VOLUME 16, NUMBER 1 August 2009

Science for Democratic Action

AN IEER PUBLICATION

Radioactive Rivers and Rain: Routine Releases of Tritiated Water From Nuclear Power Plants

BY ANNIE MAKHIJANI AND ARJUN MAKHIJANI, Ph.D.

Nuclear power plants generate tritium in the course of their operation and release it both to the atmosphere and to water bodies. Tritium releases have also occurred as a result of malfunctions such as leaks (referred to by the Nuclear Regulatory Commission (NRC) as "unintended releases") from several nuclear power plants.[1] One such example of leaks was at Exelon's Braidwood plant in Illinois. (See Figure 1.) Many reactors have experienced leaks that have not been monitored.[2] Further, releases of tritiated water vapor from the stacks of nuclear power plants can result in radioactive rainfall, which can contaminate surface water bodies as well as groundwater.[3] The NRC does not require monitoring of rainfall or water bodies that may be contaminated by radioactive rainfall (unless the water is otherwise required to be monitored).

COURTESY OF JOE COSGROVE

Figure 1. Water contaminated with tritium (up to 1,000 picocuries per liter) was found in ditches running along the west side of Center Street, a public road northeast of the Braidwood Nuclear Power Station, in March 2006. Exelon workers are seen here vacuuming the tritiated water out of the ditches. (Source: Illinois Environmental Protection Agency, *Exelon Braidwood Nuclear Facility: Update on Tritium Releases and Groundwater Impacts,* Fact Sheet 2 (April 2006) at http://www.epa.state.il.us/community-relations/fact-sheets/exelon-braidwood/exelon-braidwood-2.html)

As radioactive water, tritium can cross the placenta, posing some risk of birth defects and early pregnancy failures.

Tritium, a radioactive form of hydrogen, is a gas in its elemental form. But, like ordinary hydrogen, tritium combines with oxygen to make water, called tritiated water, with the crucial difference that tritiated water is radioactive. As radioactive water, tritium can cross the placenta, posing some risk of birth defects and early pregnancy failures. Ingestion of tritiated water also increases cancer risk. In this article we will only discuss tritium in the form of radioactive water.

This article describes the problem of routine tritium emissions, which in our opinion is underappreciated, especially because non-cancer fetal risks are not yet part of the regulatory framework for radionuclide contamination and because tritium releases constitute the largest routine releases from nuclear power plants.

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INSIDE

Retiring Reference Man

The Use of Reference Man in Radiation Protection with Recommendations for Change[1]

BY ARJUN MAKHIJANI, Ph.D., AND LISA LEDWIDGE

Reference Man — a hypothetical adult White male — is currently the basis of many federal regulations and compliance guidelines, including workplace radiation exposures, cleanup of radioactively contaminated sites, and some radionuclide limits in drinking water, notably alpha-radiation-emitting transuranic radionuclides. The use of Reference Man is scientifically inappropriate because the vast majority of people, including women and children, fall outside the definition:

> *Reference man is defined as being between 20-30 years of age, weighing 70 kg [154 pounds], is 170 cm [5 feet, 7 inches] 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. (International Commission on Radiological Protection, 1975)*[2]

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Plant operators and the NRC initially dismissed public concerns about leaks, saying that tritium levels measured offsite by the plant operators were well below the EPA drinking water standard of 20,000 picocuries per liter[4] and were "safe"[5] even though all radiation protection regulations and the most recent report of the National Academies (commonly known as the BEIR VII report)[6] concluded that the hypothesis that best fits the facts is that every exposure to radiation produces a corresponding cancer risk – low exposures produce low risk, and that risk increases with exposure. There is no threshold below which there is zero risk. The EPA's method of expressing this reality is to set a Maximum Contaminant Level Goal (MCLG) which corresponds to zero health risk. The EPA value for MCLG for all radionuclides, including tritium, is zero.[7]

> The problem of routine tritium emissions is, in our opinion, underappreciated, especially because non-cancer fetal risks are not yet part of the regulatory framework for radionuclide contamination and because tritium releases constitute the largest routine releases from nuclear power plants.

Further, tritium releases generally constitute the largest routine releases from nuclear power plants and as such have caused widespread contamination of water bodies at low-levels. It is this widespread nature of tritium pollution combined with the fact that it affects water bodies and is, in fact, radioactive water that had led the Ontario Drinking Water Advisory Council, in a report commissioned by the Ontario Minister of the Environment, to recommend a very substantial tightening of the Ontario Drinking Water Quality Standard for tritium to 20 becquerels per liter (540 picocuries per liter) from the current 7,000 becquerels per liter.[8]

We covered the issue of the various risks of tritium earlier, in our *Science for the Vulnerable* report and in a *Science for Democratic Action* article.[9] In this article we document the routine releases of tritiated water to the environment from nuclear power plants. A sampling of the data is published in this issue and a more extensive dataset will be published separately on our Website (at http://www.ieer.org/sdafiles/16-1/tritium_releases.html). We chose recent years to present the data for effluent releases (gaseous and liquid) and environmental measurements in water. Releases vary from year to year. Interested parties are encouraged to examine annual environmental reports to ascertain trends.

Tritium production and releases from pressurized and boiling water reactors

The quantity of tritium released to the air and to water depends on the type of reactor; however, it also varies a great deal even among reactors of the same general design.

In pressurized water reactors (PWRs) most of the tritium that is released to the environment is produced by the interaction of neutrons with boron and lithium. The boron is added to the primary cooling water to control the rate of the nuclear reactions in the fuel and the lithium is added to control corrosion.[10] This is not an issue with boiling water reactors (BWRs), in which neither boron nor lithium is added to the primary water.[11] Primary cooling water is the water that removes the heat generated by fission reactions in the fuel present in the reactor vessel. BWRs have a secondary cooling loop, where the steam generated from

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Science for Democratic Action

Science for Democratic Action is published by the Institute for Energy and Environmental Research:

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We gratefully acknowledge our funders whose generous support makes possible our project to provide technical assistance to grassroots groups working on nuclear weapons-related environmental and security issues, our global outreach work, and our efforts to promote sound energy policy.

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Thanks also to the SDA readers who have become donors to IEER. Your support is deeply appreciated.

Credits for this Issue

Printing: Ecoprint
Editor: Lois Chalmers

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the primary water is condensed. In PWRs, the water in the primary does not boil. The high pressure primary water is used to boil water in a secondary loop in a device called a steam generator. The primary water transfers its heat to water that is converted to steam, which drives the turbine, which in turn drives the electricity generator. The condensing loop, where the steam is condensed back to water, is the tertiary cooling loop. (See Figure 2.) Routine tritium discharges and emissions are mainly associated with the primary water of the reactor.

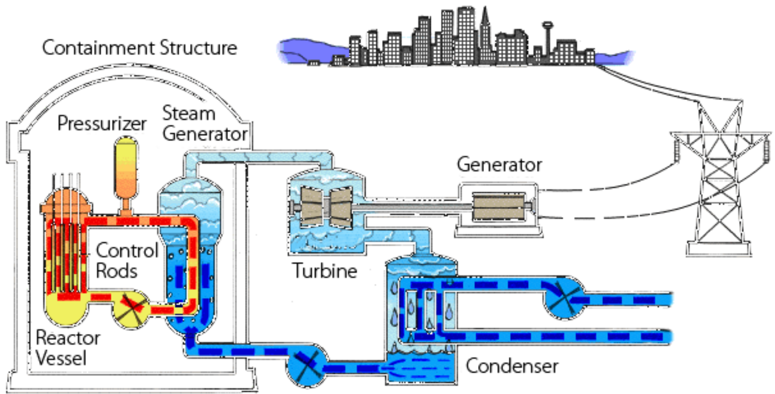

Figure 2. Pressurized water reactor diagram. For the animated version, go to http://www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html. *Source:* U.S. Nuclear Regulatory Commission

Tritium is also produced, in greater quantities, in the fuel rods of both PWRs and BWRs from ternary fission[12] (fission in which there are three fission fragments). Only a tiny fraction of this leaks into the primary cooling water along with some other fission products through very small cracks and holes that form in a small number of the fuel rods.[13] The PWR's cooling water is constantly taken out for chemical treatment, volume control, and to reduce the radioactivity. Then most of it is sent back into the reactor vessel. The chemical treatment is mainly to reduce the amount of boron as the reactivity in the fuel decreases with time.[14] Some of the fission products that leak into the primary water of the reactor are removed by passing the water through ion exchange resins; however, this does not affect tritiated water which, being chemically identical to water, just passes right through.[15] The part of the cooling water which is not returned to the reactor vessel is put in holding tanks. It is periodically released to the environment after further treatment and dilution to bring the tritium concentration to a level deemed "safe" by the nuclear industry and the NRC. Fresh water is mixed in with the balance of the primary water to make up for the water that is withdrawn into the holding tanks.

EPA's Maximum Contaminant Level Goal for all radionuclides, including tritium, is zero.

A 1985 study by Peterson and Baker estimated that about 780 curies of tritium per 1,000 megawatt electric (MWe) from a PWR, operating at 82 percent capacity for the whole year, are released to the environment, of which 85 percent are waterborne effluents (663 curies) and the rest are airborne effluents (107 curies).[16] The liquid effluents are discharged in batches in lakes, rivers, and oceans, often through underground pipes. Leaks can occur in such pipes and when they do, they contaminate the soil and groundwater.

