ETHICS IN SCIENCE: The Exaggeration of Radiation Hazards

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Radiophobia Aggravated by Misrepresentation of Radiation Effects

Subsequent to the 1986 Chernobyl reactor explosion, a perceptional gap surfaced between the original large casualty predictions, compared to current assessments of minimal radiation-health impact. Unfounded injury predictions have resulted from substandard scientific methodology, misinformed journalism, and indifferent editing.

Excessive psychological trauma and tangible disruption, accompanied by wasted expenditures, could have been minimized if systemic rules of scientific evidence about radiation effects had been practiced in the years following the Chernobyl radiation release. Adding credibility to the hype has been selective use of epidemiological studies on radiation effects, as well as undue emphasis on "consensus."

As a result, unfounded fear of radiation, adversely impacting public understanding of nuclear phenomena, has reinforced radiophobia. Decision-makers have overreacted without understanding the underlying science and without applying the scientific method.

ETHICS IN SCIENCE: The Exaggeration of Radiation Hazards

Radiophobia Aggravated by Misrepresentation of Radiation Effects
(Lapses in Scientific Methodology)

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Introduction

Despite the Chernobyl reactor explosion in 1986, the death toll — examined 20 years later — has been considerably less than many individuals had predicted. Nevertheless, based on unrealized projections of cancer and other unfulfilled medical outcomes, enormous and wasted resources were applied to site remediation and regional relocation.

For damning but unrealistic expectations to have persevered so long indicates that significant errors took place in forecasting latent medical consequences, irrespective of extensive and credible research undertaken throughout the world.

Moreover, radiophobic misrepresentation — inadvertent or otherwise — has aggravated a pervasive fear of any radiation, at the expense of its beneficial applications.

This paper delves into some media-amplified instances that are associated with conspicuously detrimental public consequences. These examples are sufficiently documentable: Specific lapses in scientific methodology by individuals and institutions are identified.

Chernobyl: Predictions and Consequences. Of universal concern and impact have been long-term health and environmental outcomes of the 1986 Chernobyl nuclear-reactor runaway meltdown that resulted in a steam explosion and graphite fire. Radioactive materials were forcefully ejected into the atmosphere and progressively contaminated surfaces up to thousands of miles away. Some predictions shortly after were that tens-of-thousands — even hundreds-of-thousands — of deaths would arise from latent radiation-induced cancer. Nearly two decades later, the casualties that are statistically attributable to the explosion are overwhelmed by a much larger backdrop of cancers and mortality from unrelated causes.

Some newsmedia became a submissive platform for distorted scientific results. Under the aegis of "balance," undue emphasis was often given to conclusions that lacked quantified characterization or boundaries for statistical properties. The avoidance of descriptive statistical constraints can leave misleading impressions.

Few news-reporters (and not all scientists) adhere to evolved norms for the scientific method which require a properly qualified statement of analytical or experimental results. Often these omissions are justified in terms of catering to readership. Such methodological lapses might reflect habitual deficiencies in science journalism and publication standards, but they are particularly detrimental if indulged in by scientists who communicate with the media.

Moreover, there is little incentive and even less individual and reportorial initiative to correct past erroneous data and opinions. Although the World Wide Web, especially its facility of blogs, offers an avenue for critique and rectification, it is still necessary for experts to condense and analyze the conflicting diversity of information. On behalf of systemic science, no formal and impartial courts of jurisprudence exist to resolve tort-less claims.

In order to exhibit specific connections between scientific misjudgment and its consequences, I have selected two Chernobyl-related examples: (1) a duo of outspoken scientists who adopted a radiophobia bandwagon that is still rolling, and (2) a notable physicist's opinion that has been ill-advisedly propagated in the newsmedia. To help understand the situation, pertinent observations are made about the traditional scientific committee-review process that serves as a mechanism for consolidating and evaluating expert opinion.

U.S. Judicial Standard for Forensic Science. In 1993 the U.S. Supreme Court revised the federal judicial standards for testimony regarding areas of science that required an explicit estimate of probabilistic error. *Daubert v. Merrell Dow Pharmaceuticals* [1] ruled that quantifiable evidence should meet four "scientific method" standards, namely peer review, replicability, documentation, and stated rates of error.[2] More specifically, the *Daubert* decision called for the admissibility of expert testimony to be based on those standards, key among them being whether the testimony is connected explicitly to a testable hypothesis, and whether there is a known or potential error associated with the evidence (See Box 1).

Judiciaries have retrospectively encountered deficiencies in *ad hoc* scientific/technical testimony and in forensic evidence that did not fully comply with a standardized methodology. Individuals have been wrongfully convicted of crimes; cancer and other illnesses have been incorrectly attributed; and epidemiological data has sometimes been misrepresented. In this paper, the focus is on radiation affecting humans.

Box 1: Limitations on Data. Measured quantities do not necessarily equate to their "true" values, and methods exist to estimate the expected deviation of measured data from "true" values. A deduced "true" value is thus associated with and qualified by an explicit range of error for measured data. But the range of error itself must be estimated (from calculations or measurements). This error-estimation boundary condition thereby limits attributable accuracy for quantifying the "true" value of a causal agent.

