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Radiation Injury and the Law

*David S. Gooden**

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INTRODUCTION

Few things strike more fear into the minds and hearts of the public than exposure to ionizing radiation.[1] The fear may arise in part because radiation is not detected by the five senses: it cannot be seen, heard, smelled, felt or tasted. Perhaps the fear arises because the public feels little direct control over potential radiation exposure. Many scientists knowledgeable in radiation injury believe that the magnitude of the public's fear is unreasonable.[2] Yet the law properly recognizes a cause of action in tort for radiation injury. In recent years, actions involving thousands of plaintiffs alleging radiation injury have been brought against the United States and defense contractors.[3] The

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[1] Science uses the term "radiation" both to describe a wide spectrum of photons (*i.e.*, radio waves, visible light, x-rays and gamma rays) and also to loosely describe energetic particles. Ionizing radiation is radiation which has sufficient energy to strip electrons from the atoms which compose matter, a process called ionization. Not all radiation is ionizing in character, but for this article, the term radiation denotes ionizing radiation. *See* H. JOHNS & J. CUNNINGHAM, THE PHYSICS OF RADIOLOGY 20-25, 77-90 (4th ed. 1983).

[2] *See* Cohen, *Most Scientists Don't Join in Radiation Phobia*, Wall St. J., Nov. 30, 1983, at 28, col. 4; AMERICAN CANCER SOCIETY, CLINICAL ONCOLOGY FOR MEDICAL STUDENTS AND PHYSICIANS: A MULTIDISCIPLINARY APPROACH 4 (P. Rubin 6th ed. 1983).

[3] *See, e.g.*, Dennis v. General Elec. Corp., 762 F.2d 365 (4th Cir. 1985); Molsbergen v. United States, 757 F.2d 1016 (9th Cir.), *cert. dismissed*, 473 U.S. 934 (1985); Cole v. United States, 755 F.2d 873 (11th Cir. 1985); Hinkie v. United States, 715 F.2d 96 (3d Cir. 1983), *cert. denied*, 465 U.S. 1023 (1984); Gaspard v. United States, 713 F.2d 1097 (5th Cir. 1983), *cert. denied*, 466 U.S. 975 (1984); Mondelli v. United States, 711 F.2d 567 (3d Cir. 1983), *cert. denied*, 465 U.S. 1021 (1984); Laswell v. Brown, 683 F.2d 261 (8th Cir. 1982), *cert. denied*, 459 U.S. 1210 (1983); Jaffee v. United States, 663 F.2d 1226 (3d Cir. 1981), *cert. denied*, 456 U.S. 972 (1982); Monaco v. United States, 661 F.2d 129 (9th Cir. 1981), *cert. denied*, 456 U.S. 989 (1982); Broudy v. United States, 661 F.2d 125 (9th Cir. 1981); Bramer v. United States, 595 F.2d 1141 (9th Cir. 1979); Blaber v. United States, 332 F.2d 629 (2d Cir. 1964); Cole v. United States, 635 F. Supp. 1185 (N.D. Ala. 1986); Barnson v. United States, 630 F. Supp. 418 (D. Utah 1985), *aff'd*, 816 F.2d 549 (10th Cir.), *cert. denied*, 484 U.S. 896 (1987); *In re* Consol. U.S. Atmospheric Testing Litig., 616 F. Supp. 759 (N.D. Cal. 1985), *aff'd*, 820 F.2d 982 (9th Cir. 1987), *cert. denied*, 485 U.S. 905 (1988); Timothy v. United States, 612 F. Supp. 160 (D. Utah 1985); Johnston v. United States, 597 F. Supp. 374 (D. Kan. 1984); Begay v. United States, 591 F. Supp. 991 (D. Ariz. 1984), *aff'd*, 768 F.2d 1059 (9th Cir. 1985); Allen v. United States,

future will undoubtedly bring even more claims against private defendants from what has become a very large non-governmental radiation industry. Courts will struggle to do justice in this impassioned and highly technical area of the law.

The purpose of this article is to assist courts in adjudicating radiation injury cases. Analyzing such cases requires a basic understanding of radiation physics, the way in which radiation causes injury, and its application and effects upon tort theory. This article describes radiation injury and suggests tests and standards for radiation litigation based on traditional tort law and the author's extensive personal experience with the radiation injury problem.[4] Admittedly, there are few court opinions that can be cited as direct authority for many of the proposals given; nevertheless, cases support the elements of the proposed methods even though they do not explicitly formulate the effective tests. The article will interest litigators who try such cases and establish precedents, and therefore specific comments regarding litigation strategy are made where appropriate.

Part I of this article provides a short introductory history of the discovery of radiation and explains the fundamental physics of radiation and radiation injury. Where applicable, part I relates these fundamentals to radiation litigation. Part II discusses the tort law of negligence and strict liability and how traditional theories can be misapplied in radiation injury cases. This part proposes alternative standards or tests which provide for a more sound adjudication of such actions. Defenses that have been used successfully by the United States as defendant are presented, and defenses that may hold merit for all defendants are identified. Part II concludes by suggesting ways to minimize the effects of jury confusion in these complex actions and clarify the use of federal safety regulations in legal tests.

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588 F. Supp. 247 (D. Utah 1984), *rev'd*, 816 F.2d 1417 (10th Cir. 1987), *cert. denied*, 484 U.S. 1004 (1988); Fried v. United States, 579 F. Supp. 1212 (N.D. Ill. 1983); Hampton v. United States, 575 F. Supp. 1180 (W.D. Ark. 1983); Prescott v. United States, 523 F. Supp. 918 (D. Nev. 1981), *aff'd*, 731 F.2d 1388 (9th Cir. 1984).