In boiling water reactors (BWRs) boron is not added to the water and therefore tritium is not produced in boron-neutron reactions in the primary water. The tritium in BWRs is mainly produced as a result of ternary fission in reactors. The Peterson and Baker study estimated that 120 curies per 1,000 MWe are released per year to the environment, of which 75 percent is in gaseous form and the rest in liquid form.[17] Leaks can also occur from BWRs that have pipes carrying primary water that are buried underground.

At some plants tritium has leaked out of the cooling pool in which spent fuel is put after being unloaded from the reactor.[18]

Monitoring of tritium releases

The NRC requires power plant operators to monitor releases of radionuclides on site and off site. The onsite and offsite releases from a plant are reported every year in the Effluent Report and the Environmental Report respectively.

In the Effluent Report the plant operator is required to give quarterly data on the amount of tritium curies released from each reactor,[19] including the concentration of tritium before the water is sent to the underground pipe,[20] the frequency at which the releases occur, and how long the releases last.[21] Table 1 gives the annual releases from a selected number of plants for the year 2005. (The exhaustive list can be found on IEER's website at http://www.ieer.org/sdafiles/16-1/tritium-releases.html.) However, the reporting is not consistent for plants that have more than one reactor. For example, for plants with two reactors, three ways of reporting are found:

– each reactor has a different amount of curies (e.g., Millstone 2 and 3)
– each reactor has the same amount of curies (e.g., Braidwood 1 and 2)
– there is only a total amount of curies (e.g., Calvert Cliffs 1 and 2)

The second and third methods of reporting indicate that discharges from each reactor may not be measured; rather only the total discharges from both reactors may be measured. This may make it difficult to detect problems or to infer their existence from the reported data. Further, the amount of tritium discharged from PWRs is highly variable. Hence the Peterson and Baker study should be regarded only as a rough guideline rather than an indication of actual releases from particular reactors.

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Table 1: 2005 annual liquid releases of tritium from selected pressurized water nuclear reactors

Braidwood 1 & 2	Unit 1	Unit 2
Location	Illinois	Illinois
Electrical output (MWe)	1,161	1,154
License	1987-2026	1988-2027
Operator	Exelon	Exelon
Releases 1 & 2 (Curies)	**881**	**881**
Curies per 1,000 MWe	**759**	**763**
Fort Calhoun		
Location	Nebraska	
Electrical output (MWe)	478	
License	1973-2013	
Operator	Omaha Public Power District	
Releases (Curies)	**142**	
Curies per 1,000 MWe	**297**	
Millstone 2 & 3	**Unit 2**	**Unit 3**
Location	Connecticut	Connecticut
Electrical output (MWe)	871	1,130
License	1975-2015	1986-2025
Operator	Dominion Nuclear Connecticut, Inc.	Dominion Nuclear Connecticut, Inc.
Releases 2 & 3 (Curies)	**495**	**1,715**
Curies per 1,000 MWe	**568**	**1,518**
Calvert Cliffs 1 & 2	**Unit 1**	**Unit 2**
Location	Maryland	Maryland
Electrical output (MWe)	825	835
License	1974-2034	1976-2036
Operator	CCNPPI - subsidiary of Constellation Energy Group	CCNPPI - subsidiary of Constellation Energy Group
Releases 1 & 2 combined (Curies)	**991**	
Curies per 1,000 MWe	**597**	

Sources: Individual reactor fact sheets and the 2005 Effluent Reports for each plant. See links at http://www.nrc.gov/info-finder/reactor/ and at http://www.nrc.gov/reactors/operating/ops-experience/tritium/plant-info.html.

For example, the number of curies per 1,000 megawatt electric (MWe) reported in the 2005 liquid effluents reports range from a low of 297 curies at the Fort Calhoun reactor to a high of 1,518 curies at the Millstone 3 reactor. Hence, the range is from more than about a factor or two lower than the Peterson and Baker liquid release estimate to more than a factor of two higher.[22]

Environmental contamination

Liquid discharges

The Environmental Reports give the concentrations of tritium in picocuries per liter for drinking, surface, and groundwater/well-water at different locations in the proximity of the plant. Unfortunately, the points of measurement are not comparable and so the inferences regarding the relationship of the measurements to potential public exposure are rather difficult to make.

Some natural background tritium in surface and groundwater arises from the interaction of cosmic radiation with the atmosphere. However, these levels are very low – typically 5 to 25 picocuries per liter in surface water and less than 6.4 to 12.8 picocuries per liter in groundwater.[23] Large amounts were added in the atmosphere and global waters due to atmospheric testing of nuclear weapons. The vast majority of atmospheric testing had stopped by 1963, though some scattered tests by France and China continued after that. The last atmospheric test was by China in 1980. Since the half-life of tritium is 12.3 years, most of the additions due to testing have decayed away. However, just radioactive decay would still leave testing tritium at a level higher than natural background. In practice, the concentration of tritium in fresh water due to testing fallout is much lower than that implied by radioactive decay alone due to the very large dilution by ocean water.[24] Tritium levels in water bodies near nuclear power plants are often much higher than the background level, which is defined as the combination of natural and testing related tritium.[25]

The concentrations of tritium in drinking water near all the power plants are well under 20,000 picocuries per liter, the EPA standard for tritium in drinking water. However, there are examples where the levels in drinking water are above 400 picocuries per liter, which is the California recommended public health goal[26] and also above 540 picocuries per liter, which Ontario is considering as its drinking water standard. Most of the measurements reported in the Environmental Reports are not for drinking water. The levels reported in Table 2 are used for reference and comparison purposes in this article. However, we note that there are several examples of drinking water that are above the recommended public health goal set by California, which IEER recommends be adopted throughout the country as a goal as well. It is based on risk estimates that guide Superfund cleanup.

The first point to make regarding the reported measurements is that the NRC requirement for a minimum detection limit, also called the Lower Limit of Detection (LLD), is 2,000 to 3,000 picocuries per liter. This is satisfactory if the EPA drinking water standard (20,000 picocuries per liter) is used as a reference, but it is quite unsatisfactory if the California public health goal (400 picocuries per liter) is the reference value. Evidently, for a reliable conclusion that the level is below 400 picocuries per liter, the LLD required should be consistently lower than that. The California public health goal is a recent development and the NRC LLD has not caught up with it.

Actual measurement practices at nuclear power plants vary quite a lot. The *Offsite Dose Calculation Manual Guidance* reports (NUREG-1301 for PWRs and NUREG-1302 for BWRs) direct the plant operator to have a lower limit of detection (LLD) of 2,000 picocuries per liter that can be increased to 3,000 picocuries per liter if no drinking water pathway exists.[27] Most plant operators have lower LLDs (in the few hundreds of picocuries); however these lower limits are not required. As a result, some power plant operators simply report that tritium levels are below the lower limit of detection. In some cases, even the LLD values are not specified. We recommend that the NRC tighten its tritium LLD to 200 picocuries per liter or less and require the specification of the LLD.

Table 2 gives the concentrations of tritium, for the year 2006, from selected plants that have levels higher than 400 picocuries per liter.

Further, we note that tritium measurements are done quarterly, with composite samples that are collected at various intervals, commonly monthly.[28] This means that samples from the times tritium is discharged (many times each quarter) and the times that it is not, are put together and averaged to give a quarterly result. There are two main problems with this approach. There is generally no independent verification by the NRC of when the samples are actually taken. The NRC (and hence the public) depends on the reactor operators' word that they are taken at the time of contaminated water discharge and not just before or well after, for instance. As a result, there is no verification of the representativeness of the samples and hence of the accuracy of the data in providing estimates of total tritium releases. While there may be NRC inspections on occasion, there is no coherent body of verification data that would enable the public to have some confidence that nuclear power plant operators are collecting and reporting accurate and representative data. Since tritium discharges are sometimes made into water bodies that are used for drinking downstream of the reactor (as is the case with the Braidwood plant),[29] this lack of independent verification of discharges is troubling, especially in the context of batch sampling.

If the samples are not coordinated with plant discharges occurring over a period of time and are not fully representative of the discharges, the estimates of total tritium discharges made using the results could be inaccurate. There is at present no independent way for communities and the public to verify what is occurring in terms of discharges measurements and reporting of the same. This has become more important in light of the controversies surrounding the failure to report known tritium leaks at the Braidwood plant for an extended

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Table 2: Tritium concentrations in drinking and surface/lake/river water near selected pressurized water reactor plants in 2006