The correlation of measured data with a causative agent must be bounded by a stated range of error and confidence. Glossed over too often is the fact that *statistical precision* (randomness of repeated measurements) for measured data is usually much easier to estimate than *systematic inaccuracy* (from inherently unknown corrective factors).

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While personally having had no direct professional experience with medical epidemiology (nor legal training), I have engaged for more than four decades in relevant professional hands-on scientific and technical work with nuclear radiation, radiation metrology, nuclear instrumentation, radiation dosimetry, data analysis, error quantification, and experiment documentation. Having retired, I do not receive professional remunerations.

The Real Tragedy of Chernobyl

Twenty years after the Chernobyl reactor rupture, considerable national and international assessment has been assimilated by international organizations,[3] collaborating under the aegis of the "Chernobyl Forum." This is an international team of scientists convened by the International Atomic Energy Agency, with scientists and experts from eight U.N. agencies — including the World Health Organization (WHO), the IAEA, and the U.N. Development Program — as well as officials from Russia, Ukraine (where the accident occurred), and Belarus.

In Box 2 below is a summary of the principle public-health findings by international commissions that have thoroughly investigated the accident.[4]

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Box 2: Major International Public-Health Findings for Radiation Effects from 1986 Chernobyl Nuclear-Reactor Accident

• About fifty emergency workers dead from site-related injuries and acute radiation.

• No physical *public-health* impact explicitly attributable to radiation exposure.

• No unambiguous evidence for increased cancer incidence, although estimates are that as many as 4000 adults (out of 600,000 persons) exposed to radiation fallout might die prematurely because of Chernobyl radiation-induced cancer.

• No excess radiation-induced leukemia.

• No birth defects attributable to radiation exposure.

• Up to a dozen thyroid-cancer juvenile fatalities not necessarily caused by Chernobyl radiation.

• No detected genetic damage to humans.

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Although the number of Chernobyl-caused deaths for the 600,000 most-exposed individuals (in the near and distant radiation-contaminated regions) is unlikely to be precisely known, the Forum's best estimates — 20 years after the accident — place an upper limit of 4000 statistically conceivable fatalities.

The 4000 predicted cancer deaths must be taken as an upper bound, *i.e.*, as 0 plus-or-minus 4000, or maybe 0 plus-or-minus 2000 fatalities at the 1-sigma (67%) confidence level, out of 100,000 "normally" occurring future cancer-caused deaths.

The International Atomic Energy Agency (IAEA) has separately examined the 1986-1987 mortality data from radiation-induced cancer and leukemia among the 200,000 emergency workers, 116,000 evacuees, and 270,000 residents of the most contaminated areas surrounding Chernobyl.[5]

> The estimated 4000 casualties may occur during the lifetime of about 600,000 people under consideration. As [a] quarter of them[150,000] will eventually die from spontaneous cancer not caused by Chernobyl radiation, the radiation-induced increase of about 3% will be difficult to observe....
>
> Confusion about the impact has arisen owing to the fact that thousands of people in the affected areas have died of natural causes. Also, widespread expectations of ill health and a tendency to attribute all health problems to radiation exposure have led local residents to assume that Chernobyl related fatalities were much higher than they actually were....

The IAEA agreed with the Chernobyl Forum that "the estimate for the eventual number of deaths is far lower than earlier, well-publicized speculations that radiation exposure would claim tens of thousands of lives."

The cited 2005 IAEA news release reflected systematic and comprehensive international, multidisciplinary evaluations of the accident, results of which have been published in considerable detail, as noted above.

The World Health Organization has variously associated 9 to 12 children[6] as having died from thyroid cancer; however, that too is a statistical extract not necessarily caused by Chernobyl radiation. As has been the case everywhere else, better medical attention, diagnosis, and treatment have resulted in significantly improved detection of latent thyroid cancers at early (and often treatable) stages. In the Soviet Union, especially in rural areas prior to the Chernobyl accident, preventative, diagnostic, and curative treatments for abnormal thyroid conditions were not as common as in the West. After the accident, considerable diagnostic and medical treatment (and media attention) was focused on possible occurrence of thyroid cancer in children. Iodine deficiency was common for children during the Soviet era.

No other fatalities from the otherwise-disastrous reactor explosion were confirmed, and none were linked by medical diagnosis or post-mortem examination to radiation exposure. Partly because of net improvements in post-accident remedial action and health care, actual premature fatalities could turn out to be much less than the 4000 estimated upper limit — in fact, even down to zero (or less than zero).

Now, how can those realities and lower limits be squared with the woeful and un-validated impressions that have been and continue to be broadly imparted through the newsmedia for the past two decades?

Lapses in Methodology

Here are two specific examples of published technical conclusions that are misleading primarily because statistical boundaries were omitted.

First Explicit Example (Physicists 1 and 2). Just months after the Chernobyl accident, two physicists for the *Bulletin of the Atomic Scientists* provided an early evaluation of long-term health effects.[7] For this, they had to make some interim radiation-dose approximations, followed by calculations of dose consequence.

In translating their dose estimates into tangible consequences, the two physicists adopted what they described as “the usual assumption ... that the probability of incurring the consequence is proportional to the radiation dose” (the so-called *linear hypothesis*). They thus extrapolated “the number of cancers and thyroid tumor cases resulting from Chernobyl” through a process that includes “simply ... summing the radiation doses of the entire exposed population.” However, that extrapolation would be valid only when the dose effect at low values is linearly related to consequences at higher doses (where measured data exist). Simplistically stated, double the dose: double the effect; halve the dose: half the effect.