[4] The author has approximately 25 years of professional experience in the radiation industry. He has served as a nuclear reactor physicist, a radiological physicist in the medical use of radiation and radioactive materials, and as a health physics consultant to hospitals, universities, utilities, and industry in the safe use of radiation and radioactive materials.

I. RADIATION PHYSICS AND RADIATION INJURY

A. The Discovery of Radiation

On November 8, 1895, Wilhelm Conrad Roentgen (1845-1923) first recognized a penetrating radiation which he called x-rays.[5] While the discovery of x-rays had a profound effect upon science, x-ray exposure carried the risk of radiation injury. Several researchers experienced radiation injury within years following Roentgen's discovery.[6] Presumably Roentgen and his wife received very high x-ray exposures during their lifetimes. Roentgen died from cancer of the rectum.[7] Possibly, Roentgen's cancer death illustrated the radiation injury that manifests itself not acutely but years after the exposure.

X-rays are manmade, but other forms of radiation occur in nature. In 1896, Antoine Henri Becquerel (1852-1908) discovered a radiation similar to x-rays arising from uranium.[8] Shortly thereafter, Marie Curie (1867-1934) identified similar radiation from thorium and two new elements she discovered, radium and polonium.[9] This process of giving off radiation is called radioactivity.[10] Curie died at age 66 of aplastic anemia,[11] a disease compatible with radiation injury resulting from long exposure to bone-seeking, heavy radioactive elements.

The discovery of radiation and radioactive materials led to their early use by the medical community. Two new medical disciplines, diagnostic radiology and radiation therapy, emerged rapidly. The penetrating quality of x-rays aided medicine by allowing physicians to see internal structures of the body. The cell-injuring capabilities of radiation proved to be an effective treatment for cancer. Medicine became and continues to be the largest man-made source of radiation exposure to the public.

Experimental discoveries slowed as theoretical scientists attempted to assimilate the information generated by the new radiations. In 1934, the daughter of Madame Curie, Irene Curie (1897-1956), and her husband, Jean Frederic Joliot (1900-1958), discovered that man-made radioactivity could be produced in

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[5] J. DEL REGATO, RADIOLOGICAL PHYSICISTS 3 (1985).

[6] *See id.* at 5-6.

[7] *Id.* at 9.

[8] *Id.* at 14.

[9] *Id.* at 15.

[10] *See* H. JOHNS & J. CUNNINGHAM, *supra* note 1, at 71.

[11] J. DEL REGATO, *supra* note 5, at 21.

materials which are normally stable in nature.[12] This important discovery lead to the production of many radioactive substances now used in biology, medicine and industry. In 1935, Joliot foresaw nuclear power and predicted that researchers would find ways of releasing enormous energy by a "veritable chemical chain reaction"[13] not previously known to exist.

Seven years later, on December 2, 1942, Enrico Fermi (1901-1954) showed that a nuclear chain reaction could be sustained when the first nuclear reactor, a uranium-graphite pile located in the west stands of the University of Chicago stadium, achieved criticality.[14] This set the stage for two additional sources of radiation exposure to man: nuclear weapons and nuclear power.[15]

B. The Physics of Radiation

To understand the physics involved in radiation injury cases, matter can be represented by the simple atomic model. In this model all matter is comprised of atoms of the basic elements.[16] Atoms have a nucleus and orbiting electrons. The nucleus is composed of positively charged protons and neutrally charged neutrons. Negatively charged electrons circle the nucleus in planet-like orbits. The chemistry of nature operates in these electron orbits. From the simple molecule of water (H_2O) to the complex molecules of life (DNA, RNA, genes and chromosomes), orbital electrons comprise the "glue" which maintains molecular structure and integrity. It is radiation's interference with these orbiting electrons, nature's glue, which may cause radiation injury.

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[12] *Id.* at 102-03. Many materials not normally radioactive can be made radioactive by bombarding them with subatomic particles such as neutrons and alphas. H. JOHNS & J. CUNNINGHAM, *supra* note 1, at 71-72.

[13] J. DEL REGATO, *supra* note 5, at 103 (quoting M. GOLDSMITH, FREDERIC JOLIOT-CURIE, A BIOGRAPHY (1976)).

[14] *Id.* at 152-55.

[15] Nuclear power usually denotes the use of nuclear reactors to produce heat for electricity generation. The nuclear power industry is composed of utilities, nuclear fuel producers and others. For this article, the nuclear power industry is considered a part of the larger radiation industry. The radiation industry is comprised of all entities using radiation or producing radiation as a byproduct of their activities, whether scientific, medical, industrial, or for national security.

[16] Matter is the substance of which a physical object, living or otherwise, is composed. Normally, matter is made up of 92 naturally occurring atoms called elements. *See infra* Table 2. These elements range from the lightest, hydrogen, composed of a nucleus containing a single proton, to the heaviest, uranium, composed of a nucleus containing 92 protons and about 144 neutrons. Heavier man-made elements also exist.

Radiation is generated in the atom's nucleus. Unstable nuclei, known as radioactive isotopes,[17] seek a more stable state by giving off energy through radiation. This process is known as radioactivity. The radiation emitted may take several forms, including energetic electrons (beta particles), energetic positively charged electrons (positrons), heavy particles (alphas), and photon energy bundles (gamma rays).