Data shown for the sample locations with the highest annual mean.*

Plant	Range (picocuries per liter)	Mean (picocuries per liter)	Distance from plant, in miles, and sampling location
Drinking Water			
Catawba 1 & 2 (SC)[1]	1,000-2,200 582-1,170	1,598 770	7.30 (indicator)** Rock Hill Water Supply 13.5 (control) Belmont Water Supply
Comanche Peak 1 & 2 (TX)[2]	<1,300-1,400	not given	9.9 Lake Granbury
McGuire 1 & 2 (NC)	697-2,290	1,460	3.3 North Mecklenburg Water Treatment Facility
Oconee 1, 2, & 3 (SC)[3]	298-370	340	18.9 Anderson water plant
Vogtle 1 & 2 (GA)	518-935 Water near intake of treatment plant 471-1,040 Finished water at treatment plant	746 766	76 Purrysburg (SC) Water Treatment Plant (Downstream from both Vogtle and Savannah River Site (part of weapons complex))
Watts Bar 1 (TN)	394-817	606	24 Public water sampling location
Surface/River Water			
Catawba 1 & 2 (SC)	15,400-18,000 442-827	16,700 583	0.45 (indicator)** Discharge Canal 4.21 (control) Lake Wylie
Comanche Peak 1 & 2 (TX)	10,500-13,400 10,200-13,100	not given	1.4 ESE (indicator)** 1.5 N (indicator) Squaw Creek Reservoir
Shearon Harris 1 (NC)	3,150-6,370	4,730	4.70 Harris Lake
McGuire 1 & 2 (NC)	730-2,570 219	1,650 219	0.45 (indicator) Discharge Canal Bridge 11.9 (control) Plant Marshall Intake Canal
North Anna 1 & 2 (VA)	2,900-4,100 2,130-4,300	3,625 3,283	3.37 Waste Heat Treatment Facility Lagoon 5.80 North Anna River
Oconee 1, 2, & 3 (SC)	2,620-13,600	6,718	0.79 Lake Hartwell
Point Beach 1 & 2 (WI)	nondetectable-1,017[4] 3,096[5]	not given	4.0 4.0 Lake Michigan
H.B. Robinson 2 (SC)	856-3,670	1,650	0.6 Black Creek
Three Mile Island 1 (PA)	<164-9,830	1,927	0.5 Susquehanna River
Vogtle 1 & 2 (GA)	1,140-3,870	2,307	0.80 Savannah River[6]
Watts Bar 1 (TN)	N/A[7]	588	9.9 Tennessee River
Wolf Creek 1 (KS)	8,624-14,276	11,286	3.2 Coffey County Lake

Sources by plant: *Annual Radiological Environmental Operating Reports* (ER) for 2006 (except for Point Beach, where the source is the ***2006*** *Annual Monitoring Report*.). Links at http://www.nrc.gov/reactors/operating/ops-experience/tritium/plant-info.html. **Page citations can be obtained from IEER**.

Table 2 Notes

* The lower limit of detection in many of these measurements is stated to be larger than the measurement, making the figures that are less than 2,000 or 3,000 picocuries per liter difficult to interpret in such cases. We have quoted the figures here since, in almost all cases, they are published without a "less than" or "<" note and are presented to more than one significant figure

** "Indicator" sampling locations are chosen because any contamination is expected to be highest at that point. "Control" locations are expected to not be contaminated by the plant (upstream if on a river), so are expected to reflect background levels of contamination, unless there is a different source of contamination upstream of the control location, for example, another nuclear power plant.

[1] The Catawba 2006 Environmental Operating Report, Section 3.2, says that some of the contamination comes from the McGuire plant situated 40 miles upstream. This could explain the high tritium level at the indicator location although this is not borne out by the tritium levels found at the McGuire plant. The report also says "Indicator and control locations were established for comparison purposes to distinguish radioactivity of station origin from natural or other 'manmade' environmental radioactivity."

[2] The Comanche Peak 2006 Environmental Operating Report, Section E, says that this location "was used as a surface drinking water location based on the proximity of the City of Granbury intake to the Granbury potable water system."

[3] The Oconee 2006 Environmental Operating Report lists other drinking water sampling sites, both closer to the plant, but no measurements seem to have been taken at the closer locations.

[4] Range for the fourth quarter 2006.

[5] For the month of September 2006. High number attributed to discharge from Kewaunee Power Station, approximately another 4 miles north of the sampling site.

[6] Station 83 is located on the right bank (west side) of the Savannah River, directly across from DOE's Savannah River Site.

[7] Only one value reported.

period of time. Further, it should also be noted Braidwood routine tritium discharges are diluted and discharged into the Kankakee River,[30] which is an important water resource in the region.[31]

Gaseous discharges

As noted above, tritiated water vapor is also discharged from nuclear power plant stacks. This occurs in both BWRs and PWRs. These discharges are also highly variable.

The reported 2004 gaseous discharges of tritium from PWRs ranged from 0 to 972 curies. The latter number is for Palo Verde 3 and is nine times higher than the value of 107 curies estimated by Peterson and Baker (cited above) as a typical reference value. The discharges from BWRs range from 0 to 281 curies.[32] Again, the highest value is about nine times higher than the reference value of 30 curies estimated by Peterson and Baker. A table summarizing the 2004 gaseous releases from all U.S. reactors will be available at http://www.ieer.org/sdafiles/16-1/tritium-releases.html.

Tritiated water vapor is also discharged from nuclear power plant stacks. This occurs in both BWRs and PWRs. These discharges are also highly variable.

Rainfall episodes that occur during gaseous discharge events result in the rainfall becoming contaminated with tritium. Such contamination could reach high levels under certain weather and tritium release conditions.

Data for rainfall near reactors are not part of the Environmental Reports filed by nuclear power plant operators. IEER has corresponded with the NRC about monitoring rainwater. Our best understanding is that the NRC does not require rainwater monitoring nor monitoring of groundwater and surface water that may be affected by contaminated rainfall events. IEER's correspondence with the NRC about this is reproduced at the end of this article. We infer that the NRC does not believe that separate pathway monitoring is necessary since the dose limits are below those required. However, this is flawed logic. If private groundwater sources and rainfall are not monitored, how can the NRC know that dose limits are not being exceeded, especially since high contamination events can occur and, under present dispensation, escape detection.

The possibility of contamination by rainfall was raised in a presentation made by Ken Sejkora, of Entergy Nuclear Northeast – Pilgrim Station, who has stated that "Localized washout can result in very high concentrations, possibly even exceeding drinking water standards."[33]

The potential that rainwater could be contaminated significantly is an important issue for several reasons. For one thing, the EPA only limits contamination of public drinking water systems. Private wells and small public water systems (generally meaning less than 15

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connections and fewer than 25 people served) are not protected. Private wells and small public water systems are not protected by EPA drinking water regulations. This is because it could be economically onerous to require individuals and small water systems to conform with EPA standards in cases where remediation was required. However, this does not make the people involved less vulnerable. Indeed, it leaves them more vulnerable if there is no means for them to find out if their water supplies are at risk of contamination. Information about contamination in cases where there is a risk of it, as for instance, near nuclear power and nuclear weapons plants, is even more important in such cases.

In its "lessons learned" document relating to tritium leaks, the NRC acknowledges that gaseous tritium releases from nuclear power plants can contaminate groundwater:

> Gaseous migration of tritium can be linked to atmospheric deposition of condensated tritiated water or condensation of subsurface water vapor containing tritium, as noted in IAEA and U.S. Geological Survey research studies.[34]

Private wells and small public water systems are not protected by EPA drinking water regulations.

In fact, the NRC has itself documented tritiated rainwater falling onto the site of the Palo Verde nuclear plant.[35] Yet, it contented itself with the observation that "no elevated levels have been found in wells located outside the protected area" of the Palo Verde reactors. However, it does not note that the NRC does not require monitoring of rainwater or of private wells, though it may sometimes be carried out.

IEER recommendations

These recommendations relate to routine releases of tritium and the contamination of air and water that they cause. The NRC's "lessons learned" document about tritium leaks contains a number of recommendations, which relate mainly to developing new guidance and conducting dialogs and looking into modernizing rules and guidelines. There is no actual hard followup in terms of actual leak prevention, tightening monitoring requirements, or other tightening of standards that follow this 2006 "lessons learned" report. IEER will make a separate assessment of the problem of leaks and issues associated with it in the future.

The main problems of routine discharges of radioactivity to the water occur as a result of periodic discharges of the reactor's primary cooling water to water bodies and of tritiated water vapor to the atmosphere, creating radioactive rainfall when the release and rainfall occur at the same time.

The high variability in tritium discharges from PWRs, the many leaks, the failure of some nuclear plant operators to disclose the leaks to the public in a timely manner, in at least some cases, and the fact that tritiated water crosses the placenta and behaves just like ordinary water in the living world but for its radioactivity leads us to call for an overhaul of the system for monitoring and reporting of both routine and non-routine tritium releases. Another reason for such an overhaul is that tritium contamination from nuclear power plants affects many water bodies and, hence, large numbers of people at low doses. This is the reason that a far tighter tritium standard is being proposed in Ontario, Canada. Finally, in the United States, there is also tritium contamination from nuclear weapons plants. Some places, such as those downstream of both the Vogtle nuclear power reactors and the Savannah River Site, a nuclear weapons plant, are affected by both.

The first principle that needs to be enforced is the NRC's rule that exposures of the public should be kept "as low as reasonably achievable." We are not convinced that tritium discharges to public water bodies are necessary at all or, if so, that they are necessary to the extent that actually occurs. Indeed, it appears possible with existing technology and moderate cost to eliminate or reduce routine liquid discharges significantly. Primary water can be reused more and the part that is not reused can be stored in tanks, as was done for a period at Braidwood after the revelations of leaks in 2005. The waste water can be grouted and the grout can be stored as low-level waste.[36]

We understand that the NRC itself is in the process of reviewing its procedures regarding early detection of leaks and reporting them to the public as a result of the scandals surrounding tritium leak disclosures.

