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Healthy from the Start:

Building a Better Basis for Environmental Health Standards—Starting with Radiation

BY ARJUN MAKHIJANI, BRICE SMITH AND MICHAEL C. THORNE[1]

The last half century has seen great progress in environmental health protection. As part of this progress there has been a growing awareness that the focus must be the protection of those most at risk. The protection of children, in particular, has grown significantly in prominence. In the United States for example, President Clinton in 1997 issued Executive Order 13045, Protection of Children From Environmental Health Risks and Safety Risks. This Executive Order was endorsed with amendments in 2003 by President Bush.

There has also been a great deal of progress in radiation protection. The International Commission on Radiological Protection (ICRP), the U.S. Environmental Protection Agency (EPA), and the Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation of the National Research Council of the U.S. National Academies of Science (known as the BEIR committee) have all made significant contributions by developing age-specific and sex-specific dose and risk factors. However, regulations have generally not kept pace with the overall trend in environmental health protection or with important developments in the scientific understanding of radiation risks.

In fact, as our knowledge has grown, the gaps in the regulatory framework have become more evident. For example, many U.S. regulations remain focused on estimating the dose received by a hypothetical

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Radiation exposures in utero *can lead to a heightened risk of cancer and other ill-health effects, yet most radiation protection standards still are based on "Reference Man," a hypothetical adult male.*

Help strengthen radiation protection standards
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Health Risks of Tritium:

The Case for Strengthened Standards

BY ARJUN MAKHIJANI, BRICE SMITH AND MICHAEL C. THORNE[1]

Part of the inspiration for IEER's project to reorient radiation standards to the protection of those most at risk came from a simple realization about the simplest radionuclide, tritium. Tritium is a form of radioactive hydrogen with two neutrons in the nucleus. Ordinary hydrogen has no neutrons while deuterium, a stable isotope of hydrogen, has one neutron.

All three hydrogen isotopes behave almost the same chemically. Therefore tritium (T) can replace hydrogen to form tritiated water (i.e. HTO or T_2O).[2] Tritium decays via the emission of a beta particle, and is thereby transformed into a stable isotope of helium (He-3). With a relatively short half-life of 12.3 years, tritium is highly radioactive. For example, one gram (approximately the weight of a quarter of a teaspoon of salt) of tritium in tritiated water will contaminate

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"Reference Man," defined as a 154-pound "Caucasian" male in his twenties. Children, when they enter the radiation protection picture at all, are still often viewed simply as little adults. A crucial manifestation of this problem is that the Reference Man model is built into the main computer program, called ResRad, that is used to assess future risks from radioactivity in the environment. In addition, while cancer risks may dominate for adults, other risks may be important for other age ranges. The problems of early miscarriages, malformations, or neurological impacts, for example, are not within the existing regulatory framework. While much scientific work is needed, interim strengthening of regulations is justifiable in many areas, based on present-day understanding.

The risks we are considering are those associated with exposure to low-level radiation from environmental contamination. "Low-level" exposure is defined as that which does not produce deterministic effects, such as skin rash, hair loss, etc. It also encompasses high cumulative doses received at a relatively slow rate over a period of time.

The connections between radiation and gene mutation and cancer have been extensively studied. In fact, these connections were first discussed during the late 1920s and early 1930s. Over time, radiation protection efforts have come to focus on cancer as the health outcome of greatest concern.

The framework of radiation protection

It is widely accepted (including by the U.S. National Academy of Sciences) that the best model of the cancer risk of radiation at low doses and low dose rates is the Linear No-Threshold Hypothesis (often abbreviated as LNT hypothesis or LNTH). It states that every increment of radiation exposure, no matter how small, produces a corresponding and proportional increment of cancer risk. This model applies to all solid tumors, which includes most cancers, but not leukemia. The no-threshold hypothesis is also applied to leukemia, but the dose-risk relationship is not linear, in other words not directly proportional to exposure.

Radiation protection has emphasized the development of a unified approach, where the impacts of a variety of external and internal exposures are squeezed into a single framework. This allows different types of radiation exposure to be aggregated. However, this approach involves considerable simplifications, and there has been a tendency to become fixed within a particular paradigm, i.e., cancer risk. For instance, the effects of radiation on mental abilities were not recognized until the late 1970s, a remarkable lapse given the early observations at Hiroshima and Nagasaki of microcephaly, a rare disorder in which the head is undersized.

The first dose limits in the United States were adopted in the early 1930s, but it was during the atom bomb program that radiation protection underwent its most important evolution. As a result, the primary focus was on protecting the workers in the nuclear weapons' complex. The first post-war revision of the standards came in 1954 and the first separate standard for the general public was set in 1959. See the chronology of radiation standards on pp. 8–9.

It was also during the 1950s that the focus on young males was officially incorporated into radiation protection. This focus evolved

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over time and, in 1975, the ICRP published their recommendations for a model known as Reference Man. The ICRP was quite explicit in its 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.[2]

Newer definitions of reference individuals have been published, including by the ICRP, which has set forth its revision in ICRP 89:

> Moving from the past emphasis on 'Reference Man', the new report presents a series of reference values for both male and female subjects of six different ages: newborn, 1 year, 5 years, 10 years, 15 years, and adult. In selecting reference values, the Commission has used data on Western Europeans and North Americans because these populations have been well studied with respect to an[a]tomy, body composition, and physiology. When appropriate, comparisons are made between the chosen reference values and data from several Asian populations.[3]

But the ICRP's 1975 Reference Man approach remains the one in primary use in U.S. radiation protection efforts, since it is the basis of the guidance report on which most of the EPA's regulations are based, Federal Guidance Report 11, published in 1988.

As the risk of developing cancer from exposure to radiation was found to be greater than originally thought, the regulations were tightened over time. By 1990 the dose limit for the public had been lowered to 100 millirem per year, a factor of five lower than its 1959. By this time, stricter standards also had been introduced by the EPA to control exposures from single nuclear facilities by all pathways and from a single pathway, such as drinking water or air. In 1991, the ICRP recommended that the worker limit be reduced to 2 rem per year. While this recommendation has been ignored in the United States, it has been adopted in Germany and in a somewhat modified form throughout the European Union.

In brief, much has been learned and the regulations have been improved over the years. However, neither the regulations nor the research has yet been fully oriented to protecting the most vulnerable. This is changing so far as research is concerned. For example, the U.K. Environment Agency is undertaking research on phosphorus-32 and phosphorus-33 because these radionuclides have substantially higher impacts on the embryo/fetus than on other age groups. There are also other signs that the focus of radiation protection is beginning to shift.

Women

In 1990, the fifth BEIR report (BEIR V) affirmed the Linear No-Threshold Hypothesis for solid cancers, and estimated that the risk of radiation exposure was considerably higher than estimated in prior official studies. At that time, the fatal cancer risk to women was thought to be about 5 percent greater than to men for the same level of exposure. Since 1990, much has changed. In 1999, the EPA published Federal Guidance Report 13 (FGR 13), in which they concluded that the cancer mortality risk due to radiation exposure was 48 percent higher for women than for men. The higher risk to women was affirmed in 2006 by the seventh BEIR report (BEIR VII) which found that the risk for females exceeded that of males by 37.5 percent.