Explicitly, on the basis of an extrapolation from high-radiation dose data, they envisioned the following aggregate medical consequences from the low doses received as a result of the Chernobyl explosion:

> • 2,000-40,000 thyroid tumor cases from iodine 131 inhalation, of which a few percent might be fatal....
>
> • 10,000-250,000 potential thyroid tumor cases....
>
> • 3,500-70,000 cancer cases from the whole-body doses of cesium 137 (external and internal), of which approximately half might be fatal....

Of these calculated effects, very few — if any — have demonstrably materialized more than two decades after the accident.[8]

The basis for the estimates was the "Linear No-Threshold" (LNT) extrapolation, derived from the notion that risk is simplistically additive:

> [It] is the addition of such small extra risks over many millions of individuals that results in our estimate of thousands to tens of thousands of extra cancer deaths.

While a linear relationship has been shown to be valid for measured higher-dose data (such as for Hiroshima and Nagasaki victims and survivors), it is yet to be established as the correct model for lower doses that fall within the range of normal human radiation background (which varies from 1 mSV/yr to well past 10 mSv/yr worldwide).[9] As a matter of fact, several theories compete to account for the dose-effect relationship of small incremental exposures to radiation; some data and theory suggest beneficial (hormetic) biological effects from low doses of radiation.

Their LNT extrapolation hypothesis is not really an oft-claimed "conservative" assumption; it is woefully inappropriate for the low-dose range. To this day, definitive data is lacking for choosing between any particular model of radiation effect at or below natural background levels, largely because the effect — if any— is so small.[10]

As a result of such data-quality deficiencies, downward extrapolation using the LNT model introduces an extant calculable (systematic) error in accuracy which must be added to the stochastic (random, sampling, or imprecision) error that accompanies any estimation of low-dose radiation effects on populations.

By giving no indication of systematic bias resulting from the adopted LNT absorbed-dose extrapolation, the two referenced physicists thus implicitly misrepresented data quality. In addition, they omitted requisite statements of statistical variance with limits of confidence.

Actually, *dose-rate* — rather than *accumulated-dose* — especially at low doses and rates, might be a more appropriate parameter to model the effects of radiation.[11] Because natural cell repair is rate dependent, cellular effects depend on the pace of radiation absorption, as well as on the accumulated dose (see Figure 1. Three Alternative Models for Extrapolation to Null Response as Ionizing Radiation Dose Decreased to Zero.).