IEER's recommendations around tritium cover a broader front:

- The NRC should conduct a thorough review of routine tritium discharges to the water from PWRs over the last two decades and analyze the reasons for the differences in discharges. The same should be done for atmospheric releases from all nuclear power reactors. The aim should be to pinpoint operational practices and design changes (in new reactors) that would greatly reduce them.
- NRC should itself monitor each discharge of primary coolant water and ensure that water authorities downstream are informed. The monitoring and record keeping should include inspection of the discharges at the time they are made. The NRC should ensure that samples are taken so as to be representative of the discharges. Split samples should be preserved and appropriate detailed entries should be made in logbooks independently maintained by the NRC onsite inspectors. Randomly selected examples of these split samples should be subjected to independent measurement.
- The NRC should develop a policy of keeping tritium releases as low as reasonably achievable as a supplement to its dose guidelines. The upper limit for environmental concentrations should be tightened to no more than 400 picocuries per liter on an annual average basis.

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- The NRC should put into place requirements for plant monitoring and hardware that would greatly reduce the risk of leaks and facilitate early detection.
- Nuclear plant licensees should be required to monitor onsite groundwater and disclose those results.
- Nuclear plant licensees should be required to monitor rainwater and offsite groundwater in a manner designed to detect rainwater and groundwater contamination. The results should be reported to the NRC by licensees as part of their annual environmental reporting.
- There should be significant penalties for failure to disclose offsite migration of radionuclides due to leaks and accidents or contamination of offsite rainwater, groundwater, or drinking water above 400 picocuries per liter.
- The lower limit of detection should be lowered to 200 picocuries per liter.
- The NRC should require licensees to make public all health and environmental documents, including all raw measurement data and times of discharges.

Measuring Tritium in Precipitation: NRC's staff response to IEER Questions

An e-mail regarding gaseous tritium releases, from Scott Burnell, NRC public affairs officer, sent on September 18, 2008, to Annie Makhijani, included an attached response, which is reproduced below:

IEER Question:

Is the NRC monitoring rainfall, surface water, and groundwater onsite and offsite? If there is monitoring in place at or near any commercial nuclear power plant, we would like to obtain the data that has been collected over the past decade.

NRC Answer:

Nuclear power plants are licensed to release radioactive effluents in strict accordance with their license's safety provisions and restrictions. Essentially, the restrictions are based on both dose limitations and on radioactive release concentrations.

NRC requires that licensees perform radioactivity monitoring both in the radioactive effluent prior to its release and in the environment, including samples of water sources, vegetation, fish and milk, after releases have been performed. Licensees must then report their monitoring results in both the annual radioactive effluent report and in the annual radiological monitoring report. These reports are publically available in the Agency Wide Documents Access and Management System (ADAMS). http://www.nrc.gov/reading-rm/adams/web-based.html.

Prior to 2005, several years of data was also made available to the public at the REIRS hyperlink you listed in your letter. However, since 2005, in order to make recent data even more accessible to the public, NRC is now providing a direct link to the effluent and environmental reports on our web page. http://www.nrc.gov/reactors/operating/ops-experience/tritium/plant-info.html. The Public Document Room will be able to assist you in locating older reports not included in the REIRS database.

IEER Question:

We would also like to know if there is an explanation for the large range of releases and what the NRC has done to encourage nuclear power plant operators to minimize atmospheric tritium releases.

NRC Answer:

Each plant must minimize its radioactive effluents in accordance with its license, with 10 CFR 50, Appendix I and with the "As Low As Reasonably Achievable" (ALARA) philosophy. NRC inspectors periodically monitor the radioactive effluent release programs and the environmental programs. This includes the licensee's procedures to limit their effluent releases to ALARA, the calibrations of monitoring equipment, observing actual releases to verify compliance with regulations, and a review of the results reported in the annual effluent and environmental reports.

The annual differences in release quantities of radioactive materials from nuclear plants occur as a result of different waste processing equipment and methods as well as in the timing of plant operations. For example, during a reactor shutdown for maintenance and refueling, larger quantities may be released than during plant operation.

Endnotes

1. *Plant Sites with Groundwater Contamination* at http://www.nrc.gov/reactors/operating/ops-experience/tritium/sites-grndwtr-contam.html
2. For instance, there were leaks at Exelon's Braidwood plant in Illinois. NRC 2006 (U.S. Nuclear Regulatory Commission, *Liquid Radiation Release Lessons Learned Task Force Final Report,* ML062650312, Washington, DC: NRC, September 1, 2006, link at http://www.nrc.gov/reactors/operating/ops-experience/tritium/nrc-actions.html) pp. 12-13. These leaks triggered widespread concerns among people who live near the plant about their safety and health.
3. Sejkora 2006 (Ken Sejkora, *Atmospheric Sources of Tritium and Potential Implications to Surface and Groundwater Monitoring Efforts,* Presented at the 16th annual RETS-REMP Workshop, Mashantucket, CT, 26-28 June 2006, link at http://hps.ne.uiuc.edu/rets-remp/presentations2006.htm)
4. *Code of Federal Regulations,* 40 CFR 141.66 2007
5. *Online NewsHour,* "Radioactive Leaks in Illinois," April 17, 2006, at http://www.pbs.org/newshour/bb/environment/jan-june06/tritium_4-17.html and Exelon Corporation, "Moustis Call for Plant Shutdown 'Uninformed,' Exelon Nuclear Says," News Releases, April 10, 2006, at http://www.exeloncorp.com/aboutus/news/pressrelease/powergen/pr+2006+04+10.htm
6. National Research Council, Board on Radiation Effects Research, *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2.* The National Academies Press, Washington, DC, 2006
7. *Code of Federal Regulations,* 40 CFR 141.55 2007
8. Ontario Drinking Water Advisory Council, *Report and Advice on the Ontario Drinking Water Quality Standard for Tritium,* ODWAC, Toronto, May 21, 2009, at http://www.odwac.gov.on.ca/reports/052109_ODWAC_Tritium_Report.pdf. CANDU heavy water reactors generate more tritium than U.S. light water reactors.
9. 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,* Institute for Energy

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and Environmental Research, Takoma Park, Maryland, October 19, 2006, at http://www.ieer.org/campaign/report.pdf and Arjun Makhijani, Brice Smith, and Michael C. Thorne, "Health Risks of Tritium: The Case for Strengthened Standards," *Science for Democratic Action* v.4, no.4 (February 2007) pp. 1, 10-12, at http://www.ieer.org/sdafiles/14-4.pdf

10. Glasstone and Sesonske 1981 (Samuel Glasstone and Alexander Sesonske, *Nuclear Reactor Engineering,* 3rd ed., Van Nostrand Reinhold, New York, 1981), para 9.97
11. Glasstone and Sesonske 1981, para 9.119
12. National Council on Radiation Protection and Measurements, *Tritium in the Environment,* Recommendations of the National Council on Radiation Protection and Measurements, NCRP Report no.62, NCRP, Bethesda, MD, March 9, 1979 (reprinted January 15, 1995), p. 1
13. Glasstone and Sesonske 1981, para 9.96
14. Glasstone and Sesonske 1981, paras 9.104 and 5.202
15. Glasstone and Sesonske 1981, paras 9.99, 9.102, and 9.104
16. Harold T. Peterson and David A. Baker, "Tritium Production, Releases and Population Doses at Nuclear Power Reactors," *Fusion Technology* v.8, no.2 (September 1985), pp. 2544-2550. Abstract at http://www.osti.gov/energycitations/product.biblio.jsp?osti_id=5767655
17. Peterson and Baker 1985
18. See, for example, NRC 2006, pp. 5-8.
19. Currently there are 68 plant sites. Thirty-two plants have only one operating reactor, thirty-three have two reactors, and three have three reactors. There are links to the reports at *Radioactive Effluent and Environmental Reports,* http://www.nrc.gov/reactors/operating/ops-experience/tritium/plant-info.html.
20. According to Sections 3/4.11.1 of *Offsite Dose Calculation Manual Guidance* for both the Pressurized Water Reactors and for the Boiling Water Reactors, NUREG-1301 and NUREG-1302, the maximum concentration of tritium that can be released to unrestricted areas is 1 million picocuries per liter, as "specified in 10 CFR Part 20, Appendix B, Table II, Column 2." However some plant operators use less restrictive values ("applicable limit") that are 3 to 10 times more lax and sometimes do not even give one.
21. The frequency of releases ranges from more than once a day to every two months. For most plants the releases are every two to ten days.
22. Gaseous and liquid release total estimate was 780 curies, 85 percent of that is 663 is for liquid releases only.
23. Merril Eisenbud and Thomas Gesell, *Environmental Radioactivity from Natural, Industrial, and Military Sources,* 4th ed., Academic, San Diego, 1997, p. 182, for surface water and R. Allan Freeze and John A. Cherry, *Groundwater,* Prentice Hall, Englewood Cliffs, NJ, 1979, p. 136, for groundwater.
24. Tuttle 1992 (R.J. Tuttle, *Tritium Production and Release to Groundwater at SSFL: Safety Review Report,* Rockwell International, Canoga Park, CA, 1 December 1992 (RI/RD92-186) at http://www.etec.energy.gov/library/Groundwater/RI-RD-92-186_Tritium_Production_at_SSFL.pdf), p. 9, says "Extrapolation of the decreasing concentration from the end of 1975, with an effective half-life of 3.2 years (faster than the radioactive decay of tritium because of dilution by ocean water), to the end of 1991 shows a remaining activity of only about 6 pCi/L from the weapons tests." A further extrapolation to 2008 shows a remaining activity of 0.15 pCi/L.
25. In some cases, notably that of the Savannah River, which has both commercial nuclear reactors and a nuclear weapons plant along its shores, most of the tritium appears to be due to the latter.
26. Anna M. Fan and George V. Alexeeff, *Public Health Goal for Tritium in Drinking Water, prepared by Office of Environmental Health Hazard Assessment,* California Environmental Protection Agency, California EPA, Sacramento, March 2006, at http://oehha.ca.gov/water/phg/pdf/phgtritium030306.pdf
27. NUREG-1301, Table 4.12-1 and NUREG-1302, Table 4.12-1
28. The EPA gives this definition "Composite sampling is a technique whereby multiple temporally or spatially discrete, media or tissue samples are combined, thoroughly homogenized, and treated as a single sample," at http://www.epa.gov/reg3hscd/risk/eco/faqs/composite.htm#q01.
29. Exelon Nuclear, *Braidwood Station Units 1 and 2 Annual Radiological Environmental Operating Report, 1 January through 31 December 2006,* Exelon, Braceville, IL, May 2007. pp. 9-10
30. Exelon Nuclear, *Braidwood Generating Station Groundwater Fact Sheet,* Exelon, Braidwood, IL, November 28, 2006, at http://www.exeloncorp.com/NR/rdonlyres/151E8B56-162C-40E9-9D99-85B9B7C0DBFC/0/Exelon_Groundwater_Fact_Sheet_11282006.pdf
31. Will County, Illinois, Resolution #09-71, in Public Health & Safety Committee Resolutions, at http://www.willcountyboard.com/Board%20Agendas/March%202009/05Health.PDF
32. NRC Database (U.S. Nuclear Regulatory Commission, Effluent Database for Nuclear Power Plants, NRC, Washington, DC, at http://www.reirs.com/effluent/EDB_rptLicenseeReleaseSummary.asp). Viewed August 2008.
33. Sejkora 2006, slide 22. Sejkora claims that testing fallout should result in a residual tritium concentration in rainwater of 100 to 300 pCi/liter (slides 6 and 21). However, he did not take the dilution effect of the oceans into account. Actual data are presented in Tuttle 1992. They show that testing-related tritium had declined to less than low-end of natural background level of 5 pCi/liter by about 1990. See Tuttle 1992, Figure 1-3.
34. NRC 2006, p. 43
35. NRC 2006, pp. 6 and 11
36. Glasstone and Sesonske 1981, pp. 599-602