Although radiation is born in the nuclei, the primary interaction of radiation with matter occurs outside the nucleus in the orbits of electrons. The radiation emitted from the nucleus strips electrons from their atoms and sets them in motion as energetic particles. This process is called "ionization."[18] Ionization is the primary way in which all radiation imparts energy to matter. Once the electrons are set into motion by ionization they cause other ionizations until the total energy of the initial radiation is expended. Through this process of ionization, radiation interferes with orbiting electrons, which may affect molecular structure and cause radiation injury.

As ionization occurs in matter, "tracks" or trails of ionized atoms and molecules are produced. Cell damage depends on the density of these ionization tracks.[19] An understanding of radiation injury requires a description of how ionization spatially deposits energy within the individual cells. The density of the ionization is described by the concepts of *low linear energy transfer* (low LET) and *high linear energy transfer* (high LET). Low LET radiation results in sparsely populated ionization tracks while high LET radiation causes very dense ionization tracks.[20] Low LET radiation includes gamma rays, x-rays, beta particles, and the energetic electrons set in motion by the ionization process. High LET radiation includes alpha particles, energetic

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[17] Isotopes are different forms of an element which contain the same number of protons in the nucleus but which contain a different number of neutrons. For example, the isotopes carbon 12 and carbon 14 both contain six protons in the nucleus, but the former contains six neutrons and the latter contains eight neutrons. Both carbon 12 and carbon 14 occur in nature. Carbon 12 comprises most of the carbon on earth and is stable. On the other hand, carbon 14 is a radioactive isotope, and comprises a very small portion of naturally occurring carbon. Carbon 14 is produced by the interaction of cosmic radiation, originating in our sun or in deep space, with the Earth's upper atmosphere. Carbon 14 represents one of the many sources of radiation from which man never escapes. *See* H. Johns & J. Cunningham, *supra* note 1, at 12-14.

[18] *Id.* at 133, 220.

[19] *Id.* at 671-72.

[20] *Id.* at 672-73.

charged particles produced in accelerators (such as cyclotrons), and protons set in motion by exposure to energetic neutrons.

The specific damage to cells from low LET radiation appears to differ somewhat from damage caused by high LET radiation.[21] Cell damage from low LET radiation is more dependent on both radiation dose rate and total dosage than cell damage from high LET radiation. LET is often an important concept in radiation injury cases since a given exposure of high LET radiation may cause more cell damage than a similar exposure to low LET radiation.

C. The Units of Radioactivity

To understand radiation injury cases, it is important to know several terms and units of measurement used to describe radiation injury and radioactivity. Modern health physics[22] uses the LET considerations described above to modify absorbed energy doses, measured in units called *rads*,[23] so that they better describe the hazard from a specific form of radiation. The *quality factor*, Q, is used for this purpose.[24] Quality factor values are multiplied by absorbed doses to produce a quantity called the *rem*. The rem is the unit of measure used for radiation protection and governmental regulatory purposes. It is a term relevant to radiation injury law since it quantitatively describes a person's exposure to a specific form of radiation, incorporating a recognized hazard factor.

The emission of radiation by a single nucleus is called a *disintegration*. This is perhaps a misnomer since the nucleus is only slightly changed by the process. The term disintegration is much like a legal term of art and causes no confusion within the

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[21] *Id.* at 675-76.

[22] Health physics is the name of the profession whose primary activity is radiation safety.

[23] The rad is the basic unit of measure of energy imparted from radiation to any material through ionization. In 1980, the International Commission on Radiation Units and Measurements ("ICRU") proposed a new unit called the *gray*, which is equal to 100 rads. Both the rad and gray are difficult to measure, and frequently an intermediate and easier measure is made. This measurement describes the ability of radiation such as x-rays, gamma rays, and high energy electrons to ionize a gas such as air. Historically, the unit of measure for x- or gamma ray's ability to ionize air was the *roentgen*. The roentgen, however, is not defined for many of the high energy x-ray beams produced today or for radiations other than x- or gamma rays. Thus, scientists use complex mathematical manipulations to convert ionizations in air directly into fairly precise values of rads without an intermediate determination of roentgens.

[24] *See infra* Table 3 (appendix).

scientific community. Radioactivity is measured by the number of disintegrations per second. The historic unit of measure for radioactivity is the *curie*, which equals 3.7×10^{10} disintegrations per second.[25]

Another basic measurement reflecting the properties of radioactivity is the physical *half-life* of elements. The half-life for a specific radioactive material is the time it takes for one-half of the radioactive nuclei to disintegrate.[26] Half-lives for different radioactive isotopes vary markedly, ranging from very small fractions of a second to many thousands of years.[27] Half-life is a factor in determining the duration of hazard in radiation cases involving ingested or inhaled radioactive materials.

D. *Radiation Injury to the Cell*

Cell damage from radiation results primarily from two causes: first, indirect damage caused by radiation-produced toxicity within the cell; and second, direct damage to the critical molecules of life. The toxicity produced within the cell occurs from the interaction of radiation within cellular water.[28] Direct damage results from the ionizations within the molecules of life themselves, *i.e.*, DNA, RNA, genes, etc. Such ionization can interrupt the intricate functions and processes of these complex molecules by breaking their molecular chains and allowing abnormal recombinations.

In relating cell damage to radiation injury, two important facts must be considered. First, the molecules of life must be damaged before radiation exposure will manifest itself as cell damage, since only these molecules carry the information of function and reproduction. Second, damage to the molecules of life occurs naturally with or without radiation insult. Such dam-

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[25] In 1980, the ICRU proposed a new unit of measure of radioactivity called the *becquerel* (Bq), which equals one disintegration per second.