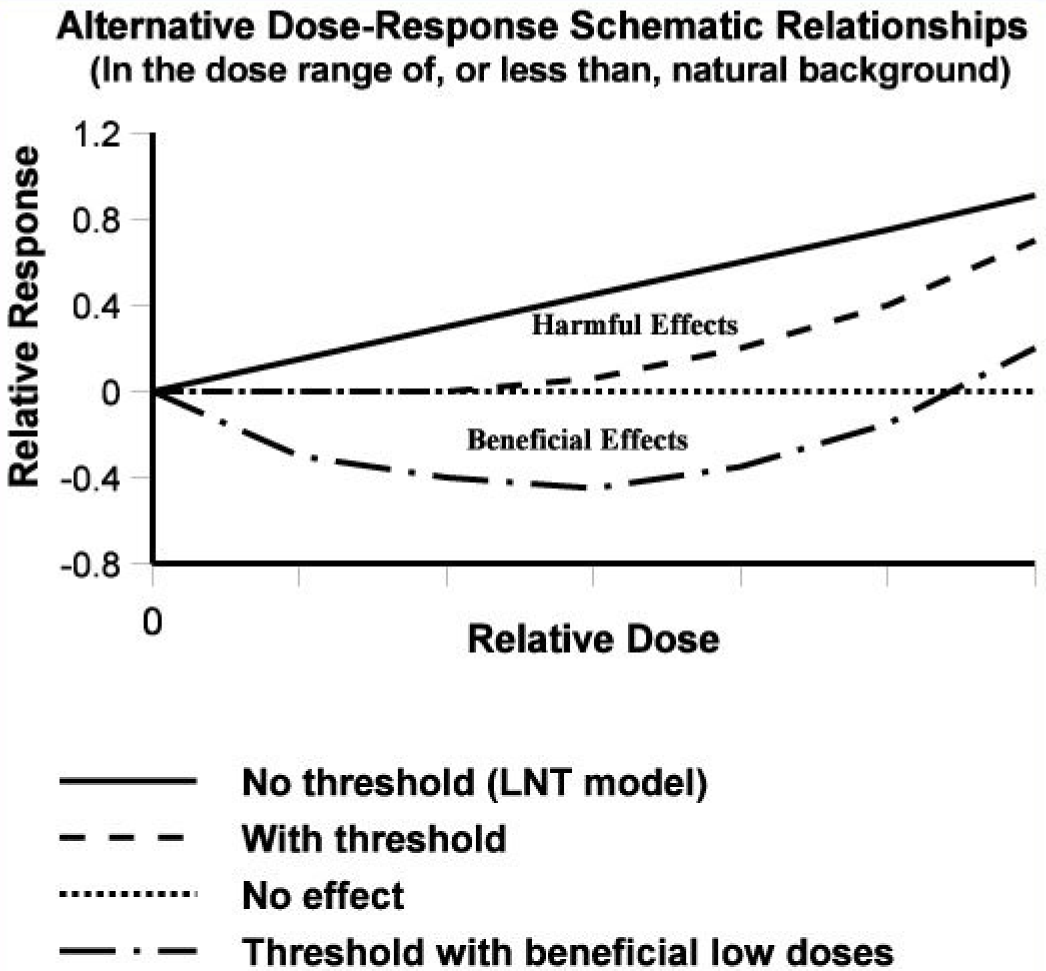

Figure 1. Three Alternative Models for Extrapolation to Null Response as Ionizing Radiation Dose Decreases to Zero.

What they could have advised is that their casualty projections were an upper limit, accompanied by a lower limit that, even in 1986, could turn out to be zero.

In any event, four shortcomings in their publication more than 20-years ago are evident: (1) The projected Chernobyl casualties have not materialized, (2) the LNT model is yet to be validated in the natural-background range, (3) no error estimates were supplied, and (4) Physicists 1 and 2 did not publish rectifications or explanations.

Second Explicit Example (Physicist 3). In 1999 an influential physicist sent a protest letter to *Physics & Society,* the public-policy journal of the American Physical Society, a primary professional organization for physicists.[12] In his quote below about Chernobyl cancers, note the absence of expressions to qualify uncertainty:

> The best judgment of the International Commission on Radiation Protection (ICRP) is that even for low-level radiation, deaths due to cancer occur at a rate of 0.04 per person-sievert (400 per million person-rem). There is little dispute over the collective exposure [from the Chernobyl accident] to the population of the European community and the (former) USSR as 600,000 person-Sv.

Physicist 3 says he had "long estimated ... 20,000 additional deaths from cancer."[13] He has not responded so far to direct requests for estimates of systematic and sampling error.[14]

Some additional, yet crucial, uncertainties not clarified by Physicist 3 in his publications are hereby noted:

• origin and justification for "a radiation dose of 600,000 person-Sv." What specific population and what average dose goes into that number?

• matrix that delineates population vs. exposure. What error range is propagated from the matrix?

• uncertainties, both random and systematic, associated with radiation dosimetry and medical diagnoses.

• systematic error introduced by 'confounding' life-style and medical-treatment factors in the affected population.

• omission of a comparison between exposure to radiation at Chernobyl with exposure to natural background radiation (where no extra cancers have been reported for people whose natural exposure is one-hundred times higher than world-average background levels).[15]

What Physicist 3 could have acknowledged was that the lower boundary of uncertainty in confidence level ranges down to nearly zero public casualties resulting from the Chernobyl accident.

Media Amplification

The flawed and un-materialized projections reported in the aforementioned articles were further propagated through newsmedia. Because of direct and indirect linkage with the preceding examples, subsequent publications in 2005 and 2006 are singled out here.

UPI International. Because the basic premise of Physicist 3 appears to be an unwarranted "best judgment" LNT extrapolation, his conclusions are simply speculative. In spite of that, he projects an unqualified $24 billion equivalent damage cost[16] (to indemnify premature deaths from Chernobyl radiation).

His prestige was sufficient to enable circulation in 2005 of an assessment without peer review through UPI International, thereby gaining media, public, and policymaker attention.

Bulletin of the Atomic Scientists. The following statements were included in a reporter's 20-year aftermath assessment.[17] of the Chernobyl accident. According to the journalist,

> [“An internationally renowned physicist”(Physicist 3)] calls the[2002 Chernobyl Forum] report “deliberately misleading,” arguing that it overlooks [contradictory evidence] in a report ... by the [U.S.] National Academy of Sciences..... “Although it is impossible to identify these 24,000 among the many tens of millions of people who would die from similar cancers from natural causes over the same period,”[The physicist] noted in his [published] op-ed, “those deaths are nevertheless a consequence of the radiation release.”

Nonetheless, the Chernobyl Forum had at its disposal not only the U.S. National Academy of Sciences report, but more importantly a detailed international assessment of the actual Chernobyl consequences.

In the *Bulletin* article, it was Physicist 3, the only knowledgeable scientist quoted, who apparently discounted various LNT-extrapolation challenges, particularly by specialists such as Z. Jaworowski[18] and more recently by Tubiana and Aurengo.[19] Physicist 3 has relied entirely on LNT extrapolation rather than measured data to reach his conclusions.

As for the alleged “contradictory evidence” from U.S. national committees, these are at odds with rigorous radiation-dose studies described below.

Because attention-getting impressions get disproportionately noted, it is difficult to assess how widely and how influential has been media amplification of the Chernobyl accident’s most unfavorable extremes.

U.S. National Committees

The Commission on Life Sciences of the U.S. National Research Council has convened a standing Board on Radiation Effects Research (BEIR), which in turn fostered official U.S. government assessments of health effects attributable to various forms of ionizing-radiation, such as residential radon.