The more biologically relevant estimate of risk, however, is not cancer mortality, but cancer incidence, since fatality rates depend on the evolution of medical capabilities. Considering cancer incidence makes the differences between men and women even more pronounced. In FGR 13, the EPA estimated that women would be 58 percent more likely to develop cancer than men for the same level of exposure. The BEIR VII Committee estimated the figure at 52 percent. See Figure 1 and Table 2 on pp. 8–9.

The risks of developing certain organ-specific cancers reveal even greater differences. The organs most responsible for the heightened risk of women in FGR 13 were the breast, colon, lung and ovary. In BEIR VII, the most important organs are breast, lung, thyroid and ovary, while the colon was estimated to be less radiosensitive for women than for men. See Table 3 on page 9.

Of particular note, given the importance of breast cancer, the BEIR VII report cited evidence that suggests radiation may interact synergistically with other risk factors for breast cancer. This raises the possibility that endocrine disrupting chemicals like PCBs and dioxins might act to increase the risks associated with radiation beyond that which would be caused by either separately.

Despite these well-documented differences, the EPA continues to average the risk to men and women in setting regulations. Although the use of the average captures the risk to a large population, it does not make sense at the level of the individual. In effect, there is an implicit discrimination against women in the EPA's approach.

If current dose limits were updated to protect women using the EPA's estimates of mortality risk, the dose limits would be reduced by about 18 percent. If the standards were updated to reflect the most recent estimates of cancer incidence published by BEIR VII, dose limits would be reduced by about a factor of two compared to the present.

For workers, the protection of women within the present framework but with updated risk factors would

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reduce the dose limit from 5 rem per year to between 3 and 4 rem per year. If the same logic is applied to the 2 rem per year standard in use in Europe, the standard should be tightened to about 1.5 rem per year. Such a reduction would require changes, but it would not be expected to pose undue obstacles.

Additional questions regarding women's health arise in the context of medical radiation. For example, the use of mammography involves deliberate exposure to radiation and therefore increases the risk of cancer. However, at the same time, it potentially increases the chances of successful treatment if a cancer exists. The risks and benefits of mammography are beyond the scope of this article (and the report on which it is based). However, we do note that health professionals have an important obligation to explain the risks and expected benefits of the procedure, to receive the informed consent of the patient, and to keep exposures as low as reasonably achievable.

Children

It is not a new realization that children are often the most vulnerable population when it comes to environmental threats. In fact, a major turning point in the history of pediatric environmental health was the formation of the Committee on Radiation Hazards and Epidemiology of Malformations by the American Academy of Pediatrics in 1957 as a result of a growing awareness that the impacts of nuclear weapons testing were disproportionately affecting children due to iodine-131 in fallout. Despite this history, it was not until the Chernobyl disaster in 1986 that there was a widespread recognition of the need to accurately determine radiation doses to children. Efforts undertaken in the wake of the accident led to the development of age-specific dose conversion factors for ingestion and inhalation.

The consideration of the risks to children is complicated by multiple factors. Except for unique pathways such as the consumption of milk or the intentional ingestion of soil, children often have lower intakes than adults (e.g., amount of air, food and water taken in every day). On the other hand, children can receive a higher dose than adults from the same level of ingestion. Also, the risk per unit of dose for children is higher than for adults. For example, the BEIR VII panel estimated that the risk of developing cancer from exposure as a young child (0 to 5 years) is 2.6 times greater for a boy than the risk for a 25 year old adult male and 3.0 times greater for a girl than the risk for an adult female. In addition, the difference between the risks to males and females is significantly more pronounced in early childhood. This is illustrated in Figure 2 and Table 4 on pp. 8–9.

While in some cases these factors combine to make the adult's risk the highest, in other cases the risk to children is highest. To illustrate this, we consider two specific examples. Even after taking lower total level of intake by children into account, we find that the cumulative thyroid cancer risk accumulated over the first five years of exposure by females from drinking milk contaminated with iodine-131 exceeds that accumulated over their entire adult lifetimes, assuming that the food and water consumed has the same level of environmental contamination at all ages. As a second example, we found that the breast cancer risk accumulated by female children over the first five years of exposure from drinking water contaminated with strontium-90 is greater than that accumulated over their entire adult lifetimes, for the same concentration of strontium-90 in the water.

The embryo/fetus

It has been known since the late 1950s that radiation exposures *in utero* can lead to a heightened risk of leukemia and other cancers. In addition, a variety of other ill-health effects can result from exposure to radiation *in utero*. As such, any effort to reorient radiation standards to the protection of the most vulnerable must include a discussion of the embryo/fetus.

We are, of course, aware of the sensitivities of this topic. The status and even the definition of the embryo/fetus in society has been a topic of serious contention. We do not seek here to enter that debate. Unlike the issues of abortion and contraception, which relate to the rights of women versus the assertion of authority by the State or organized religion when the woman does not want to be pregnant, the issues that concern this work are centered on society's environmental responsibilities when a woman decides that she wants to become or stay pregnant.

The risks to the embryo/fetus are much less understood for the early period of embryonic development (0 to 14 weeks). It appears likely that the main risk in the first two weeks is a failed pregnancy. It would be very difficult to detect any early failed pregnancies caused by radiation due to the very high rate of natural, or presumably natural, early failed pregnancies. Research definitively indicates that above certain levels of radiation, an early failed pregnancy is the result. Whether there is a threshold or whether some women may be more susceptible than others is not possible at present to say.

Malformations are also a special risk in early pregnancy, when organs are being formed. Once formed, the growth of organs entails a high rate of cell proliferation, giving little time for repair mechanisms to function. This makes particular organs or systems of the embryo/fetus sensitive to damage during later development. This can be a particular concern for systems that develop over a long period of time — and this vulnerability can continue into childhood. For example, the central nervous system is known to be more susceptible to damage from radiation exposure *in utero* and in early childhood, since

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its development continues after birth. Multigenerational risks are also involved for females because their ova are formed while they are *in utero*. In addition, it has been demonstrated in animals that prenatal irradiation can interact synergistically with chemical carcinogens. This may be a particular concern for human health given the large number of chemicals that are known to cross the placental barrier.

To date, children and the embryo/fetus have been given specific regulatory consideration only in relation to medical and occupational exposures. Over time, U.S. regulations were enacted that set the dose limit for the embryo/fetus over the course of the pregnancy to the same value as the annual dose limit for a member of the public, which was set at 500 millirem in 1959. This limit comes into effect only when a woman voluntarily declares her pregnancy in a notice to her employer. If the 500 millirem limit has already been exceeded at the time of the woman's declaration, the exposure of the fetus over the rest of the pregnancy is limited to 50 millirem.