[26] For example, if one starts with two curies of radioactivity, then one curie will remain after one half-life, and one-half curie will remain after the second half-life.

[27] Table 4, *infra* (appendix), gives half-life values for some isotopes commonly associated with radiation injury litigation.

[28] Water makes up 70% of the cell. Radiation striking the cell most often interacts with electrons that are a part of the water molecule. Radiation causes a complex array of toxic substances when it interacts with water. Interactions include the following:

$H_2O — H_2O + e — H_2O + e(aq)$

$H_2O — .OH + H$

$H_2O — H_2O^* — H. + .OH.$

The toxicity is produced within the cell; thus, it is in close proximity to the delicate molecules of life. *See* H. JOHNS & J. CUNNINGHAM, *supra* note 1, at 673-75.

age is a part of the process which characterizes life and occurs thousands of times each day in every individual. The cell has highly efficient mechanisms for repairing this damage[29] and preventing injury to the organism as a whole.[30] Nevertheless, there can be radiation-induced cell damage which causes manifest injury to the organism. Such damage does not appear to differ in type from that which is normally repaired, but for some reason the repair process seems to fail.

E. *Radiation Injury to the Organism*

Radiation-induced cell damage may affect the organism in four different ways. First, the cell damage may be repaired without injury to the organism. Second, the cell damage may cause cell death. Cell death is a common, natural occurrence and usually causes no effect in the organism, but a very large number of cell deaths in specific cell types can cause acute injury to the organism. Third, the damaged cell may continue to function but lose its ability to reproduce. Again, this is generally not injurious to the organism, but when it occurs in a sufficient number of specific cells, acute injury can result. Fourth, radiation damage to a cell which goes unrepaired may modify the cell's code for function or reproduction in such a manner that injury to the organism is manifest years later.

As these effects suggest, radiation injury to the organism manifests itself in two distinct ways. First, acute injury may occur when a person is exposed to large doses of radiation over a short period of time. Acute injury becomes manifest soon after exposure and is easily identified. Because the effects are apparent and readily identifiable, acute radiation injury presents no special problems to tort law.

The second type of injury, late injury, does not become manifest for many years. Late injury is often called stochastic injury because its occurrence appears to follow statistical laws of probability. It is indistinguishable from injury which occurs naturally or from causes other than radiation. Late injuries manifest themselves as a general compromise in the health of the individual exposed to radiation. The long lag time between radiation exposure and manifest injury coupled with the indeter-

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[29] *See* Giannelli, *DNA Repair in Human Diseases*, 5 J. CLINICAL AND EXPERIMENTAL DERMATOLOGY 119, 119-22 (1980).

[30] *See* H. JOHNS & J. CUNNINGHAM, *supra* note 1, at 689-91, 705-06.

minacy of causation significantly complicate the adjudication of late radiation injury cases. In this sense, the issues and problems involved in late radiation injury cases parallel the latent injury and indeterminate causation problems of toxic waste torts.[31]

F. Mathematical Models

The most significant effects of late radiation injury are cancer and leukemia. Such radiation-induced cancers and leukemias can be assessed only through inexact mathematical models.[32] The models are developed from statistical data regarding populations which have received large exposures to radiation, *e.g.*, Japanese atomic bomb survivors.[33] They are developed for scientific purposes and for input into the governmental regulatory process for radiation protection. They were not designed for adjudicatory process, but the statistical models have been pressed into its service.

For low LET radiation there are four basic models which describe late effects: the general form model, the linear model, the quadratic model, and the linear-quadratic model.[34] For the regulatory process, the scientific community generally agrees that the linear-quadratic model best predicts radiation-injury effects for low LET radiation.[35] This model assumes that radiation injury per unit dose is somewhat less for lower total doses than for higher total doses. However, the linear-quadratic model as-

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[31] *See generally* Note, *The Inapplicability of Traditional Tort Analysis to Environmental Risks: The Example of Toxic Waste Pollution Victim Compensation*, 35 STAN. L. REV. 575 (1983). Two facts distinguish the adjudication of radiation injury from toxic waste injury. First, the radiation industry has been highly regulated for over 30 years. Second, a great deal of research has been done on radiation injury. The toxic waste industry, in contrast, does not have a long history of strict government regulation and toxic waste injury is not yet well researched.

[32] *See* COMMITTEE ON THE BIOLOGICAL EFFECTS OF IONIZING RADIATIONS, NAT'L RESEARCH COUNCIL, THE EFFECTS ON POPULATIONS OF EXPOSURE TO LOW LEVELS OF IONIZING RADIATION: 1980 at 136-37 (1980) [hereinafter BEIR III].

[33] *Id.* at 143.

[34] *See infra* Figure 1 (appendix).