BEIR VI. The Board’s Committee on Health Risks of Exposure to Radon issued a sequence of assessment reports.[20] Although acknowledging that “the most direct way to assess the risks posed by radon in homes is to measure radon exposures among people who have lung cancer and compare them with exposures among people who have not developed lung cancer,” the BEIR VI committee instead chose “to use the lung-cancer information from studies of miners, who are more heavily exposed to radon.”

(As a example of an epidemiological profile that conforms to “the most direct way,” see the subtopic below, Radon in Basements.)

BEIR VII. The seventh in a series of BEIR reports addressed effects on human health of exposure to low-dose Linear Energy Transfer (LET) ionizing radiation.[21] Their conclusions stressed a LNT dose-response relationship, except for a threshold in the induction of cancers. Adverse health effects in children of exposed parents have not been found, although there was no reason to believe that humans would be immune to this sort of harm.

Irrespective of the scholarly and comprehensive nature of the U.S. National Research Council BEIR VI and VII assessments, crucial deficiencies in data selection and methodology have resulted in recommendations that are, in my assessment, (1) at odds with the aforementioned international Chernobyl assessments, (2) at variance with some rigorous epidemiological studies that were assigned questionably low rankings, and (3) weakened because the committee used a consensus process for decision-making instead of an less-subjective statistically weighted matrix.

Some under-weighted epidemiological studies that contradict reliance on the LNT extrapolation are described next.

Rigorous Radiation-Dose Studies

The international scientific evaluation of Chernobyl's health and societal effects is supported by many previously conducted rigorous epidemiological evaluations of other specific populations. Box 3 contains a summary of key radiation-dose studies.

Box 3: Key Radiation-Dose Studies. Regarding research with substantial control of confounding (covariate) factors in low-dose radiation epidemiology, the technical literature draws attention to three particular studies: One relates to occupational gamma-radiation exposure, another involves public radon exposure, and the third is a sustained analysis of atomic-bomb survivors in Japan. Key results of these three key long-term epidemiological radiation studies can be summarized as follows:

• Workers at U.S. nuclear shipyards were not harmed by chronic low-doses of radiation from occupational exposure.

• Radon in U.S. basements is far less harmful than widely feared.

• The oft-cited Hiroshima-Nagasaki studies show remarkable survival.

Nuclear Shipyard Workers. In the course of dismantling irradiated components from decommissioned U.S. Navy nuclear reactors, a large number of workers at nine U.S. shipyards were exposed for many years to monitored low-dose occupational radiation — more or less than 5 mSV accumulated in excess of local environmental background (~7.6 mS/yr).

(Worldwide exposures to natural radiation sources are generally found to be in the range 1-10 mSv/yr, with 2.4 mSv/yr being the present estimate of the central value.[22] The United States is 1.5 times higher on average,[23] although it was 3 times higher in the locations of the nuclear shipyards.)

The naval-shipyard survey was screened by two independent technical-review panels. It was exemplified belatedly as "an ideal population in which to examine the risks of[ionizing] radiation in which confounding variables could be controlled."[24] Out of 600,000 non-nuclear shipyard workers, 32,510 age- and job-matched controls were selected to be compared to a cohort of 27,872 nuclear workers (from a pool of 100,000).

Experiment design, control, and analysis was formulated to avoid shortcomings in previous epidemiology of people exposed to radiation. In particular, ***complete and documented dosimetry*** was obtained for all personnel during the entire study — an experiment-design protocol of major consequence for avoidance of systematic error. An evaluation of comparable design, stratified according to nuclear-plant radiation workers in 15 countries, was carried out by E. Cardis, et al[25] with less determinate results.

The U.S. nuclear-shipyard radiation-worker longitudinal study from the 1950s/60s through 1981 found clear evidence that a chronic dose of added radiation comparable to natural-background exposure was not harmful.

The statistically significant results (95% probability) on mortality and cancer among the shipyard workers show that the U.S. BEIR VII dependence on linear extrapolation (LNT) from doses much higher than natural background is not adequately supported by data collected for dose increments comparable to or less than natural background.

Epidemiological design for the U.S. naval shipyard worker evaluation carefully attended to the experiment structure and normalization of confounding factors. One glaring omission in the BEIR VII evaluation was failure to mention the naval shipyard worker study at all.[26] Judging from my freelance assessment, the shipyard study should be considered the "gold standard" in this category of radiation epidemiology.

A U.S. government-funded typewritten "Final Report" of the stringently controlled shipyard radiation-dose evaluation was completed in 1991, but the funding agency (Office of Health and Environmental Research, U.S. Department of Energy) failed to support traditional journal publication. Instead, in 2005, it was undertaken voluntarily by Ruth Sponsler and John Cameron.[27] The latter described it as the "world's largest and most thorough study of health effects of low-dose-rate ionizing radiation to nuclear workers."

Radon in Basements. Low statistical weight was given in BEIR VI [28] to the well-organized systematic epidemiology of Bernard Cohen,[29] who examined the effect of natural radon throughout the United States.

The intensive research regimen by Cohen revealed a "negative association between lung-cancer mortality and average indoor radon concentration."[30] As a result, he concluded that "in general, the average dose does not determine the average risk, and to assume otherwise is what epidemiologists call the ecological fallacy."[31]

Evidently, little or no radiation hazard exists from radon radiation rising from under residential homes. Despite the buildup of opportunistic businesses for measuring and managing natural radon emanations, the most definitive epidemiological data has been found on humans to be negligible or non-existent.[10] However, radon or other radiation associated with environmentally deficient mining (especially for uranium) might have adverse medical effects, although the effects are compounded by chronic tobacco smoking.