More IEER Materials on Tritium

(in reverse chronological order)

- **Tritium Releases to Air and Water from Nuclear Power Plants: Tables of Release Data from 2004 or 2005** (Aug. 2009), at http://www.ieer.org/sdafiles/16-1/tritium_releases.html
- **Health Risks of Tritium: The Case for Strengthened Standards** (newsletter article, Feb. 2007), at http://www.ieer.org/sdafiles/14-4.pdf
- **Memo on Tritium, Review of Braidwood Generating Station Groundwater Issue:** Frequently Asked Questions (March 20, 2006), at http://www.ieer.org/comments/tritium060320.html
- **Statement on Tritium,** prepared for a February 7, 2006, public forum in Godley, Illinois. (February 2006), at http://www.ieer.org/comments/health/tritium.html
- **Statement on Tritium before the House Committee on Intergovernmental Coordination, State of Georgia** (October 1999), at http://www.ieer.org/comments/tritstmt.html
- **Tritium Production: DOE Moves Ahead Where Nonproliferationists Fear to Tread** (newsletter article, winter 1996), at http://www.ieer.org/sdafiles/vol_5/5-1/tritium.html
- **Tritium: The environmental, health, budgetary, and strategic effects of the Department of Energy's decision to produce tritium** (IEER report, January 1996), at http://www.ieer.org/reports/tritium.html

COURTESY OF PACIFIC NORTHWEST NATIONAL LABORATORY

Figure 3: The bottle manikin absorption (BOMAB) phantom simulates Reference Man in size and internal body density. It is used to "calibrate systems used to detect and quantify the amount of radioactive materials in workers." BOMAB is loaned to DOE sites by the Pacific Northwest National Laboratory. Phantoms for a Reference Female and four-year old child are also available. (Sources: http://picturethis.pnl.gov/picturet.nsf/by+id/AMER-5XBN9N, http://www.pnl.gov/phantom, and http://www.pnl.gov/phantom/bomab)

The continued use of Reference Man does not take into account the greater radiation doses received by some parts of the population that result from the same environmental conditions and the higher cancer risks per unit of dose that they face. This especially applies to women (including pregnant women) and children.

Specifically, the overall fatal cancer risk experienced by females is 37.5 percent greater than that experienced by males for the same radiation exposure. The differential cancer *incidence* risk is even higher (52 percent higher for women than men).[3]

For children, the fatal cancer risk per unit of dose is higher than for adults. The risk of developing cancer from exposure is about 3.7 times greater for an infant boy than the risk for a 30 year old adult male receiving the same radiation dose and 4.5 times greater for an infant girl than the risk for an adult female. A female infant has about a seven times greater risk of getting cancer than a 30-year old male for the same radiation exposure.[4]

It also should be noted that, even though Reference Man is taken to be an adult male in his twenties, the definition makes no mention of the possibility that a man may become a father and what that might mean in terms of the impacts on the framework of radiation protection regulations. Further, while radiation dose to the gonads is calculated in the Reference Man framework to take account of possible hereditary effects, non-cancer reproductive effects are not part of the U.S. regulatory framework for radiation protection.

This article provides some examples where Reference Man is currently used in U.S. radiation protection standards or official guidance documents, and makes some recommendations for change. It examines some key policies of three U.S. federal agencies: the Environmental Protection Agency (EPA), the Nuclear Regulatory Commission (NRC) and the Department of Energy (DOE). We also comment on the recent correspondence between then Senator Obama, Congressman Henry Waxman, and the EPA about Reference Man. (A link to this correspondence is at http://www.ieer.org/sdafiles/16-1/referenceman-letters.html)

Environmental Protection Agency

External dose

EPA calculates a person's external dose using guidelines provided in Federal Guidance Report 12 (FGR 12). The calculations are based almost entirely on Reference Man, with the exception of the inclusion of sex-specific organs of women such as the uterus. Children are not at all considered in this guidance.

Specifically, FGR 12 calculates "[a]ll organ doses" using a hermaphroditic phantom[5] (See Figure 3) that is based on the Reference Man model. The weight, location of the organs, density of organs, and other features of this model are, with the exception of the female specific sex organs, those of a male that is slightly heavier than the Reference Man as defined above (73 kilograms versus 70 kilograms) and also somewhat taller (179 cm versus 170 cm). Thus, while FGR 12 does include doses to the ovaries and breasts, the basic geometry of the body and the weight of the model is that of an adult male.

Even so, the model does not accurately represent female adult doses to many organs, since women are on average lighter than men. Generally, the lighter a person, the greater the dose from a given amount of external radiation to internal organs, all other things being equal, since there is less shielding of these organs by the rest of the body. Therefore, the same external radiation field would produce a greater dose in the internal organs of females.

Moreover, the chemical composition of female bodies is different from that of men. For example, on average, females have a greater proportion of their body weight as fat than men. Hence it is critical to have a model that is specific to females of various ages, if external doses to many organs are to be accurately estimated.

The problem is even greater in the case of children. The approach used in FGR 12 would generally underestimate doses experienced by children's organs, for instance, because their bodies are thinner and more radiation gets through the outer layers to reach the various organs. This is even acknowledged in FGR 12. Further, the chemical composition of children's bodies is substantially different, including that of radiosensitive organs.

One reference[6] cited in FGR 12 contains data on infants and children of various ages that could have been used to

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estimate external exposure doses to people of varying ages. But the EPA did not do so.

The problems of using a Reference Man approach (with a couple of female organs added into the model) are compounded by the facts that

> Children are at higher risk than adults of getting cancer from the same dose of radiation. Females are at higher risk than males of getting cancer from the same dose of radiation.

Using a hermaphrodite model that is basically a grown man with female organs added on is not a suitable substitute for scientifically sound models for women and children (of various ages) in their own right.

Internal dose

The current guidance generally used for internal dose calculations is Federal Guidance Report 11 (FGR 11). FGR 11 uses Reference Man. The newer FGR 13 contains dose and risk factors for children, but the dose conversion factors in FGR 11 are still the basis of most U.S. radiation protection regulations. Dose conversion factors are the numbers used to convert intakes of amounts of radionuclides to radiation dose (which, according to regulations and the National Academy of Sciences, is proportional to cancer risk for solid cancers).

The 2002 update to FGR 13 specifies dose conversion factors at various ages, although it continues to average the values for males and females. Hence it is possible to calculate the doses to infants and to children at various ages in order to determine whether the same environmental conditions, such as water or food contamination, produce a higher dose for adults or for children. However, it is not possible to use FGR 13 to determine if boys would receive a higher dose than girls or vice versa.

> In the case of the Clean Air Act regulations (40 CFR 61 Subpart H), children are specifically excluded from the compliance calculations in order to maintain "consistency" with earlier compliance models.

When FGR 13 is used to estimate the dose from internally deposited radionuclides for a specified set of environmental conditions, the segment of the population that gets the highest dose may or may not be children. For instance, the dose to the thyroid experienced by infants to due breathing air contaminated with iodine-131 will be about 11 times greater than that for an adult male, after taking into account the fact that infants breathe only about one third the amount of air per day on average as an adult male. But the ingestion dose from drinking water contaminated with iodine-129, another radioisotope of iodine, will be greater for an adult. This is because the higher dose conversion factors for infants for iodine-129 are outweighed by the higher water consumption of adults.