[35] Of the 21 eminent scientists who produced BEIR III, 19 endorsed the linear-quadratic model as best describing the relationship between radiation exposure and manifest injury for purposes of radiation protection legislation. BEIR III, *supra* note 32, at iii-ix. One scientist argued for the linear model. *Id.* at iii, 227-53. Another argued for the quadratic model. *Id.* at iii, 254-64. The quadratic model predicts there is less effect per unit dose of radiation at lower radiation doses than at higher doses. The linear model predicts equal effects per unit dose regardless of total dose. The linear model predicts greater effects (*i.e.*, more cancer production) at lower doses. The linear-quadratic model predicts results between the two other models.

sumes no threshold for injury, *i.e.*, all radiation exposure is assumed to be injurious.[36] The "no threshold" theory is employed as a conservative approach to the regulatory process and is not scientifically proven.[37]

The mathematical models are used to produce "induced cancers versus radiation exposure" data. The data may be of value to a court in evaluating the causation element in radiation injury cases. Data for low LET radiation induced cancers appear in the 1980 report by the National Academy of Sciences Committee on the Biological Effects of Ionizing Radiation (BEIR).[38] Other scientifically recognized data regarding radiation injuries appear in the reports of the National Council of Radiation Protection and Measurements (NCRP),[39] the International Commission on Radiation Units and Measurements (ICRU),[40] and the International Commission of Radiological Protection (ICRP).[41] Some of these reports contain specific data on high LET radiation.[42]

While there are many other sources of sound scientific data, there is also much literature in this area which is of dubious character.[43] Any document which presents positions or data

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[36] From before World War II, scientists charged with providing information for radiation protection legislation chose to adopt the hypothesis that no threshold existed for radiation injury, *i.e.*, all radiation exposure is injurious. This is clearly a conservative approach since standard toxicological science generally assumes that there is a safe threshold for all harmful chemicals. It is also clearly adverse to the weight of scientific evidence. Many studies on radiation injury, including BEIR III, have shown fewer cancer deaths in populations exposed to low levels of radiation. Regulators ignore these findings when considering protective legislation and regulations. However, the goals of protective legislation differ from the goals of radiation litigation. It is quite possible that the eminent scientists who produced BEIR III would propose a far less conservative hypotheses if charged with developing measures of causation for radiation injury litigation.

[37] Regarding the threshold issue, the scientists of BEIR III state that "[o]n statistical grounds . . . the existence or nonexistence of a threshold dose is practically impossible to determine. . . ." BEIR III, *supra* note 32, at 22.

[38] *See supra* note 32.

[39] Titles and information on the NCRP publications may be obtained by directing an inquiry to: NCRP Publications, 7910 Woodmont Ave., Suite 1016, Bethesda, Maryland 20814.

[40] Titles and information on ICRU publications may be obtained by directing inquiry to: USA, Pergamon Press, Fairview Park, New York 10523.

[41] Titles and information on ICRP publications may be obtained by directing inquiry to: USA, Pergamon Press, Fairview Park, New York 10523.

[42] *See, e.g.*, COMMITTEE ON THE BIOLOGICAL EFFECTS OF IONIZING RADIATIONS, NAT'L RESEARCH COUNCIL, HEALTH RISKS OF RADON AND OTHER INTERNALLY DEPOSITED ALPHA-EMITTERS (1988).

[43] *See, e.g.*, J. GOFMAN & E. O'CONNOR, X-RAYS: HEALTH EFFECTS OF COMMON EXAMS (1985). This book, published by Sierra Club Books, does not explain the scientific

which vary significantly from the sources listed above is very likely to be outside the consensus of expert opinion.

G. Sources of Radiation Exposure

Radiation produced by a defendant is never the only radiation to which the plaintiff is exposed. Life exists in a virtual sea of ionizing radiation generated by natural sources and human technology. Virtually everything in this world is radioactive: soil, buildings, clothes, the paper and ink of this page, even man's physical body.[44] The largest source of whole body radiation exposure to our population is natural background radiation.[45] It arises from naturally occurring heavy elements such as uranium, thorium, radium, radon and polonium, and from lighter radioactive isotopes such as potassium 40, carbon 14 and hydrogen 3. There is no protection from natural background radiation. In addition to radiation from the Earth, cosmic radiation arising primarily from our sun also adds to our radiation exposure.

The medical use of diagnostic x-ray is the largest source of man-made radiation exposure. The worldwide atmospheric testing of nuclear weapons in the 1950s and early 1960s produced the second largest source of man-made radiation to the public. Other sources of radiation exposure include the nuclear power industry, other industrial users of radiation, research activities, building materials, television receivers, and airline travel.[46]

Although everyone is exposed to radiation, and radiation causes cell damage, injury to the organism is infrequently manifested. The courts face the problem of determining who has a cause of action for radiation injury and how tort theories can best provide justice for both the plaintiff and the defendant in such complicated cases.

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derivation of cancer risks and cancer deaths which it presents. Such a work would not be considered valid by a consensus of the scientific community.

[44] *See infra* Table 7 (appendix).

[45] *Id.*

[46] *Id.*

II. Tort Law Applied to Radiation Injury Actions

A. *Negligence*

1. Duty

A tort based on negligence requires a duty owed to the plaintiff by the defendant. In practice, the duty issue presents little problem in adjudicating radiation injury cases. Duty arguments can be predicated upon either common law theory or regulatory standards.[47] The use of radiation is highly regulated, and the regulations require that radiation be used in a safe manner. Dean Prosser details the difficulties in formulating an all-encompassing standard for duty, but concludes, "No better general statement can be made, than that courts will find a duty where, in general, reasonable men would recognize it and agree that it exists."[48]

Both the plaintiff and the defendant are properly served in finding that the radiation user has a duty to conduct his activities in such a manner so that he does not cause a recognizable injury to others. Outside of an affirmative defense, such as the "discretionary function" defense available to the federal government,[49] it will be difficult for a defendant to successfully argue "no duty."[50] Perhaps no duty is owed the malicious trespasser (*e.g.*, the terrorist, burglar, disruptive protestor, *etc.*) and maybe there is no duty to protect against unforeseeable injury, but so far neither of these arguments have been tested in a late radiation injury action.