Atomic Bombing Survivors. Hiroshima-Nagasaki time-wise longitudinal studies, show that around half the 86,500 survivors (doses >100 mSv) were still living 60 years after the atomic bombings.[32]

The survivors are healthier than the general population. (Such a high survival rate quite likely was enhanced by intense American medical treatment and oversight.)

For the purpose of atomic-bomb survivor studies, chronic and acute doses were generally lumped together. This practice tends to skew results well outside the range of low-dose, low-rate exposures that are characteristic of radiation that escaped from Chernobyl or incurred from natural background.

The three exacting studies outlined above give sufficient reason to recognize that confidence levels are overly high for LNT extrapolation of measured radiation dose effects down to the levels where natural background is significant.

Radiophobia, a Subjective Fear

Radiophobia is the term used to describe abnormal, unjustified fear of radiation. Radiophobia — anticipatory, proximate, or latent — is manifested specifically through individual and public reactions to radiation and aggravated by nonspecific anti-nuclear attitudes.

Excessive radiation doses can be harmful or even lethal; yet low-level natural radiation is a normal adjunct of life, perhaps even an essential stimulant to human existence. Since the inception of life, radiation impinging on or emanating from our planet has contributed incessant and significant terrestrial doses to all fauna and flora.

Visible, ultraviolet, and infra-red spectrum radiation are vital to animal and plant survival. Admittedly, ionizing radiation poses a potential unseen hazard; it wasn't until the 20th century that scientific and technical means became available for observing and quantifying most variants of radiation and their effects.

The public, psychosomatic, and economic policy implications of radiophobia are considerable and vastly overindulged. Delving deeper into specifics about the underlying phenomenology leads to some examples of impact far more emotional than science grounded.

Three Mile Island and Chernobyl. After the 1979 TMI nuclear-reactor meltdown in Pennsylvania,[33] unwarranted fears and exaggeration of its effects resulted in injury expectations that never materialized. Contrary to persisting overstatement,[34] no palpable deaths or injuries were suffered by plant workers or nearby residents:[35]

> [A] total of almost 20 years of follow-up ... provides no consistent evidence that radioactivity released during the TMI accident ... has had a significant impact on the mortality experience....

On the other hand, medical experts have presented reasoned arguments that certain psychoneurological syndromes — not directly correlated to dose (absorbed radiation) nor level of contamination — have nevertheless resulted in chronic fatigue, sleep disturbances, and impaired memory attributable to radiophobia.

In the geographical area surrounding TMI, compared to Chernobyl, these psychologic effects were not as severe nor as widespread — largely because of minimal radiation escape from the TMI reactor — although considerable public, media, and official attention elevated the local and national level of radiophobia.[36]

Beneficial outcomes from the two severe reactor accidents include sweeping safety improvements to generic reactor design, engineering, and operation. At both sites, adjacent nuclear-power reactors continue normal operation. New power reactors are being built with external containment and inherent safety features. While these improvements have stabilized the nuclear industry, they would not be expected to eliminate psychological concerns as much as they diminish engineering and operational weaknesses that might foster radiophobia.

LNT. The default concept that even the slightest doses of radiation pose danger is embodied in the "linear no-threshold" (LNT) extrapolation model (Figure 1), proposed in 1949 by the U.S. National Council on Radiation Protection and Measurements. "No-threshold" refers to a linear-extrapolation process used in the absence of definitive low-level-radiation epidemiological data. The extrapolation is inconsistent with the survival and domination of humans from time when the earth's background radiation levels were an order of magnitude larger.

In the absence of validated data, the health effects of radiation are extrapolated linearly downward to zero effect for zero dose. Although it was thought nearly 60 years ago to be a prudent recommendation, the still-unsupported straight-line extrapolation has had significant unjustified, adverse, and costly economic, medical, psychological, and public-policy consequences.

The LNT extrapolation is usually applied to small radiation doses that are comparable to or less than the pervasive natural background (which was at higher levels during the Quaternary period when humans became differentiated from primitive mammals).[37] Moreover, the effects of additional ionizing radiation at low doses (from, say, natural background) are so small that they cannot be clinically distinguished from biological consequences of ingestion, inhalation, or contact with extrinsic chemicals. Low-radiation dose effects — good, bad, or indifferent — are difficult to reliably differentiate. Although the LNT model was formulated in order to temporize with what was thought to be a cautious means of estimating low-dose risk on large populations, its strict linear extrapolation seems to badly overestimate those consequences.

In any event, systematic error is so large [38] for LNT extrapolation to low doses that evaluators, authors, and regulators should avoid propounding crucial conclusions that are dependent on the linear assumption.

***Science*.** Here's an illustrative example (about chronic radiation releases at Mayak, a radioactive-fuel processing facility in the former Soviet Union) unrelated to the Chernobyl accident, taken from the November 2005 issue of the prestigious journal *Science*.[39]

The one-sided article tries to attribute substantial death causation to radiation at Mayak; yet, of 1842 solid-tumor cancer deaths, at best only 2.5% could be associated with radiation. Moreover, no indication is given whether individuals inhaled tobacco smoke, lived in poverty, imbibed alcohol, or endured stress — four prevalent 'confounding' life-risk factors that dominated cancer and morbidity in the former Soviet Union.