The voluntary nature of this declaration means that there would be no point in declaring a pregnancy that

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COMBINED EFFECTS OF CHEMICALS AND RADIATION

Ionizing radiation can cause breaks in DNA, some of which may remain unrepaired or may be misrepaired by the body. The consequences of such failures of repair include cell death and mutation. Chemical toxins can also damage DNA. Chemical toxins generally affect particular chemical compounds and particular biochemical pathways in the body. In addition to damaging DNA, chemicals can have other impacts, such as suppression of ability of the immune system to detect and remove malignant cells. Therefore, despite the highly specific nature of the damage caused by individual chemicals, the wide range of toxins to which humans are exposed makes the range of adverse effects from chemicals more diverse than is observed with radiation.

In most cases, the primary risk from radiation exposure is cancer. (See tritium article on page 1 for a discussion of non-cancer effects.) The development of cancer is generally a multi-stage process in which more than one mutation is necessary for the disease to manifest itself. Complicating this picture is the fact that even a single clinically characterized type of cancer may arise by multiple alternative pathways from a normal cell to a cancerous cell.

Because of the multi-stage nature of the disease, exposure to multiple toxins that affect different stages in the process can thus cause damage in excess of that expected from simply adding the individual impacts of each toxin in isolation. This more-than-additive effect of exposures to multiple toxins is referred to as a synergism or synergistic effect. For instance, the suppression of immune-surveillance by a chemical after exposure to radiation could cause such an effect. Conversely, if two chemicals affect unrelated biochemical pathways, then exposure to one may have no affect on the likelihood or severity of adverse outcomes induced by the other.

The non-specific nature of the damage that radiation causes, and the generally long period between exposure and expression of an associated cancer, suggest that radiation primarily has a role in the early stages of cancer development. Chemicals that also cause non-specific damage to DNA might be expected to act similarly. Therefore, exposures to radiation and such chemicals could reasonably be treated as additive. However, most chemicals will induce a particular type of damage or will have effects other than damage to DNA. In these circumstances, a synergistic effect between ionizing radiation and chemical toxins is readily envisaged and may be the norm.

One example where the synergistic effect between exposure to radiation and chemical toxins is discernable from human epidemiological data is the interaction between radon and smoking. Studies of uranium miners indicate that the carcinogenic impact of radon may be increased by roughly three-fold when it is combined with exposure to tobacco smoke. The potential scale of such a synergistic interaction, if it also applies between indoor radon and smoking, indicates that synergisms can be a major public health issue.

Another case where synergisms may arise is from exposure in the womb to radiation and endocrine disruptors like diethylstilbestrol (DES) or dioxins. In such cases, there is the potential for a synergistic interaction between the radiation, which can cause mutations, and the endocrine disruptors, which alter the environment in which those cells develop and can also predispose toward cancer development. A heightened risk of breast cancer may be of particular concern in such cases.

A further example arises from the fact that a wide range of metal salts are known to interfere with the repair of DNA damage induced by x-rays or ultraviolet light. As such, a synergistic effect between exposures to radiation and to metals or semi-metals, such as arsenic, cadmium, mercury and nickel, is to be expected.

Finally, in some cases, interactions between radiotoxic and chemically toxic effects may arise from an exposure to a single substance. Work being conducted at the Armed Forces Radiobiology Research Institute has highlighted this possibility for exposures to uranium (see SDA, vol. 13 no. 2, June 2005).

In summary, the multi-stage nature of cancer development makes it highly likely that synergistic effects will exist between radiation and some kinds of toxins. Thus, when considering the development of radiological protection standards, it is proper to bear in mind that variations in sensitivity will arise not only due to age and sex, but also due to exposure to toxic chemicals that will interact with radiation in complex and poorly understood ways.

Based on Chapter 6 of *Science for the Vulnerable: Setting Radiation and Multiple Exposure Environmental Health Standards to Protect Those Most at Risk* (IEER, 2006). The chapter was written by Mike Thorne. This summary was prepared by Brice Smith.

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a woman has decided to terminate. Therefore, the philosophy that the developing fetus should be protected in the same manner as the general public is not in conflict with a woman's ability to decide to terminate her pregnancy. The present approach of voluntary pregnancy declarations has worked well to protect women's rights as well as limit doses to the embryo/fetus. This approach can be maintained until the larger and more complex questions surrounding these issues can be addressed.

However, the specific dose limit of 500 millirem to the embryo/fetus has been obsolete for more than fifteen years, since the annual dose limit for exposure to the general public, which was the reference point for fetal exposure when the limit was first adopted, was lowered to 100 millirem per year by the Nuclear Regulatory Commission in 1991.[4] Hence, the maximum dose limit to the embryo/fetus in the case of a declared pregnancy in the workplace should be reduced to 100 millirem. This also would be consistent with the limit recommend by the European Atomic Energy Community (EURATOM) and adopted into national law in Germany.

There is, however, a gap in this framework in the sense that an embryo/fetus might accumulate considerable exposure before the pregnancy declaration. Since radiation may have certain deleterious impacts in the first few weeks post-conception, this gap needs to be addressed. This raises the question of whether standards should be set that are adequately protective of women of child-bearing age without them having to declare themselves pregnant. This is a complicated matter, however, especially as it could place constraints on women's role in providing medical care where staff exposures can be relatively high. (The protection of sperm is addressed in the next section.)

A related concern is the need for a U.S. standard for workers who are breast-feeding to protect the infant from radionuclides that may be passed through the breast milk. Germany has already adopted a EURATOM directive that allows women who voluntarily declare that they are breast feeding to be assigned work that does not involve the risk of internal contamination with radionuclides. A similar standard should be adopted in the United States.

Men as prospective fathers

Despite the focus on Reference Man, regulators have not yet taken into account the fact that nature has given a reproductive role to men, even if it is rather modest by comparison with the role of women. There is some evidence that the progeny of men who were exposed around the time of conception have an increased risk of cancer. However, this is an area where research is extraordinarily difficult and the results are uncertain and to a large extent unclear from the point of view of causation.

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Despite the focus on Reference Man, regulators have not yet taken into account the fact that nature has given a reproductive role to men, even if it is rather modest by comparison with the role of women.

Among the best known studies indicating an increased risk of leukemia among offspring of fathers exposed to radiation is the study done by M. J. Gardner *et al.* in the vicinity of the Sellafield nuclear installation in Britain. However, another review attributed the observed increase in this case to the small numbers of cancers involved. Another assessment was carried out by Sever *et al.* under contract to the U.S. Department of Energy for workers at three U.S. nuclear weapons plants (Hanford, Idaho National Laboratory, and the K-25, Y-12, and X-10 facilities at Oak Ridge) and their children. This study found no statistically significant association between the risk of cancer in children and the occupational exposure of their fathers.

One major limitation of these studies, however, is that they focused on external radiation exposure. The only internal dose estimate used by Sever *et al.* was for tritium, and even then it was only used where data was available and hence likely to be incomplete. Conditions at these plants were conducive to significant internal exposures. Just because records cannot be found does not lead to the conclusion that exposures did not occur. In fact, data on internal exposure at many nuclear weapons facilities from the early years tend to be rather sparse because many workers were not monitored or were only partially monitored.