2. Breach of duty

The element of breach of duty is a critical issue in the adjudication of radiation cases and one that presents significant problems. The problems arise out of the necessity to create or adopt a legally sufficient standard by which to measure breach.

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[47] In 10 C.F.R. §§ 1-171.25 (1989), the Nuclear Regulatory Commission (NRC) establishes standards for the use of all nuclear reactors, all radioactive materials produced as by-products of fission, and all naturally occurring fuel materials. The Federal Bureau of Radiological Health sets the standards for the industrial and medical use of x-ray devices. State regulations usually include police control of other sources of radiation and radioactive materials not covered by federal law.

[48] W. Prosser, Handbook of the Law of Torts 327 (4th ed. 1971).

[49] The discretionary function defense is described *infra* note 102.

[50] *See, e.g.*, Allen v. United States, 588 F. Supp. 247, 347-58 (D. Utah 1984), *rev'd*, 816 F.2d 1417 (10th Cir. 1987), *cert. denied*, 484 U.S. 1004 (1988).

The answer to the problem in this highly regulated area should be straightforward: compliance or noncompliance with applicable government safety standards provides an excellent measure of breach. One of the strongest comments in this regard comes from Professors Stason, Estep and Pierce.[51] These authors recommend that where the Nuclear Regulatory Commission (NRC) (formerly the Atomic Energy Commission) makes a deliberate determination on the specific issue of maximum radiation levels, a judge should hold that compliance with the regulatory standard is proof of reasonable conduct:[52]

> Compliance or noncompliance with industry safety codes certainly should be given weight, and in most cases perhaps should constitute *prima facie*, if not conclusive, proof, when no evidence to the contrary is introduced. Courts, however, should avoid a rigid rule and decide individual cases on the basis of the specific evidence produced.[53]

If judges choose to use compliance with government standards as *prima facie* reasonableness, they must be wary of the evidence against reasonableness. If there is compliance with applicable regulations, the evidence must overcome the presumption of reasonableness; at a minimum, it must satisfy the preponderance of evidence standard. Judge Kelly used the test properly in *Johnston v. United States* when he said, "This Court readily adopts these exposure standards since it is apprised of no reason to disagree with the national and international consensus of eminent radiation scientists, the view of [plaintiff's expert witnesses] notwithstanding."[54] Moreover, where there is compliance, no theory should operate to shift the burden of proving the absence of breach to the defendant. A defendant who has substantially complied with stringent federal safety regulations should not bear the burden regarding breach. Unfortunately, this is not uniformly the law today.

Insight regarding the weight which should be given to compliance with federal regulations in analyzing radiation injury cases was given by the United States Supreme Court in *Silkwood v. Kerr-McGee Corp.*[55] *Silkwood* was a radiation injury

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[51] E. Stason, S. Estep & W. Pierce, Atoms and the Law (1959).

[52] *Id.* at 124-28.

[53] *Id.* at 155.

[54] 597 F. Supp. 374, 392 (D. Kan. 1984).

[55] 485 F. Supp. 566 (W.D. Okla. 1979), *aff'd in part*, 667 F.2d 908 (10th Cir. 1981), *rev'd*, 464 U.S. 238 (1984). The administrator of Ms. Silkwood's estate brought a strict

case brought against a nuclear facility on behalf of an employee. At the trial level, the sole issues before the jury were whether Kerr-McGee was responsible for the plutonium's escape and whether Silkwood was injured as a result of the escape.[56] Kerr-McGee asserted that their compliance with federal regulatory standards was "conclusive evidence of non-negligent conduct," and that it prevented the imposition of state strict liability.[57] However, the court instructed the jury that it was not bound by the federal regulations, *i.e.*, the jurors themselves were to determine what constitutes the exercise of reasonable care, then measure the defendant's conduct according to their own standard.[58] The jury found for the plaintiff and awarded both compensatory and punitive damages.[59]

On appeal, the Tenth Circuit reversed the award of punitive damages, holding that the award infringed on an area which was "occupied" by Congress and therefore preempted by federal law.[60] In a five-to-four decision, the Supreme Court reversed the Tenth Circuit and reinstated the award of punitive damages, holding that the award was *not* preempted since Congress had not sought to exclusively occupy this area of the law.[61] Speaking for the dissent, Justice Powell lamented, "Until today, I had not understood that a jury lawfully could be instructed on the basis of its own determination of 'human credence' to conclude that a presumptively valid federal regulation simply could be ignored."[62]

Although the decision did not directly address the use of federal standards for determining elements such as breach of duty, it does appear to send a message to lower courts: the deci-

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liability action against Kerr-McGee to recover for injuries resulting from contamination of Ms. Silkwood's person and apartment by radioactive plutonium from the nuclear facility operated by Kerr-McGee. The jury found for Silkwood, and the district court denied motions for judgment notwithstanding the verdict and new trial. *Id.* at 594. The Tenth Circuit reversed the punitive damages award, holding that such damages were preempted by federal law. 667 F.2d at 922. Upon certiorari, the Supreme Court reversed the Tenth Circuit and held that the award of punitive damages was not preempted by federal law. 464 U.S. at 258.

[56] *Silkwood*, 485 F. Supp. at 571.

[57] *Id.* at 577.

[58] *Id.* at 598 (Jury Instruction No. 10).

[59] *Id.* at 570.

[60] *Silkwood*, 667 F.2d at 923.

[61] *Silkwood*, 464 U.S. at 256.

[62] *Id.* at 284 (Powell, J., dissenting, joined by Chief Justice Burger and Justices Marshall and Blackmun).

sion seems to approve of juries sitting in judgment of established governmental standards even in this highly sophisticated and technical area of radiation injury.