However, the risk to infants of developing cancer from the ingestion of iodine-129 will still be greater despite the lower radiation dose received, with the difference being greatest between female infants and adult males. This is because radiation doses received in childhood are more likely to lead to cancer than the same dose received as an adult. In the case of the risk of thyroid cancer, for example, the risk to female infants drinking the same contaminated water as adult males is about 26 times greater, even after taking into account the fact that infants drink much less water on average than adults.[7]

Definitions

Dose: A measure of the energy deposited due to radiation exposure in a person, organ, or other medium. Units are rad or gray (Gy), with 1 gray = 100 rad. When the relative biological effectiveness of a particular radiation type (relative to gamma radiation) is taken into account, the value of rad or gray is multiplied by a quality factor to yield the units rem or sievert (Sv); 1 sievert = 100 rem.

Risk: The probability of injury, disease, or death, usually expressed as a value ranging from zero to one. In radiation protection, "risk" is shorthand for the chance that a given radiation dose will lead to death from cancer.

External dose: Dose received by a radiation source outside the body, e.g., from an x-ray machine or gamma-emitting radionuclides in soil.

Internal dose: Dose received by a radiation source inside the body, e.g., an inhaled dust particle containing plutonium or ingested tritiated water.

Clean air standards

The U.S. regulation that governs air emissions of radionuclides (excluding radon) from Department of Energy facilities is specified in 40 CFR 61 Subpart H and is administered by the EPA. (CFR stands for Code of Federal Regulations.) It specifies that the dose to the maximally exposed member of the public due to radionuclides released to the air shall not exceed 10 millirem per year.

An air dispersion model developed by EPA, called CAP-88, is generally used to estimate the doses for compliance calculations. The most recent version still uses adult dose conversion factors. According to the user guide, "Although FGR 13 contains age-dependent dose factors, CAP88-PC only uses the adult factors in order to retain consistency with previous versions."[8]

Hence, in the case of the Clean Air Act regulations (40 CFR 61 Subpart H), children are specifically excluded from the compliance calculations in order to maintain

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"consistency" with earlier compliance models. This is unjustifiable from the point of view of public health.

Nuclear Regulatory Commission

Nuclear Regulatory Commission (NRC) radiation protection regulations in the workplace and for the general public generally use Reference Man, with a minor and unsatisfactory adjustment for age in the case of some external exposure calculations. These regulations are specified in 10 CFR 20, which cover NRC licensees including all nuclear power plants and commercial fuel fabrication plants.

Workers, including pregnant ones

The regulations for workers are based on Reference Man, with one exception: pregnant workers. When a woman declares her pregnancy to her employer, the dose to the fetus must be restricted to 500 millirem for the duration of the pregnancy.

This limit was set in the 1970s to provide the fetus with the same protection as was then given to the general public, once a woman declares her pregnancy, which is, in effect, a declaration of her intent to carry the pregnancy to term. However, the maximum allowable exposure for the general public was reduced from 500 millirem to 100 millirem per year in the late 1980s, while the limit for fetal exposure in the workplace has been left unchanged.

The fetal exposure limit is obsolete by a factor of five or more. It should be reduced to, at most, that of the general public. "At most" because

- In the latter stages of pregnancy, fetal exposure results in risks that are comparable to those of infants;
- In the early stages of pregnancy, there are risks of non-cancer effects that have not yet been adequately studied or quantified and are not yet considered in radiation protection regulations; and,
- The limit does not address the radionuclide burden a woman may accumulate before she realizes she is pregnant, which will irradiate the fetus and may even be preferentially remobilized and relocated to fetal tissues.

General public

The use of Reference Man carries over to the regulations governing exposures of the general public, notably without regard to gender. A reduction in the air concentration limits derived from adult values by a factor of two is made for many radionuclides "to adjust the occupational values (derived for adults) so that they are applicable to other age groups."[9]

As with occupational exposure, the regulations for the general public ignore females in the population, despite the fact that they are the majority. The factor of two adjustment to account for the fact that the general population is exposed from childhood to adulthood does not include gender differences.

Moreover, although the factor of two is sufficient adjustment for some radionuclides and routes of exposure, such as the ingestion of cesium-137, it is inadequate for others, especially for the heightened risks of exposure early in life. For instance, for a given level of intake, the thyroid dose due to inhalation of iodine-131 in the first five years of life is over five times greater than the dose received during the entire adult lifetime, defined as ages 18 to 70 years.[10] Further, for external dose where the person is submerged in an external radiation field, the NRC regulations drop the factor of two for lifetime exposure.

The curious case of Connecticut Yankee

The perverse effect of relying on Reference Man has long been evident. For instance, in the Connecticut Yankee decommissioning proceedings, the utility argued it was only required to consider Reference Man in its decommissioning plan. In summarizing the arguments of Connecticut Yankee, the Commission, referring to its regulations that establish radiation protection standards (10 CFR 20), noted:

> Although the plain language of the regulation does not restrict the terms "critical group," "individual," or "human being" to mean any specific age, race, or gender, CY [Connecticut Yankee Atomic Power Company] argues that the regulation incorporated the Environmental Protection Agency's "Reference Man" concept, which assumes a person is a white male, age 20-30. CY contends that the critical group at Haddam Neck should be composed of resident farmers, as CY described them in its License Termination Plan, and that the "average" member is therefore an average farmer. Doses to children are therefore irrelevant, it argues.[11]

The Commission eventually ruled that the Connecticut Yankee should consider doses to children, but that:

> If the evidence shows, as CY claims it will, that doses to children are lower than doses to adults, CY will prevail without the need for an appeal. But even if the evidence shows that doses to children are higher, CY will still have the opportunity after the [NRC's Atomic Safety and Licensing] Board's final decision to argue before the Commission that our regulations prohibit considering doses to children.

The NRC's decommissioning guidance sets metabolic parameters either for Reference Man or "at the mean of the distribution for an *average human*."[12] The decommissioning guidance also states that

> The metabolic parameters were set at "***Standard*** Man" or at the mean of the distribution for an average ***man.***"[13]

Evidently, the NRC uses the term "average human" and "average man" interchangeably, which is a lamentable confusion, with significant consequences for a majority of the U.S. population.

While the NRC uses Reference Man in its overall regulations specified in 10 CFR 20, it uses a different framework in evaluating the effect of the emissions from power plants. These emissions are supposed to be kept "as low as reasonably achievable" (ALARA). The design criteria for this are specified in federal regulations 10

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CFR 50, Appendix I. The 1977 guidance for use by the NRC staff in evaluating nuclear power plant applications includes dose conversion factors for infants, four-year-olds, teenagers, and adults. In its guidance, the NRC specifies the evaluation of internal doses to the public in each of these age groups to ensure that the dose to the most exposed does not exceed ALARA guidelines. In evaluating the design of reactors to meet the ALARA criteria, the NRC's guidance, in effect since the mid-1970s, specifies parameters that enable the calculation of internal radiation doses for exposed individuals of various ages, including infants.[14] However, external radiation doses were not estimated according to age in this guidance.

Department of Energy

Reference Man is also used in the DOE guidance, "Radiation Protection of the Public and the Environment,"[15] because it uses the dose conversion factors from FGR 11. The DOE guidance allows for exceptions to the use of Reference Man, but the use of other models requires special permission and must be approved by DOE. Further, the guidance allows parametric variation, such as location of the individual in relation to the radiation source, but not variation for gender or age.

For external doses, the DOE guidance specifies using dose conversion factors for submersion from EPA's FGR 12, but also refers to a 1988 DOE document that considers a hermaphrodite model that is an improvement over the Reference Man model. The use of a lower weight (58 kilograms) and the locations of the ovaries and breasts are more appropriate than that in FGR 12, but there is still no routine consideration of children in the DOE guidance.

RESRAD

Reference Man is also built into the main computer program used by government and industry to assess risks from radioactivity remaining after remediation of radioactively contaminated sites and for projections of radiation doses from low-level waste disposal facilities. This model, called RESRAD, was developed and is maintained by DOE's Argonne National Laboratory.[16]

In the 2007 version of RESRAD, dose conversion factors for children are included, but these new libraries are not required to be used for compliance calculations. In fact, its default dose conversion factor library remains that from FGR 11, which is based on Reference Man. This version of RESRAD is an improvement over prior ones, since one can now calculate doses to children using RESRAD which was not possible with previous versions of the program without modification by the user. However, insofar as the decommissioning regulations of the NRC are based on Reference Man – and they generally are, as discussed above – the nuclear industry is still free to argue that children are not relevant to the regulations and guidance.

Obama-Waxman-EPA correspondence[17]

On May 30, 2008, then-Senator Barack Obama and Congressman Henry Waxman, then Chairman of the House Oversight and Government Reform Committee, sent a letter to then-Administrator Stephen L. Johnson of the EPA, inquiring about the use of Reference Man in EPA guidelines and standards and plans to phase out the use of the Reference Man model.

In EPA's July 24, 2008, response, Robert J. Meyers, then Principal Deputy Assistant Administrator of the EPA's Office of Air and Radiation, described the current situation as regards Reference Man as follows:

> EPA regulations, guidance documents, and procedures issued prior to 1990 (prior to ICRP Publication 60) were based on Reference [Standard] Man….For some regulatory applications, numerical values to radionuclide-specific doses – as distinct from risks – are still taken from the adult worker dose conversion factors provided in Federal Guidance Reports 11 and 12. However, for many years, our calculations of risk and our regulatory actions and guidance for environmental exposures have factored in the varying age-sensitivity of the population.