A second problem with the epidemiological studies is that the external exposure data are generally unreliable tools for estimating the external doses to particular

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organs, like the gonads. If the external exposure field is not uniform, the badge data may have very limited utility in accurately estimating exposure to the gonads. In addition, the film badges only record the deep gamma dose. While the beta dose received by uranium processing workers, for instance, is unimportant for most organs given the weaker penetrating power for beta particles, high energy beta radiation could affect the testes.

More direct evidence of the effects of radiation on sperm were indicated in a 1975 paper by Popescu and Lancranjan. This work found an increased incidence of weak sperm, low sperm counts, and malformed sperm in the exposed population. Since this work involved direct study of sperm and since all of the subjects were chosen to be otherwise healthy, the results can be regarded as more reliable than the epidemiologic studies discussed above. The Popescu and Lancranjan study indicates that gonadal exposure may be more problematic and involve much broader concerns than has been recognized so far in radiation protection.

Conclusions and recommendations

Generally, radiation protection regulations, including those in the United States, are geared almost solely to cancer risk and omit other risks. Our recommendations here are focused on the United States, but most of them are likely to have broader applicability. For instance, concern regarding early miscarriages and malformations are absent from the regulatory arena. There are no regulations that govern exposure to men who plan to become fathers. Even in the context of cancer, the higher risk of women and children is not reflected adequately in standards. U.S. radiation protection standards for workers generally, and for women who voluntarily declare their pregnancies in particular, are far more lax than those in the European Union. Unlike in Germany, there are no standards in the United States specifically designed to protect breast-fed children.

In addition, the cancer risks of combined exposure to radiation and toxic chemicals are not currently considered; neither are non-cancer risks, including those that may aggravate cancer risk. In particular, consideration of damage to the immune system as a result of radiation exposure, notably from radionuclides like strontium-90 and uranium, or as a result of combined radiation and chemical exposure, is absent from the regulatory landscape.

For a start, replacing the concept of "Reference Man" with a framework for protecting those most at risk should be straightforward at least in principle, though we recognize that actually accomplishing this goal could be quite complex. As a first step, U.S. regulations should be modified to take into account the higher cancer risk experienced by women, and as a result the current dose limits should be immediately lowered by about one-third across the board. Further, the permissible exposure of the embryo/fetus in the workplace after a woman declares her pregnancy should be reduced to 100 millirem and a regulation protecting breastfeeding infants should be created.

To facilitate the protection of the most vulnerable, the government's computer program used to assess radiation doses from environmental radioactivity (called ResRad) must be modified to include as a standard function the ability to calculate doses to infants and children. We also recommend that the source code be made freely available so that it can be modified independently of government action to account for non-cancer risks as well as doses to breast-fed infants and the embryo/fetus.

We recognize that a major problem in setting more protective standards remains the lack of adequate knowledge on which to base them. Therefore, broader and more intensive research is needed. In particular, it is essential that the federal government initiate or intensify research to better understand the health effects of combined exposure to radiation and toxic chemicals. This research effort must tap the vast knowledge at the grass-roots that has been gathered in large measure by mothers concerned about their children's health.

Given the importance of the developing immune system, special research attention should be devoted to radionuclides like strontium-90 which preferentially affect it. Similarly, uranium, tritium, carbon-14 and radioactive isotopes of iodine require special attention, including when exposure is experienced in combination with certain chemicals like endocrine disruptors.

The time is long overdue to abandon the grossly outdated focus in radiation protection on a 154-pound "Caucasian" male. It is vital that the radiation protection community keep pace with efforts to make the most vulnerable the center of environmental protection efforts and to accelerate the inclusion of the most up-to-date science concerning the risks of radiation to women, men as prospective fathers, children, and the embryo/fetus into the regulatory framework.

1 Arjun Makhijani, Ph.D., is president of IEER. Brice Smith, Ph.D., is senior consultant to IEER and assistant professor of physics at SUNY-Cortland. Mike Thorne, Ph.D., is a private consultant and an expert on radiological protection and environmental transport of radionuclides. This article is based on the October 2006 IEER 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. The report can be accessed on the Web at www.ieer.org/campaign/report.pdf. The report was summarized for this article by Dr. Smith. References can be found in the report.

2 ICRP 23, p. 4.

3 ICRP 89, p. 5.

4 The regulation is published at 10 CFR 20.1301.

5 Some of our recommendations are based on stricter standards already in force in all or part of the European Union.

Radiation Protection Standards in the U. S.: Some Nuts and Bolts

TABLE 1: CHRONOLOGY OF EXTERNAL RADIATION EXPOSURE STANDARDS IN THE UNITED STATES

1931–34	1940–41	1942	1951	Mid-1950s
U.S. Advisory Committee on X-Ray and Radium Protection (precursor to the National Council on Radiation Protection and Measurements) adopts X-ray "tolerance dose" of 0.1 roentgen per day.	U.S. Advisory Committee proposes, but does not implement, lowering the X-ray tolerance dose to 0.02 roentgen per day.	U. of Chicago Metallurgical Laboratory adopts a "maximum permissible exposure" standard of 0.1 roentgen per day. Becomes standard for entire Manhattan Project.	National Bureau of Standards reduces the limit of external whole body radiation to 0.3 roentgen per week.	Atomic Energy Commission (AEC) adopts National Bureau of Standards recommended maximum long-term dose limit of 5 rem per year. Sets additional limits for internal exposures at 15 rem per year for most organs.

Table adapted from SDA vol. 6, No. 2, 1997. For external radiation sources, roentgen and rem are considered to be equivalent.

OFFICIAL DEFINITION OF "REFERENCE 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."

— 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. Incorporated by reference into EPA's Federal Guidance Report Number 11.

WHO'S WHO IN U.S. RADIATION PROTECTION

A number of bodies study radiation or regulate it. Some of the principal ones (as they concern the United States) are:

EPA: U.S. Environmental Protection Agency. The EPA issues official guidance documents on radiation, called Federal Guidance Reports (FGRs), which give a regulatory imprimatur to the science, allowing it to be used in regulations (though it may or may not actually be used). FGR 13 is the most current EPA guidance but FGR 11 is the one used in regulations.

BEIR COMMITTEE: Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation (formerly called the Committee on the **B**iological **E**ffects of **I**onizing **R**adiation) of the National Research Council of the National Academy of Sciences. Committees are empanelled roughly once every ten years to review the effects of ionizing radiation. The BEIR reports are influential for standard setting bodies, like EPA. The BEIR VII report (2006) is the most recent report in the series.

NCRP: National Council on Radiation Protection and Measurements, a scientific advisory body.

NRC: Nuclear Regulatory Commission. The NRC regulates commercial nuclear power plants and commercial licensees using or processing nuclear materials. It also sets standards for public and worker exposure from such facilities and for decommissioning of commercial nuclear facilities.

FIGURE 1: CANCER INCIDENCE RISK PER UNIT OF RADIATION EXPOSURE

EPA Federal Guidance Report 13 and BEIR VII report

The BEIR VII report shows an increase in the risk of radiation exposure for both sexes, while both reports agree that women are at a higher risk compared with men.