Today, *Silkwood* is the law, but it is not sound law. Admittedly, reasonableness rather than compliance with government regulations has always been the standard for determining breach of duty. But surely the inference of reasonableness is better measured by federal regulations which have evolved through years of scientific research rather than some arbitrary standard a jury of non-experts thinks up during the heat of litigation. As Justice Powell stated, "[Juries] are unlikely . . . to have even the most rudimentary comprehension of what reasonably must be done to assure the safety of the employees and the public."[63] Juries should not be left to establish their own safety criteria in this highly complex and technical area of the law. The radiation industry is extremely important; a jury's ad-hoc safety criteria serves neither justice nor public policy. This author recommends that the *Silkwood* decision be overturned, legislatively corrected, or read narrowly so that compliance with federal regulations may still be determinative of reasonable conduct.

3. *Causation*

Courts must realize that causation for late radiation injury is more than merely complicated — it is indeterminate.[64] The primary late effect of radiation exposure is the possible induction of cancer or leukemia. Both cancer and leukemia frequently occur without radiation insult and may affect as many as one out of every four persons.[65] Although science and medicine recognize a causal link between radiation and these late effects, this does not mean that everyone exposed to radiation will develop cancer or leukemia.[66] Moreover, it is impossible to trace cancer or leukemia occurring in an individual exposed to radiation di-

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[63] *Id.* at 285 (Powell, J., dissenting).

[64] Titus & Bowers, Konizeski *and the Warner Amendment: Back to Ground Zero for Atomic Litigants*, 1988 B.Y.U. L. REV. 387, 391-92; DiStefano, *Dangerous Doses?*, 16 BRIEF 26, 28-30 (Spring 1987); Udall, *Toxic Chemicals and Radiation*, 38 MERCER L. REV. 511, 518 (1987); Ball, *The Problems and Prospects of Fashioning a Remedy for Radiation Injury Plaintiffs in Federal District Court: Examining* Allen v. United States, 1985 UTAH L. REV. 267, 293-95; Comment, *Probability of Causation in Radiation Tort Litigation*, 24 TULSA L.J. 479, 481-508 (1989).

[65] AMERICAN CANCER SOCIETY, *supra* note 2, at 2. In 1981 alone, over 800,000 people in the United States were diagnosed as having cancer.

[66] BEIR III, *supra* note 32, at 136.

rectly to the exposure. Radiation-induced cancer and leukemia are indistinguishable at both the organism and cellular level from those induced by other causes.[67] No medical test exists which can determine that such late injuries were caused specifically by radiation. These facts combine to create significant obstacles for courts or juries analyzing the element of causation.

Cancer is characterized by the loss of an organism's normal control of cell proliferation and/or function. Cancer can occur in any of the tissues comprising the organism, but tissues vary in sensitivity to radiation-produced cancers.[68] By comparing the relative sensitivities of radiation-produced cancers in various tissues, courts can better determine the probability of radiation-induced cancer and defendant's causation. The relative periods of seeming inactivity between the time of radiation exposure and manifest injury, known as latent periods, also provide additional guidance in distinguishing radiation induced cancers and determining causation.[69]

In summary, science and medicine can provide courts with only the following facts to assist in determining causation:

(1) Radiation causes cell damage, but most cell damage is repaired without manifesting itself as injury to the organism.

(2) Cells damaged by radiation can sometimes cause late injury such as cancer or leukemia in the organism.

(3) The incidence of radiation-induced cancer and leukemia depends upon the amount of radiation received, but not in a direct one-to-one (linear) fashion.

(4) Cancers and leukemia induced by radiation are indistinguishable from those occurring naturally or from other non-radioactive causes.

(5) Mathematical models can statistically predict increased cancer and leukemia incidence in large populations which are exposed to large amounts of radiation, but they cannot uniquely determine causation for the individual.

(6) The mathematical models are not precise, especially at low exposures (below ten rems).[70]

(7) The mathematical models for high LET radiation vary from models for low LET radiation.

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[67] *Id.* at 202-21.

[68] *Id.* at 137. *See also infra* Table 6 (appendix).

[69] *See infra* Table 5 (appendix).

[70] BEIR III, *supra* note 32, at 144.

> (8) The latency period for most radiation-induced cancers is greater than ten years. The latency period of radiation-induced leukemia and some bone cancers is from three to thirty years.
>
> (9) Some types of cancers are more likely caused from radiation than are other types.

Notwithstanding the judiciary's traditional abhorrence of statistical evidence,[71] these limited facts must be fashioned into a test for analyzing causation which is least prejudicial to either the plaintiff or the defendant. These facts can serve the court best in the application of a five-point test:

1. The court should determine if and at what levels the plaintiff was exposed to radiation. Federal and state regulations require that individual workers be monitored for exposure; these data can be used to determine the exposure. For those people who are not so monitored, an expert will be necessary to estimate exposure.[72] Data used for expert estimates will include such factors as proximity to the radiation source, duration of exposure, partial shielding of radiation, *etc.* If the plaintiff cannot demonstrate that he received exposures in excess of applicable regulatory standards,[73] the court should find for the defendant.

