring all other contributions.*

3. How many kilowatt-hours of electricity would be produced by a one thousand megawatt (1,000 MW = 1,000,000 kW) reactor over one year if it operated 85 percent of the time at full power (i.e., if it had an 85 percent capacity factor)? *Hint: How many hours are there in one year?*

4. How many grams of indirect CO_2 are emitted per kilowatt-hour of electricity generated by the nuclear reactor due to the enrichment of uranium at the gas centrifuge plant being built in southeastern New Mexico?

Send us your answers via e-mail (info[at]ieer.org), fax (1-301-270-3029), or snail mail (IEER, 6935 Laurel Ave., Suite 201, Takoma Park, Maryland, 20912, USA), postmarked by January 31, 2009. IEER will award a maximum of 25 prizes of $10 each to people who send in a completed puzzler, by the deadline, right or wrong. One $25 prize will be awarded for a correct entry, to be drawn at random if more than one correct answer is submitted. International readers submitting answers will, in lieu of a cash prize (due to exchange rates), receive a copy of the paperback, *Carbon-Free and Nuclear-Free: A Roadmap for U.S. Energy Policy* or another IEER book with a price of $25.00 or less. See the list at http://www.ieer.org/pubs/index.html.

ERRATA

For corrections, revisions, or clarifications made to IEER printed materials, please check our Web site at http://www.ieer.org/errata.html. Corrections to *Carbon-Free and Nuclear-Free* relate to page 108 and table 5-1, on page 111. These corrections do not affect the book's analysis, conclusions, or recommendations.

ANSWERS TO ATOMIC PUZZLER, SDA VOL. 15, NO. 3

Calculating CO_2 emissions from nuclear power (uranium enrichment via gaseous diffusion)

1. 110 metric ton SWUs per year x 1000 kilograms per metric ton = 110,000 kilogram SWUs per year.
110,000 kilogram SWUs per year x 2,450 kilowatt-hours per kilogram SWU = 269,500,000 kilowatt-hours per year = 2.695×10^8 kilowatt-hours per year.

2. 2.695×10^8 kilowatt-hours per year x 0.61 = 1.644×10^8 kilowatt-hours per year from coal.
1.644×10^8 kilowatt-hours per year from coal x 982 grams CO_2 per kilowatt-hours from coal = 1.614×10^{11} grams CO_2 per year.
1.614×10^{11} grams CO_2 per year x 0.001 kilograms per gram = 1.614×10^8 kilograms CO_2 per year.

3. 1,000,000 kilowatts x 365 days per year x 24 hours per day x 0.85 = 7.446×10^9 kilowatt-hours per year.

4. 1.614×10^8 kilograms CO_2 per year from Paducah / 7.446×10^9 kilowatt-hours per year from the reactor = 0.0217 kilograms CO_2 per kilowatt-hour.

Thank you.

IEER is especially grateful to our superscribers (donors of at least $100), hyperscribers (at least $250), and Dr. Egghead's Financial Angels ($1,000 or more).

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