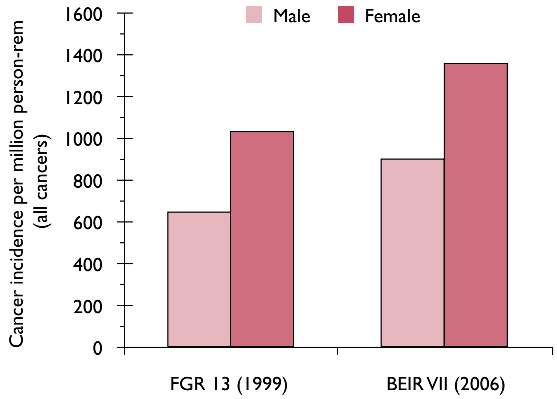
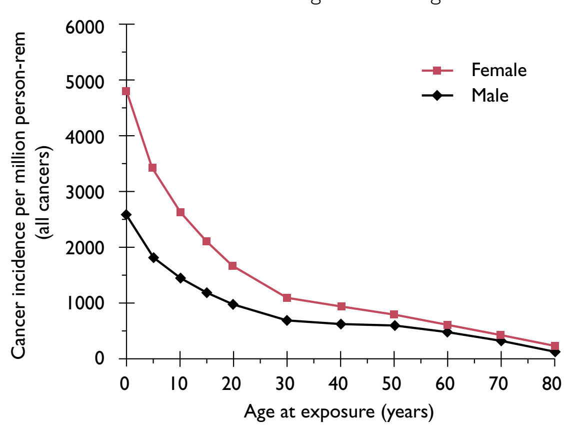


FIGURE 2: CANCER INCIDENCE PER UNIT OF RADIATION EXPOSURE

Source: BEIR VII

The change in cancer risk for people under the age of 20 is steeper for females than males, indicating a difference between their risks. The exposure occurs at the stated age; the risk is over the lifetime remaining after that age.



1959	Late 1980s – 1990	1991
Dose limit for workers remains 5 rem per year. AEC also adopts dose limits for the public equal to one-tenth of those allowed for workers: 0.5 rem for external exposure; and 1.5 rem for most organs for internal exposure.	Department of Energy (DOE) adopts dose limit for the public of 100 millirem (0.1 rem) per year; dose limit for workers remains 5 rem per year. A new model for calculation of internal doses to workers is adopted, the "committed effective dose equivalent."	International Commission on Radiological Protection recommends worker dose limit be reduced to 2 rem per year. Recommendation is not adopted by DOE. Nuclear Regulatory Commission adopts 100 millirem limit for the general public.

TABLE 2: CANCER INCIDENCE AND FATALITY ESTIMATES PER MILLION PERSON-REM

Lifetime dose, BEIR VII report – best estimates

(Estimates corresponding to 90 percent confidence interval are shown in parentheses)

	Males, solid cancers	Females, solid cancers	Males, leukemia	Females, leukemia	All cancers, males	All cancers, females	Ratio, female to male
Incidence (all cases, fatal and non-fatal)	800 (400, 1600)	1,300 (690, 2500)	100 (30, 300)	70 (20, 250)	900	1370	1.522
Fatal cases only	410 (200, 830)	610 (300, 1200)	70 (20, 220)	50 (10, 190)	480	660	1.375

TABLE 3: RATIO OF CANCER INCIDENCE RISK, WOMEN TO MEN

As estimated in FGR 13 and BEIR VII

	FGR 13	BEIR VII
Esophagus	2.18	included in residual
Stomach	1.50	1.26
Colon[a]	1.48	0.60
Liver	0.63	0.44
Lung[a]	1.55	2.14
Bone	1.02	included in residual
Skin	1.10	included in residual
Bladder	0.46	0.96
Kidney	0.61	included in residual
Thyroid[a]	2.14	4.76
Residual[b]	1.20	0.93
Leukemia	0.73	0.72
Total	**1.58**	**1.52**

NOTES: (a) These are the organs most responsible for the heightened risk of women compared to men. In FGR 13, the most important single organs are, in descending order, breast, colon, lung and ovary. In BEIR VII, the most important organs are breast, lung, thyroid and ovary, while the colon is now estimated to be less radiosensitive for women than for men. (b) The risk to men of developing breast cancer was assumed to be zero in both reports, but men do have a low rate of breast cancer in the general population and would, as such, be expected to have a small incremental risk of breast cancer from exposure to radiation. Ratios for breast and ovarian cancer are not shown since one is very rare in men and the other does not occur in men.

TABLE 4: CANCERS PER MILLION PERSON-REM OF EXPOSURE

		Colon	Lung	Breast	Thyroid	Leukemia	All solid cancers	All cancers
Infant	Female	220	733	1171	634	185	4592	4777
	Male	336	314	N/A	115	237	2326	2563
Age 5 Yrs	Female	187	608	914	419	112	3265	2277
	Male	285	261	N/A	76	149	1667	1816
Age 30 Yrs	Female	82	242	253	41	63	1002	1065
	Male	125	105	N/A	9	84	602	686
Ratio, Infant : 30 yrs	Female	2.68	3.03	4.63	15.46	2.94	4.58	4.49
	Male	2.69	2.99	N/A	12.78	2.82	3.86	3.74

Tables and charts from *Science for the Vulnerable: Setting Radiation and Multiple Exposure Environmental Health Standards to Protect Those Most at Risk* (IEER, 2006), on the Web at: www.ieer.org/campaign/report.pdf. Sources for table and chart data: BEIR VII report (2006) and EPA's Federal Guidance Report No. 13 (1999). See *Science for the Vulnerable* for more information.

TRITIUM
FROM PAGE 1

almost 500 billion liters of water up to the current drinking water limit of 20,000 picocuries per liter set by the U.S. Environmental Protection Agency (EPA). One ounce of tritiated water (HTO) would contaminate the entire annual flow of the Savannah River above the present drinking water limit.[3]

In addition to forming tritiated water, tritium can also displace non-radioactive hydrogen in other types of chemicals. Tritium that is part of a carbon-tritium bond is difficult to remove and is therefore referred to as non-exchangeable organically bound tritium (OBT). Animal studies indicate that one to five percent of the tritiated water in mammals is incorporated into organic molecules inside the body.

> Low-energy beta particles, like those emitted by tritium, are often much more effective at causing harm than currently assumed by regulations.

From these observations, it is clear that tritiated water and organically bound tritium can cross the placental barrier. This tritium can then be incorporated into an embryo/fetus and irradiate rapidly dividing cells, thereby raising the risk of birth defects, early miscarriages, and other problems.[4] Tritium therefore provides an important case study for examining how radiation protection standards need to be changed in light of risks to those who are not adult men.