At least one such factor (tobacco smoking) was not excluded, which implies an absence of sufficient rigor to make the study meaningful. The occupational doses tolerated were, in fact, at levels much less than that received from normal background.

As in previous examples, no error boundaries are cited, the ubiquitous LNT extrapolation was implicit, and perspective was lacking in reporting radiation effects.

More correct would have been to give indications of potential systematic bias that constrain applicability of the results. (Of course, that would diminish newsworthiness of the reported data.)

As Figure 1 indicates, there are at least three readily conceivable heuristic models for extrapolating high dose ionizing-radiation data to zero response.[40] For the bottom curve, an optimum is achieved at which point the maximum potential ***beneficial*** effect of radiation is incurred.

Because of the underlying controversial assumption that all (ionizing) radiation is physically destructive, the LNT model has itself become a focal point for independent review and analysis. Research into radiation hormesis is uncovering salutary effects at low doses.[41]

Overly conservative safety and environmental rules based on the LNT hypothesis impact societal by causing excessive limitations on use of radioactive materials in medicine and extraordinary costs of radiation cleanup and remediation (such as in the region around Chernobyl). Based on interim and unproven fears, highly expensive precautionary procedures and steps remain the rule.

An Appendix containing the most recent assessment of radiation consequences on humans follows the References at the end of this paper.

Dirty Bombs. Deliberate use of explosives to disperse radiation would constitute a radiological weapon, loosely characterized as a "dirty bomb" by the popular press.

In order for harm to befall an individual from explosively scattered radioactivity, the original source must be concentrated and be of high intensity; it must be dispersed in a manner that aggravates the dose to individuals distant from the point of origin; and the targeted individuals would have to remain in the vicinity long enough to unwillingly absorb a harmful dose. None of these provisos is particularly plausible because radioactivity distributed by a "dirty bomb" would be diluted by the explosion (see Box 4), thus invariably weakening the dose vulnerability that might cause acute or chronic illness.

Box 4: Radiation Dispersion. A very hazardous 1000-curie (3.7 x 10^{13} Bq) Co-60 gamma-ray source, if uniformly spread over an area of about two football fields (a typical city block), would induce about 25 mSv/hour average radiation dose. Victims who experience only radiation exposure (no blast or thermal trauma) would have up to an hour or so to get out of the area without receiving much more than a year's dose of radiation above typical background. Only those close to concentrated gamma-radiation fallout, felled by injury and unable to be evacuated within many hours, might have their physical trauma aggravated by radiation exposure.

A realizable physical danger, though, is from the device's conventional explosive — its blast, heat, and incendiary effects. Although considerable psychosocial impact might be induced by a radiation-dispersion device, little or no amplification of physical injury is likely to result from dispersal of its radioactivity. Explosive dispersion dilutes radiation flux, making it difficult to imagine a reasonable scenario wherein medical harm is increased by the deliberate dispersal of radioactivity.

Nevertheless, an article on "dirty bombs" published on behalf of the Federation of American Scientists (FAS) gained considerable press play and invited congressional testimony.[42] It illustrates how terror caused by deliberate dispersal of radioactivity can be exacerbated without a firm scientific basis.

Conclusions and Summary

With decades having now passed since prominent public episodes of acute and chronic radiation exposures, it has become clear that dreadful health-consequence expectations have been badly overstated, particularly for the Chernobyl and TMI reactor incidents. The scientific, technical and journalistic professions, though not alone, must share significant responsibility for premature and exaggerated predictions that have not materialized nor been rectified.

Authors who have vastly misjudged radiation-dose health consequences appear to have little hands-on experience with radioactive materials, lack relevant technical credentials, do not adhere to professional methodology, and/or supply minimal analytical justification to make their damming assertions. Too often, statistical limits are not stated nor even required. This omission alone has caused selective data to be represented as more meaningful than deserved, amplification of radiophobia being one unjustified outcome.

Some lapses in scientific methodology are correlated with unwarranted procedural forfeitures. The published reports singled out in this paper illustrate systematic inadequacies: specifically, the lack of probabilistic confidence levels and, more generally, the absence of a process considered "scientific" by much of the technical community and adopted by the U.S. Supreme Court. Of four guiding tenets stated in the Court's *Daubert* decision, two of them — peer review and probability estimates — are often conspicuously shortchanged.

In order to establish probative radiation-exposure standards, a process of quantified probabilistic analysis (systematic risk assessment) is needed for anticipating consequences of being exposed to ionizing radiation. Official estimates of cancer risk from low-level radiation are currently based on the linear-no-threshold theory, itself derived from largely discredited concepts of radiation carcinogenesis, with essentially no experimental verification in the low-dose region. General acceptance or simplicity of the LNT notion is not, of itself, adequate to meet a scientific-method standard. Since alternative risk models have a credible theoretical basis, the minium systematic error reported should reflect the current large uncertainty in the LNT model. Linear extrapolation to low radiation doses gives a misleading impression for occupational and incidental background-level radiation exposures.