The EPA also made the following statement in the same letter:

> EPA does not believe in continued use of Reference Man, and generally stopped using it in 1990. EPA continues to update and improve its age- and gender- specific models in light of continuing research. EPA's radionuclide-specific cancer risk coefficients are used for calculating the excess cancer risk to the general population from chronic low level exposure to radionuclides in the environment. Our risk coefficients and regulatory actions are "conservative" in that they sum the risks from an entire lifetime exposure, taking into account age-dependent differences in intake, biokinetics, and sensitivity to radiation. Thus, our regulations are fully protective of the entire population, including infants and children.

We applaud EPA's declaration that it "does not believe in continued use of Reference Man."

We applaud EPA's declaration that it "does not believe in continued use of Reference Man." An explicit statement along these lines is long overdue and it is a sign of great progress that it has been made. However, the latter part of the same sentence – that the EPA "generally stopped using it [Reference Man] in 1990" is not fully consistent with the first quote from the letter in which EPA admits

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that it continues to rely on FGR 11 and FGR 12 for "some regulatory applications." Not only are these guidance documents based on Reference Man, they are applied widely, in the EPA as well as in the NRC and DOE. EPA's Clean Air Act compliance is also based on Reference Man.

Further, while the EPA letter states that "the varying age-sensitivity of the population" is factored in to its guidance, there is in fact no specific guidance that even enables a calculation of external doses to children. Children's external organ doses are estimated as if their bodies were as developed as those of Reference Man, which underestimates doses in many situations. The EPA also has not published guidance for calculating radionuclide-specific internal doses to women of any age for a given intake.

EPA does use updated lifetime risks in its calculations, but such calculations are not at issue. EPA, NRC, and DOE regulations are not based on risk but on radiation dose. If the guidance for calculating doses is based on Reference Man, then doses to women and children will be *systematically underestimated* in many situations.

The lifetime cancer incidence risk for females, using the BEIR VII risk coefficients, is about 1 in 100, if the annual dose limit of 100 millirem is maintained. This is very high; a significant tightening of radiation protection standards for the public is in order.

Hence, it is clear that the EPA did not "generally stop" using Reference Man in 1990. Rather, the use of Reference Man continues to be pervasive. And even in the cases where FGR 13 is properly applied to estimating dose that includes age-dependence, the dose conversion factors for males and females continue to be averaged, as are the risk factors.

The use of Reference Man continues to be pervasive.

We appreciate that the EPA has committed to review the gender-specific dose and risk situation in light of the publication of the BEIR VII report, as noted in its letter:

> At issue now is whether separate male and female risk coefficients should be published for the general population, given the approximate two-fold difference in risk per unit dose estimated in BEIR VII. EPA is now examining how best to account for this difference in future guidance and regulations. Any proposed changes in EPA's radiation risk assessment approach will be subjected to interagency review and public comment through the usual rulemaking and guidance development procedures.

Despite this acknowledged "two-fold" difference in risk between males and females, the EPA's letter also claims "that the BEIR VII risk estimates do not differ dramatically from those currently in use by the EPA" and that "current standards and guidance are protective." This is misleading.

Current standards are in terms of dose limits, which were largely set in the era of Reference Man. The fatal cancer risk implied by current standards[18] is all over the map, ranging from about 1 in 240 for the overall NRC dose limit of 100 millirem per year to the pathway specific limit of about 1 in 6,000 (rounded) for the 4 millirem per year drinking water limit for most beta and gamma emitting radionuclides that give a whole body dose. However, the fatal cancer risk to females is about 1 in 200 and that to males is considerably lower – about 1 in 300.

The situation is even more problematic when cancer incidence risk is taken into account. The best estimate for cancer incidence risk for women in BEIR VII is more than 60 percent higher than the EPA's estimate in FGR 13 which averages the risks for males and females. The lifetime cancer incidence risk for females, using the BEIR VII risk coefficients, is about 1 in 100, if the annual dose limit of 100 millirem is maintained. This is very high; a significant tightening of radiation protection standards for the public is in order.

Conclusions

While there has been a modest amount of progress in incorporating some recent guidance that concerns women into radiation protection, the use of Reference Man in radiation protection regulations remains pervasive. Children have often been ignored, even though the science to determine when they may get higher doses has long been available. Women are either partially included or not included at all.

Current radiation protection standards were mostly set before publication, in the last decade, of conclusions that women and children are generally at much greater risk of developing cancer than men from the same exposure. Hence, radiation protection standards are outdated in two ways that reinforce a lower level of protection for women and children:

- Radiation dose calculations done for proving compliance with regulations use dose conversion factors for Reference Man, with relatively minor adjustments in some cases. This underestimates radiation doses to children in most cases and to women in some cases for the same environmental conditions. Female children are the most adversely affected in many situations.
- Cancer risks from the same radiation dose are generally higher for children and women, though, for some specific cancers, men have a higher risk.

The failure to estimate doses to children and cancer risks to children when they are in excess of doses and risks received by adults would appear to be in violation of President Clinton's 1997 Executive Order on children, which was reaffirmed by President Bush, with some changes, in 2003:

SEE **REFERENCE MAN** ON PAGE 16, ENDNOTES PAGE 17

A growing body of scientific knowledge demonstrates that children may suffer disproportionately from environmental health risks and safety risks. These risks arise because: children's neurological, immunological, digestive, and other bodily systems are still developing; children eat more food, drink more fluids, and breathe more air in proportion to their body weight than adults; children's size and weight may diminish their protection from standard safety features; and children's behavior patterns may make them more susceptible to accidents because they are less able to protect themselves. Therefore, to the extent permitted by law and appropriate, and consistent with the agency's mission, each Federal agency:

(a) shall make it a high priority to identify and assess environmental health risks and safety risks that may disproportionately affect children; and

(b) shall ensure that its policies, programs, activities, and standards address disproportionate risks to children that result from environmental health risks or safety risks.[19]

A summary of IEER's recommendations follows.

RECOMMENDATIONS

1. **End the use of Reference Man** for estimating both dose conversion factors and cancer risk in radiation protection regulations and guidance.
2. **Calculate compliance to the part of the population receiving the highest dose.** Compliance with annual maximum exposure limits should be calculated using dose conversion factors for the portion of the population that would receive the highest radiation dose for a given set of environmental conditions.
3. **Develop and publish dose conversion factors for females.** EPA's FGR 11 should be retired and replaced with an updated version of FGR 13 with dose conversion factors and cancer risks for males and females separately (not averaged) at various ages.
4. **Develop and publish age and gender specific external dose conversion factors.** EPA's FGR 12 should be revised to include dose conversion factors at various ages for males and females.
5. **Develop and publish fetal dose conversion factors** for use in compliance calculations for cases of declared pregnancy.
6. **Fill critical gaps in early fetal dose estimation methods and put protective standards into place until then.** The assumption that the dose to the embryo/fetus in the first eight weeks of pregnancy is the same as that to the uterine wall is not valid for all radionuclides. Consideration should be given to tightening the maximum contaminant limits for tritium and alpha-emitters until a satisfactory scientific framework can be put into place.
7. **Calculate risks for those most at risk.** Lifetime risk calculations should be based on those most at risk. In general, this means that lifetime risks would be calculated for females, unless risks for specific cancers to which men are more vulnerable are being evaluated.
8. **Revise the default parameters in RESRAD.** DOE Argonne should modify the RESRAD program so that the default calculations always refer to those who would get the highest dose and are at highest risk from a given set of environmental conditions.
9. **Reduce maximum allowable fetal exposure in the workplace.** The maximum allowable fetal exposure in radiation-related workplaces (including DOE facilities and those regulated by the NRC) in cases where a radiation worker declares her pregnancy should be reduced from 500 millirem to 100 millirem using dose conversion factors for fetal exposure. This limit should be reduced when dose limits to members of the public are reduced.
10. **Publish reference characteristics for populations not adequately covered.** The EPA should examine and publish reference biological characteristics for sections of the U.S. population not adequately covered, including African Americans and Hispanics.
11. **Tighten NRC and DOE rules for maximum allowable exposure from nuclear fuel cycle and nuclear weapons facilities.** The NRC's present radiation protection standard for the general public[20] of 100 millirem per year is inadequate and obsolete, especially in light of the BEIR VII report's conclusions. The NRC should revise 10 CFR 20 for nuclear fuel cycle facilities and limit the dose from nuclear fuel cycle facilities combined to conform with 40 CFR 190, which specifies the EPA standard for dose from a single nuclear fuel cycle facility. The DOE should similarly modify DOE Order 5400.5 to reduce the maximum dose to the general public from 100 millirem per year from nuclear weapons facilities to conform with 40 CFR 190. A considerable tightening of drinking water standards for transuranic radionuclides is also in order.[21]
12. **Publish a White Paper on risk-based radiation protection.** Current radiation protection standards are based on dose limits (or maximum concentrations derived from dose limits) rather than on risk. Their risk implications are quite varied, with lifetime risk being greater for females and annual risk being generally greater for children, especially female children. Even under the tightened standard proposed here, the lifetime risk to females if the maximum dose were received each year would be about 1 in 400. We recommend that the EPA publish a White Paper on risk-based or risk-informed radiation standards where both doses and risks are calculated on a gender- and age-specific basis and where the lifetime risk to a maximally exposed individual is kept much lower than that implied by the current single fuel cycle facility limit specified in 40 CFR 190.