Deficiencies in the regulations

The scientific models used to evaluate the adverse health impacts of tritium have a number of serious weaknesses. For example, the models assume tritiated water is uniformly distributed throughout the body. As a result, the EPA predicts that all organs, except for portions of the gastrointestinal tract, receive the same dose for a given intake of tritium. However, tissues with a high water content would be expected to receive a higher dose than tissues like bone or fat. Fetal tissues have higher water content than maternal ones. As a result, tritiated water is likely to be present in higher average concentrations in fetal tissues, and this is indicated by animal studies. Furthermore, if organically bound tritium becomes incorporated into DNA, it does not uniformly irradiate the whole cell; it preferentially irradiates the nucleus. Hence, the risk of damage to the DNA and of adverse health effects (including cancer but not only cancer) is considerably greater than if the tritium expended its energy in the cytoplasm of the cell.

> Tritiated water and organically bound tritium can cross the placental barrier.

Finally, the models used to evaluate the dose received by the embryo in the first several weeks of pregnancy are seriously deficient. Current models assume that the dose to the embryo for the first eight weeks is the same as the dose received by the uterine wall. This is a reasonable assumption only for penetrating gamma rays. It does not apply to alpha-emitting radionuclides like uranium; nor does it apply very well to radionuclides like tritium that emit relatively low-energy beta particles.[5] This is because alpha particles and low-energy beta particles do not travel very far, and thus the damage they cause is more localized than that from gamma rays.

Tritium's damage potential

A related concern is the fact that low-energy beta particles, like those emitted by tritium, are often much more effective at causing harm than currently assumed by regulations. The effectiveness of different kinds of radiation in causing damage is taken into account by the "relative biological effectiveness" (RBE) factor. Current standards generally assume that gamma rays, x-rays,

SEE **TRITIUM** ON PAGE 11, ENDNOTES, PAGE 12

TABLE 1: INTEGRATED RELATIVE BIOLOGICAL EFFECTIVENESS OF TRITIATED WATER AND ORGANICALLY BOUND TRITIUM

Age group	Form of tritium	5% Confidence limit	Median	95% Confidence limit
Adult	HTO	1.2	2.3	3.8
	OBT	2.3	5.0	11.6
Fetus (maternal ingestion during pregnancy)	HTO	2.1	4.4	8.1
	OBT	4.0	9.8	23.1

NOTE: HTO = tritiated water in which one atom of ordinary hydrogen has been replaced by an atom of tritium. OBT = organically bound tritium. The numbers in the columns for confidence intervals mean that the RBEs would be less than the cited number for the percent of times indicated by the confidence interval were a series of identical experiments to be performed.

SOURCE: Estimated from Harrison, Khursheed and Lambert 2002, Table 8. The Integrated RBEs were calculated by dividing the tritium doses shown in this paper by the dose conversion factor for tritiated water in the EPA's Federal Guidance Report 11.

TRITIUM
FROM PAGE 10

and all beta particles have an RBE of one — that is, the damage caused is directly proportional to the amount of energy deposited in the tissue. Alpha particles, on the other hand, which deposit all their energy in a smaller number of cells or even entirely in one cell, are assigned an RBE of 20. That is, the standards assume an alpha particle will do 20 times more biological damage than a gamma ray that deposits the same amount of energy in the body.

As noted, the low energy of the tritium beta particle can result in the deposition of all the energy in a short distance, which could be particularly damaging if the tritium is in the DNA. This makes tritium's beta particles not unlike alpha particles in some situations. Therefore, the RBE of tritium should not be taken to be equal to one for all forms of tritium, nor for all age groups. To examine this question more closely, Harrison, Khursheed and Lambert published a study in 2002 examining the assumptions used in current models. The dose conversion factors for various age groups estimated from this paper indicate a RBE of both tritiated water and organically bound tritium higher than one (see Table 1 on opposite page).

This work highlights the importance of the chemical form of tritium and the age at exposure in determining the amount of damage done by tritium. For example, using the median estimates from the table, we find that the damage done to a fetus from organically bound tritium is more than four times that done to an adult from tritiated water and nearly ten times bigger than that assumed by current models.

The importance of organically bound tritium

Organically bound tritium produces more serious health risks than tritiated water for the same amount of tritium intake for two main reasons. First, the chemical form influences the likelihood of tritium being integrated into DNA or other biomolecules. Since tritium's low energy beta particles don't travel very far, there will be a big difference in the damage done by tritium located in the nucleus of the cell (where the DNA is located) to that located in the cytoplasm. Organically bound tritium ingested through food, for example, is more likely to be incorporated into biomolecules than tritium ingested by drinking tritiated water.

> Estimates of the health risks from tritium that focus only on cancer likely underestimate its actual impacts.

The second reason OBT is more dangerous is that it is generally retained in the body longer than tritiated water. Human studies indicate that half of the tritiated water in the body is removed every 10 days, whereas removing half of the OBT present takes 21 to 76 days. For certain molecules with very slow turnover rates, this time can grow to 280 to 550 days. The longer retention times of OBT are a particular concern if the tritium is incorporated into tissues such as neurons (the main cells of the nervous system) or oocytes (immature egg cells). Considering that ova are formed once per lifetime, the effects of radiation on the reproductive system of female fetuses, and the possible effect on the children of females irradiated in the womb, could be significant.

A specific example where the importance of OBT is very clear is tritiated thymidine. Experiments indicate that tritiated thymidine, an organic compound that can be incorporated into DNA, causes over 1,000 times as much damage during certain stages of embryonic development in mice as is caused by the same concentration of tritiated water. This large difference would not be the case for all forms of OBT, since thymidine is a DNA precursor. However, this example illustrates the critical importance of considering the specific chemical forms of tritium, notably organically bound forms.

> Additional research is needed regarding the health impacts of tritium.

A final concern regarding models relates to tritium that has replaced a hydrogen atom in DNA. Because helium-3 does not bond easily to carbon, the decay of this tritium atom creates a free helium ion that breaks away from the molecule. This can lead to a variety of effects, such as single-strand DNA breaks. Point mutations are also possible, in which tritium's conversion into helium can convert one of the four building blocks of DNA (cytosine) into a different building block (thymine). However, the current models expect the direct damage from the beta particles to be more significant than the damage caused by the creation of helium-3.

Non-cancer effects

Beyond issues with cancer risk models, estimates of the health risks from tritium that focus only on cancer likely underestimate its actual impacts. The increased risks to pregnant women and the embryo/fetus include early miscarriages, malformations, and genetic defects. Risks can also be multi-generational given that a woman's ova are produced while she is in her mother's womb.

Much additional research is needed regarding the health impacts of tritium. For example, since we do not have a quantitative understanding of early pregnancy failure, it is currently impossible to make a quantitative assessment of that health risk. Further, the ICRP model of radiation dose in the early weeks of pregnancy is not relevant for tritium dose. In addition, the effects of *in utero* exposure to tritium combined with chemical toxins, such as endocrine disrupting chemicals, needs to be studied, as does the potential for neurological effects.

SEE **TRITIUM** ON PAGE 12, ENDNOTES, PAGE 12

TRITIUM
FROM PAGE 12

Tritium in the environment

While tritium is naturally present in very small concentrations, the use of tritium in nuclear weapons and the creation of tritium by commercial nuclear power plants have resulted in specific areas of concern. For instance, the Savannah River is polluted with tritiated water mainly due to nuclear-weapons-related activities at the Savannah River Site.