Another soft spot involves population-epidemiology surveys that do not fully account for confounding factors and are reported without justifiable statistical confidence regarding harmful health consequences forecast from low doses of ionizing radiation. Generic flaws regarding radiation mortality are (1) inaccuracy in occupational and background radiation doses for particular individuals, (2) poor statistics because of the small number of deaths attributed to radiation, and (3) bias arising from confounding life-risk factors that are correlated with known life-style carcinogens.

Impressions stemming from examples cited in this paper have hardly been without consequence: Unqualified data has been used selectively for partisan purposes. Flamboyant numbers, yet to be retracted, have been offered by other scientists.[43] Unsubstantiated characterizations contribute to public confusion, rather than clarification. Inordinate risk estimates have lead to the expenditure of tens of billions of dollars to protect against dangers whose existence is highly questionable.

The diffuse nature of the Chernobyl reactor accident, its impact, and the demise of the Soviet Union, have left unresolved many human, environmental, and institutional consequences. Very poor public and scientific understanding of ionizing-radiation effects at levels near ordinary background has induced Immense psychological, economic, and social costs. Systemic physical harm from low-level radiation doses has not been substantiated at all.

Needed for clarification of health effects from low-level ionizing radiation is revised methodological evaluation concentrating on doses at and below natural-background rates. U.S. national BEIR VI and VII recommendations represent more of a committee consensus than probabilistically weighted analytical results.

Inasmuch as average dose does not determine average risk, particular care should be taken not to make or give credibility to the “ecological” or “collective-dose” fallacy, a methodological flaw propagated in publications critiqued within this paper. Moreover, a few prominent physicists and professionals [44] have alleged radiation hazards that, when publically questioned or refuted, often were replaced by some other allegation.

Costs and delays associated with over-regulation and over-reaction have induced and incurred enormous individual and societal burdens. Hundreds of thousands of residents in the area surrounding Chernobyl have been subjected to overly extended deprivation of their vitality, families, homes, lands, livelihood, and expectations. Many have suffered unwarranted mass psychological disturbances, unjustifiable economic losses, and traumatic social consequences.

Important societal decisions regarding radiation exposure have been based on unverified scientific recommendations inferred without the benefit of updated critical experience derived from atomic-bomb survivors, nuclear-shipyard workers, home-radon surveys, and the traumatic TMI and Chernobyl accidents. Chronic exaggeration of radiation effects and reflexive exploitation of radiological dispersion (dirty bombs) are public phenomena unsupported by prevalent scientific evidence;

radiophobic fixations are partly traceable to persistent lapses in scientific methodology, amplified by non-discriminatory newsmedia.

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44: E.g., Steven Milloy, Helen Caldicott, John Gofman, and Ernest Sternglass.

Appendix: Most Recent International Assessment of Radiation Effects

The most recent publication ["Effects of Ionizing Radiation" UNSCEAR 2006, United Nations, NY (2008)] of the United Nations Scientific Committee on the Effects of Atomic Radiation reinforces the evidence put forth in this paper based on earlier reports. Here are some relevant quotes, selected primarily from Volume I:

Public confusion:

> Uninformed reporting of postulated numbers of projected exposure-related deaths as a result of the [Chernobyl reactor] accident, especially reporting before and at the time of the twentieth anniversary of the accident in April 2006, had created [unnecessary] confusion among the public.

The public death toll:

> [It] was not possible to attribute any specific [clinically attributable] death [to the exposed general population] to late effects of exposure to radiation as a result of the [Chernobyl] accident.

Epidemiological studies of radiation and cancer:

> [Most] low dose studies reported in the literature have inadequate statistical power. Also, for low dose studies with numbers of effects that are expected to be small and which do not have any statistical power, the value of the relative risk found for any supposedly "statistically significant" results is likely to be a substantial overestimate of the "true" risk.

Thyroid cancer:

> Thyroid cancer is one of the less common forms of cancer, and cases constitute somewhat less than 2% of all cancers....
>
> As in several other studies of persons exposed to radioactive contamination resulting from the Chernobyl accident, the increased thyroid cancer rates compared with rates in the general population appear to be due to heightened medical surveillance rather than to the radiation exposure.

Japanese atomic-bomb survivors:

> [Analyses] restricted solely to low doses [of radiation received by Hiroshima and Nagasaki atomic-bomb survivors] are complicated by [1] the limitations of statistical precision, [2] the potential for misleading findings arising from any small, undetected biases and [3] the problem of observing statistically significant results purely by chance when performing multiple tests to establish a minimum dose in which elevated risks can be detected.

Radon in homes:

> [Epidemiological] data provide little evidence for increased risks of mortality [from radon] other than for that due to lung cancer.
>
> There are various sources of error in the assessment of miners' exposures [to radon], especially for the earliest years of mining when exposures were higher.
>
> Recent pooled analyses of residential case-control studies support a small but detectable

> lung cancer risk from residential exposure, and this risk increases with increasing exposure.... Because of the synergistic interaction between the effects of radon exposure and those of inhalation of tobacco smoke, smokers account for nearly 90 per cent of the population-averaged risk from residential exposure to radon.

(The missing context surrounding the quotes can be readily accessed through the Internet.)

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