SEE **REFERENCE MAN** ENDNOTES PAGE 17

Endnotes

1. This article summarizes the December 2008 IEER report, *The Use of Reference Man in Radiation Protection Standards and Guidance with Recommendations for Change,* by Arjun Makhijani. (Revised April 2009). Full citations can be found in the report, at www.ieer.org/reports/referenceman.pdf. Also see the table, "Where is Reference Man?" summarizing regulatory standards in *Science for Democratic Action* vol. 15, no. 4, at http://www.ieer.org/sdafiles/15-4.pdf.
2. International Commission on Radiological Protection, *Report of the Task Group on Reference Man,* [ICRP Publication] No. 23. Pergamon Press, Oxford, 1975, p. 4
3. NAS-NRC 2006 *(Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII – Phase 2,* National Research Council of the National Academies, 2006, at http://www.nap.edu/openbook.php?isbn=030909156X.), p. 15
4. NAS-NRC 2006, p. 311
5. A "phantom" is a mannequin constructed to compute radiation doses to various parts of the body under specified radiological conditions. For instance, dose to internal organs due to an external source of radiation can be computed in this way.
6. M. Cristy and K.F. Eckerman, *Specific Absorbed Fractions of Energy at Various Ages from Internal Photon Sources – [Vol.] I Methods,* ORNL/TM-8381/V1, Oak Ridge National Laboratory, October 1987, at http://ordose.ornl.gov/documents/tm8381V1.pdf
7. Risk calculations as based on BEIR VII report, summarized in IEER's report, *Science for the Vulnerable: Setting Radiation and Multiple Exposure Environmental Health Standards to Protect Those Most at Risk,* by Arjun Makhijani, Brice Smith, and Mike Thorne (October 19, 2006, at www.ieer.org/campaign/report.pdf), pp. 27 and 38. Intake and inhalation rates are from the EPA's 1997 *Exposure Factors Handbook: Volume I – General Factors,* EPA/600/P-95/002Fa, (August 1997, at http://rais.ornl.gov/homepage/EFH_Final_1997_EPA600P95002Fa.pdf), p. 5-24 for air and p. 3-26 for water.
8. U.S. Environmental Protection Agency, *CAP88-PC Version 3.0 User Guide,* December 9, 2007, at http://www.epa.gov/radiation/docs/cap88/userguide_120907.pdf
9. R.E. Zelac, et al., *Consolidated Guidance: 10 CFR 20 – Standards for Protection Against Radiation. Final Report,* NUREG-1736, U.S. Nuclear Regulatory Commission, October 2001, at http://www.nrc.gov/readingrm/doc-collections/nuregs/staff/sr1736/sr1736.pdf, p. B-3
10. Calculated from FGR 13 dose conversion factors in the 2002 CD Supplement, with linear interpolation between the ages of 1 and 5, 6 and 10, 11 and 15, and 15 and 18 years.
11. This excerpt and the following from U.S. Nuclear Regulatory Commission, "In the Matter of Connecticut Yankee Atomic Power Company (Haddam Neck Plant), Docket No. 50-213-OLA, (License Termination Plan), December 5, 2001," CLI-01-25. IN *Nuclear Regulatory Commission Issuances: Opinions and Decisions of the Nuclear Regulatory Commission, With Selected Orders, July 1, 2001-December 31, 2001,* NUREG-0750 Volume 54, NRC, 2001, pp.368-375, at http://www.nrc.gov/reading-rm/doccollections/nuregs/staff/sr0750/nrci54.pdf, p. 372 and 374 (footnotes omitted).
12. Shepherd, et al. 2006 (J.C. Shepherd, et al., *Consolidated Decommissioning Guidance - Decommissioning Process for Materials Licensees - Final Report,* NUREG-1757, vol. 1, Rev. 2, U.S. Nuclear Regulatory Commission, September 2006, at http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1757/v1/sr1757v1r2.pdf), p. H-5. [emphasis added]
13. Shepherd, et al. 2006, Table B-2, footnote a (p. B-3). [emphasis added]
14. U.S. Nuclear Regulatory Commission, *Regulatory Guide 1.109: Evaluation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR 50, Appendix I.* Revision 1. Washington, DC: NRC, October 1977, at http://www.nrc.gov/reading-rm/doc-collections/reg-guides/power-reactors/active/01-109/01-109.pdf
15. U.S. Department of Energy, *Radiation Protection of the Public and the Environment,* (Order, DOE 5400.5, Change 2: 1-7-93), February 8, 1990; January 7, 1993, at http://www.directives.doe.gov/pdfs/doe/doetext/oldord/5400/o54005c2.pdf
16. Argonne National Laboratory, *RESRAD 6.4,* Argonne, IL, ANL, U.S.Department of Energy, 2007, at http://web.ead.anl.gov/resra/register2
17. The Obama-Waxman-EPA correspondence is reproduced as Attachments in the IEER report at www.ieer.org/reports/referenceman.pdf and also at http://www.ieer.org/sdafiles/16-1/referenceman-letters.html.
18. Average of male and female risks, using a fatal cancer risk coefficients in BEIR VII report, p. 312.
19. William J. Clinton, "Executive Order 13045 – Protection of Children From Environmental Health Risks and Safety Risks," Federal Register v. 62, no. 78 (April 23, 1997) pp. 19885- 19888, at http://www.epa.gov/fedrgstr/eo/eo13045.pdf
20. Our analysis and recommendations are focused on members of the general public (with the exception of pregnant women who are radiation workers) and on nuclear fuel cycle and nuclear weapons facilities. Specifically, we are not addressing medical, academic and other similar facilities, or the circumstances under which workers in such facilities are radiation workers or members of the general public.
21. See 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,* IEER, August 2005, at http://www.ieer.org/reports/badtothebone/index.html.

CO_2 Emissions: Coal, Gas, Nuclear

The past four Atomic Puzzlers – in SDA vol. 14, nos. 3 and 4, and SDA vol. 15, nos. 3 and 4 – challenged readers to determine carbon dioxide emissions from four different types of electricity generating sources given reasonable assumptions: a coal-fired power plant, a natural gas fired plant, a nuclear power plant with fuel enriched via gaseous diffusion, and a nuclear power plant with fuel enriched via gas centrifuge.

Here we wrap up this special puzzler series with a side-by-side comparison of the answers. The table below shows that nuclear power emits far less CO_2 per unit electricity than coal or natural gas.

Comparison of CO_2 Emissions: Coal, Natural Gas, Nuclear

Electricity source	CO_2 emitted per kilowatt-hour of electricity generated (in grams)	CO_2 emissions of nuclear power relative to coal fired power plant	CO_2 emissions of nuclear power relative to natural gas fired plant
Coal fired plant	**982**		
Natural gas fired plant	**404**		
Nuclear reactor – uranium enrichment via gaseous diffusion	**21.7**	**2.2%**	**5.4%**
Nuclear reactor– uranium enrichment via gas centrifuge	**0.502**	**0.051%**	**0.12%**

Despite this, it is not low-CO_2 energy sources that we lack. What we lack is time and money. Based on this simple rubric, nuclear fails.[1] Factor in proliferation, waste, and safety headaches[2] and it becomes clear that nuclear has no place in a sensible, economical, and safe energy future.

1. See Arjun Makhijani, *Carbon-Free and Nuclear-Free: A Roadmap for U.S. Energy Policy* (IEER Press and RDR Books, 2nd printing, 2008), at http://www.ieer.org/carbonfree/CarbonFreeNuclearFree.pdf.
2. See Brice Smith, *Insurmountable Risks: The Dangers of Using Nuclear Power to Combat Global Climate Change* (IEER Press and RDR Books, 2006), at http://www.ieer.org/reports/insurmountablerisks.

ANSWERS TO ATOMIC PUZZLER IN SDA VOL. 15, NO. 4

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

1. 110 metric ton SWU/year x 1,000 kg/metric ton = 110,000 kg SWU/year.
110,000 kg SWU/year x 55 kilowatt-hours/kg SWU = 6.05 × 10^6 kilowatt-hours/year.

2. 6.05 × 10^6 kilowatt-hours/year x 0.46 = 2.783 × 10^6 kilowatt-hours/year from coal.
2.783 × 10^6 kilowatt-hours/year from coal x 982 grams CO2/kilowatt-hours from coal = 2.733 × 109 grams CO_2/year = 2.733 × 106 kg CO_2/year from coal.
6.05 × 106 kilowatt-hours/year x 0.41 = 2.480 × 106 kilowatt-hours/year from natural gas.
2.480 × 106 kilowatt-hours/year from natural gas x 404 grams CO_2/kilowatt-hours from natural gas = 1.002 × 10^9 grams CO_2/year = 1.002 × 10^6 kg CO_2/year from natural gas.
Total = 2.733 × 10^6 kg CO_2/year from coal + 1.002 × 10^6 kg CO_2/year from natural gas = 3.735 × 10^6 kg CO_2/year.

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

4. 3.735 × 10^6 kg CO_2/year from LES / 7.446 × 10^9 kilowatt-hours/year from reactor = 0.000502 kg CO_2/kilowatt-hour.

5. 0.000502 kg CO_2/kilowatt-hour for nuclear / 0.982 kg CO_2/kilowatt-hour for coal = 0.00051 = 0.051%.
0.000502 kg CO_2/kilowatt-hour for nuclear / 0.404 kg CO_2/kilowatt-hour for natural gas = 0.0012 = 0.12%.

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