In addition, following revelations of tritium leaks from a nuclear power plant in Illinois, it has come to light that deliberate discharges and accidental leaks may be a more widespread concern at commercial nuclear power plants than previously suspected. Significantly, even in the midst of the scandal in the summer of 2006, the Nuclear Regulatory Commission did not yet fully understand all of the sources of the tritium entering the environment or the full extent of the leaks.

Conclusion

In light of the deficiencies in the current models and the variety of potential non-cancer health effects, a more protective limit for tritium than the one in current use may be needed. We have concluded that 400 picocuries per liter for surface water should be considered as an interim target limit for offsite surface water at all nuclear power plants and U.S. Department of Energy nuclear sites while a better understanding of the impacts of tritium is developed. This level is 50 times lower than the EPA's current drinking water limit and corresponds to a lifetime risk of a fatal cancer of about one in a million.[6]

Significantly, the Department of Energy has already agreed to an action level of 500 picocuries per liter for tritium in surface water in the clean up at Rocky Flats. This level corresponds to Colorado's standard for tritium in surface water. It is based on the dose conversion factor for tritium in EPA's Federal Guidance Report 11 (FGR 11). If one uses the most recent guidance, FGR 13, the limit would be 400 picocuries per liter, which has been adopted by the state of California as its health goal. Both the Colorado and California levels are set using a one in a million lifetime risk of a fatal cancer, which is the goal of cleanup under the Superfund law, formally called the Comprehensive Environmental Response, Compensation, and Liability Act, or CERCLA.

The case for tightening the tritium limits as a preventive measure is even more persuasive when one considers the higher RBE of tritium, its possible non-cancer health effects, its possible synergisms with chemical toxins, and its potential effects arising from exposure *in utero* at certain crucial times during pregnancy.

1 Arjun Makhijani, Ph.D., is president of IEER. Brice Smith, Ph.D., is senior consultant to IEER and assistant professor of physics at SUNY-Cortland. Mike Thorne, Ph.D., is a private consultant and an expert on radiological protection and environmental transport of radionuclides. This article is based on chapter 7 of the report *Science for the Vulnerable: Setting Radiation and Multiple Exposure Environmental Health Standards to Protect Those Most at Risk* (IEER, October 19, 2006), on the Web at www.ieer.org/campaign/report.pdf. The report chapter was written by Dr. Makhijani and it is summarized here by Dr. Smith with input from Dr. Makhijani. References can be found in the report.

2 Tritium can also combine with deuterium (D) to form DTO. This is important in situations where heavy water (D_2O) is used in nuclear reactors, such as in Canadian nuclear power reactors or the plutonium production reactors in the United States at the Savannah River Site. The latter are now closed.

3 Assuming an average flow rate of 10,000 cubic feet per second (Makhijani and Boyd, *Nuclear Dumps by the Riverside: Threats to the Savannah River From Radioactive Contamination at the Savannah River Site (SRS)*, 2004, p. 18. On the Web at www.ieer.org/reports/srs/index.html.)

4 Unless otherwise specified, the forms of tritium discussed in this article are either tritiated water or OBT.

5 A typical beta particle emitted from tritium has 35 times less energy than a typical beta particle emitted by strontium-90.

6 Calculated from dose conversion factors at various ages in FGR 13 compact disk (EPA 2002), approximate variations in water consumption with age, and an average cancer fatality risk factor of 0.057 cancers per sievert.

ANSWERS TO ATOMIC PUZZLER SDA 14-3
CALCULATING THE EMISSIONS FROM A COAL FIRED PLANT

1. 22,880,000 Btu per metric ton x 0.001 ton per kilogram x 1055 joules per Btu = 24,140,000 joules per kilogram = 2.414×10^7 joules per kilogram

2. 1 kilowatt-hour = 1,000 joules per second per kilowatt x 3600 seconds per hour = 3,600,000 joules per kilowatt-hour = 3.6×10^6 joules per kilowatt-hour

3. 2.414×10^7 joules of heat energy per kilogram/3.6×10^6 joules per kilowatt-hour = 6.704 kilowatt-hours (thermal) per kilogram

4. 6.70 kilowatt-hours (thermal) x 0.34 = 2.28 kilowatt-hours (electrical) per kilogram of coal ➔ 1/2.28 = 0.439 kilograms of coal per kilowatt-hour of electricity

5. 0.439 kilograms of coal per kilowatt-hour of electricity x 0.61 kilograms carbon per kilograms of coal = 0.268 kilograms of carbon per kilowatt-hour of electricity

6. 0.268 kilograms of carbon per kilowatt-hour of electricity x 3.67 kilograms of CO_2 per kilogram of carbon = 0.982 kilograms of CO_2 per kilowatt-hour of electricity

HELP STRENGTHEN RADIATION PROTECTION STANDARDS

PHOTO CREDIT: MARTIN FODOR

WE INVITE YOU TO SIGN ON TO THIS OPEN LETTER to fix an important problem in public health protection: the widespread use of "Reference Man" in setting radiation protection standards.

Instead, federal agencies need to protect those *most at risk* from exposure to radiation and/or toxic chemicals, be they pregnant women, the embryo/fetus, infants, children and/or some other group.

We are under no illusions that the White House will act with haste on this important issue. However, if we get thousands of signatures, especially from groups representing a broad spectrum of society, we are likely to get the attention of the media and Congress and educate large numbers of people about this important environmental health matter.

We invite you, our readers, to sign the letter. If you are affiliated with one or more organizations — whether professional, faith-based, PTA, neighborhood, health-related, etc. — please ask them to sign on, too. Please spread the word about this important issue.

Sign on at www.ieer.org/campaign/ or call IEER at 301-270-5500. IEER will forward additional signatories to the White House until positive action is taken.

If you have questions or would like more information, please contact Lisa Ledwidge of IEER at ieer@ieer.org or 612-722-9700.

OPEN LETTER TO PRESIDENT BUSH ON PROTECTING THE MOST VULNERABLE

Dear President Bush:

We are writing to call your attention to a serious problem in public health protection and ask that you take action to fix it.

Presently, many federal radiation protection standards are based on average lifetime exposure or on "Reference Man," a hypothetical adult "Caucasian" male who is 20 to 30 years old, weighs 154 pounds, is five feet seven inches tall, and is "Western European or North American in habitat and custom." Reference Man is widely used to set federal rules and regulations, for instance, limits on how much residual radiation will be allowed in radioactively contaminated soil.

The problem is that different groups are affected differently than adult men when exposed to radiation or toxic materials. According to the National Research Council of the National Academies, cancer mortality risks for women are 37.5 percent higher than for men for the same radiation exposure. Sometimes the most vulnerable period is not in adulthood but rather in infancy, childhood, puberty, or when the ova are developing in a female fetus. Prenatal exposures to certain toxic chemicals or radiation can increase the risk of certain disorders, like breast cancer, later in life. The combined effects of chemicals and radiation are little understood.

Further, the use of Reference Man is not in accord with Presidential Executive Order 13045 on the Protection of Children From Environmental Health Risks and Safety Risks, which you endorsed with amendments in 2003. The Order acknowledges that children are disproportionately vulnerable to environmental hazards and directs federal agencies to ensure their policies address the disproportionate risks.

It is urgent that these problems be addressed systematically and broadly. Today, public water bodies used for drinking, irrigation, and recreation are polluted with radionuclides, such as tritium, that can cross the placenta and toxic materials, such as mercury, which affect developing fetuses and children.

We are counting on your leadership to make it a central principle of federal rules and regulations to protect those who are most susceptible to radiation and toxic chemicals, whether they be women, pregnant women, children, the embryo/fetus at various stages of development, or, indeed, in some cases, men. To accomplish that goal we urge you to take the following measures:

1. Issue a Presidential Executive Order to all federal agencies and departments to:
   a. Review their definitions of "Reference" persons and modify them as necessary so that all rules protect those *most at risk* from exposure to radiation and/or toxic chemicals, be they pregnant women, the embryo/fetus, infants, children, and/or some other group;
   b. Review their rules regarding protection of prospective parents and pregnant women to ensure that future generations are not endangered or being harmed due to workplace exposures and to ensure that no discrimination or loss of seniority results from necessary health protections;
   c. Update computer models and other models used to estimate dose and risk for regulatory purposes so they take into account the embryo/fetus and children, and keep the models updated as new scientific evidence becomes available; and,
   d. Prohibit discrimination based on genetic information when creating or enforcing workplace health protections, including protections for pregnant women, and ensure strict privacy in genetic matters.
2. Support legislation or propose new legislation in Congress requiring all federal regulations that affect public health and the environment to be regularly reviewed and revised so as to protect those most at risk; and,
3. Initiate or intensify research to better understand and estimate the human health effects of combined exposure to radiation and toxic chemicals.

Thank you very much for considering our request on this crucial matter related to public and environmental health. For more information, please contact Dr. Arjun Makhijani (arjun@ieer.org) or Lisa Ledwidge (ieer@ieer.org), President and Outreach Director of the Institute for Energy and Environmental Research, respectively, or visit www.ieer.org.

Sincerely,

(See www.ieer.org/campaign/ for list of current signatories.)

Sharpen your technical skills with Dr. Egghead's
Atomic Puzzler

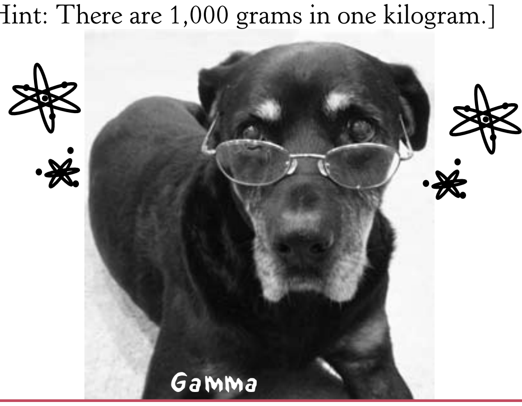
Calculating the CO_2 emissions from a natural gas fired plant

Dr. Egghead's dog, Gamma, continues to be dogged by global warming worries. Will you help him calculate the amount of carbon dioxide (CO_2) emitted by nuclear power plants versus fossil fuel fired power plants? Do so and win a prize! (See box below.)

This is the second part of a multi-part Atomic Puzzler. (Don't worry, you need not have done the first part to try your hand at this part.) In this Puzzler you will calculate CO_2 emissions from a natural gas fired power plant. If you did the first Puzzler, found in the last issue of SDA, you would have calculated the CO_2 emissions from a coal-fired plant. In subsequent Atomic Puzzlers you will calculate CO_2 emissions from a nuclear power plant.

In this problem we will be calculating the CO_2 emitted directly from the natural gas fired power plant — that is, the amount of CO_2 released as a result of burning the natural gas. There are additional indirect emissions associated with the mining and transportation of the fuel and the construction of the power plant. For fossil fuels, the direct CO_2 emissions are dominant.

1. The complete combustion of one cubic meter of natural gas releases 36,410 British thermal units (Btu) of energy. One Btu is equal to 1,055 joules. How many joules of energy would be released by the complete combustion of one cubic meter of natural gas?
2. The watt is defined at one joule per second. How many joules are there in one kilowatt-hour? [Hint: There are 1,000 watts in one kilowatt]
3. How many kilowatt-hours of thermal energy would be released by the complete combustion of one cubic meter of natural gas? [Hint: You will need to use your answers to Questions One and Two.]
4. The density of natural gas is approximately 800 grams per cubic meter. How many kilowatt-hours (thermal) would be released by the complete combustion of one kilogram of natural gas? [Hint: There are 1,000 grams in one kilogram.]



5. The average efficiency of existing combined cycle natural gas fired plants is about 50 percent. That is, 50 percent of the energy released by burning the natural gas is ultimately converted into electrical energy while the remaining 50 percent is wasted as heat and other types of energy losses. An efficiency of 60 percent for new plants is likely to be achieved over the coming years. How many kilograms of fuel would need to be burned in a current natural gas fired plant to produce one kilowatt-hour of electricity? [Hint: For a plant with an efficiency of 50 percent, how many kilowatt-hours of energy would have to be released by the burning natural gas in order to generate one kilowatt-hour of electricity?]
6. Typical natural gas is 73.4 percent carbon (by mass) on average. How many grams of carbon would be released by such a plant in producing one kilowatt-hour of electricity?
7. When the carbon is burned the additional weight of the oxygen means that every kilogram of carbon emitted is equivalent to 3.67 kilograms of carbon dioxide (CO_2). How many grams of CO_2 are emitted by a natural gas fired plant per kilowatt-hour of electricity generated?

Send us your answers via e-mail (ieer@ieer.org), fax (1-301-270-3029), or snail mail (IEER, 6935 Laurel Ave., Suite 201, Takoma Park, Maryland, 20912, USA), postmarked by March 30, 2007. 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 *Insurmountable Risks: The Dangers of Using Nuclear Power to Combat Global Climate Change* (IEER Press and RDR Books, 2006).

Thank you.

IEER is 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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Your generous support helps SDA continue to be an important, useful and free resource for activists, educators, students, policy makers, journalists and others.

Thanks also to our foundation funders, listed on page 2.

Help Protect the Future—with Your Pocketbook

Because many radiation standards are geared to "Reference Man," in October IEER launched the *Campaign to Include Women, Children, and Future Generations in Environmental Health Standards.* This spring, we will publish a report on transitioning the U.S. economy to one without nuclear power and without CO_2 emissions. In summer 2007, we'll hold our second curriculum development workshop to finalize college/university and advanced high school course modules based on IEER materials and others of similar technical integrity. From your favorite website (ieer.org, of course!) to CNN International, IEER's work is reaching a wide audience.

Support IEER's work today to help bring about a brighter tomorrow. Your children and grandchildren will thank you.

Yes! I'd like to support the Institute for Energy and Environmental Research.

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