2. The court should determine the specific injury resulting from the alleged radiation, *i.e.*, leukemia, thyroid cancer, lung cancer, prostate cancer, *etc.* If the specific injury is one which is not associated with radiation, *e.g.*, prostate cancer, the court should find for the defendant.[74]

3. The court should determine when the exposure to radia-

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[71] An example of a court's distaste for statistical evidence is found in *Johnston v. United States*, where the court stated, " A statistical method which shows a greater than 50% probability does not rise to the required level of proof [under Kansas law]. . . . A simple review of [evidence presented by plaintiffs' witnesses] shows that their analysis that plaintiffs' cancers were caused by radiation . . . is not a medical opinion but is statistical sophistry." 597 F. Supp. 374, 412 (D. Kan. 1984).

[72] *See, e.g.*, Allen v. United States, 588 F. Supp. 247 (D. Utah 1984), *rev'd*, 816 F.2d 1417 (10th Cir. 1987), *cert. denied*, 484 U.S. 1004 (1988). *Allen* involved 24 "bellwether" claims arising out of nearly 1,200 plaintiffs who alleged radiation injury against the United States as a result of radioactive fallout from open-air atomic bomb tests of the 1950s and 1960s. The trial court found for 9 of the 24 plaintiffs. On appeal, the Tenth Circuit reversed, holding that the government's actions were protected as a "discretionary function." 816 F.2d 1417. The trial court's opinion in *Allen* gives a good description of the difficulties in reconstructing exposure levels years after the incident. 588 F. Supp. 247.

[73] *See, e.g.*, 10 C.F.R. §§ 20.101, 20.103-04 (1989) (NRC standards for protection against radiation).

[74] *See Allen*, 588 F. Supp. at 429-30 (involving cancer of the kidneys).

tion occurred, then establish the time period between exposure and manifestation of injury. If the period is substantially outside normal latencies,[75] the court should find for the defendant.[76]

4. (a) The court should require expert testimony on the number of alleged radiation-induced cancers or leukemias that would be expected if a large population was exposed to the amount of radiation determined in step 1, *supra*, by using mathematical models. An estimate of the probability that the cancer was caused by the specific radiation exposure to the plaintiff is found by dividing the number of cancers predicted by the model by the size of the population. For example, if the model predicts 3,000 radiation-induced cancers in a population of 1,000,000, the probability will be 0.003 that a cancer will be caused in an individual by a specific radiation exposure. (b) The court should then require expert testimony on the number of cancers which would occur in the population without the radiation insult.[77] In addition to natural causes, the court should consider plaintiff's exposure to other non-radiation cancer-causing agents, such as cigarette smoking, *etc.*[78] The estimate of the probability that a cancer resulted from non-radiation causes is found by (1) determining the predicted number of naturally-occurring cancers and then dividing it by the size of the study population, and (2) determining the predicted number of cancers resulting from the non-radiation cancer-causing agents to which plaintiff was exposed, then dividing it by the size of the study population, and (3) adding together the probabilities of cancer resulting from natural causes and other carcinogenic agents to which plaintiff was exposed. For example, if the statistical data predicts 68,000 natural cancers in a population of 1,000,000, there is a probability of 0.068 that the cancer resulted from natural causes. If plaintiff was a cigarette smoker and the data on cigarette smoking predict 20,000 resultant cancer cases in a population of 1,000,000, the probability is 0.02 that the cancer resulted from

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[75] Whether or not the latency period is outside normal latency periods will be a legal determination based on scientific evidence. The age of the plaintiff at the time of the alleged exposure may be important. *See id.* at 430-31.

[76] In *Allen*, the court did not explicitly use this prong of the test to deny plaintiff's recovery; however, the attention given to plaintiff Bradshaw's latency period suggests that the court was willing to consider this as a factor for recovery. *See id.*

[77] The determination of naturally occurring cancers requires statistical data. This data may be obtained from the American Cancer Society. Tumor registries of large urban hospitals or university medical centers may also be of some value.

[78] *See, e.g.*, *Allen*, 588 F. Supp. at 435.

cigarette smoking. Combining the two sources, the probability is 0.088 that the cancer resulted from some non-radiation cause.

5. The court should then apply the "more likely than not" test. If the probability of non-radiation cancers is greater than or equal to the probability for radiation-induced cancers, the court should find for the defendant. If the probability for non-radiation cancers is less than the probability of radiation-induced cancers, then the court should find for the plaintiff. Here the example is given in general terms. In practice, steps 3 and 4 must be applied to specific cancers such as leukemia, thyroid cancer, lung cancer, *etc.*

The "more likely than not" test favors the defendant to the same extent that tort law has always favored the defendant: the plaintiff must show by a preponderance of the evidence that the defendant was the legal cause of the injury. In the example cited above, the radiation used by defendant would have to result in 88,001 cancers in a population of 1,000,000 before liability would attach. Though the test is stringent, it is not a bar to the plaintiff.[79]

In radiation cases, courts might apply a "substantial factor" analysis, thereby shifting the burden to the defendant to prove that he or she did not cause the injury.[80] However, such a method is inappropriate. True, it is difficult for the plaintiff to show that his or her cancer or leukemia was caused by radiation, but shifting the burden to the defendant is a misuse of tort theory for this type of injury. The substantial factor test evolved in tort law to correct the under-inclusiveness of the "but for" test and allow recovery in cases of joint causation: if two defendants

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[79] In *Allen*, the trial court struggled to properly apply what amounted to the five-point test. *See id.* The court properly applied the test in finding against 15 plaintiffs and for four plaintiffs who had contracted leukemia. *Id.* at 429-43. Whether or not the court followed the suggestion to find testimony significantly at variance with BEIR, NCRP, ICRU and ICRP to be suspect cannot be determined from the decision. *See supra* text accompanying notes 38-43. Following this suggestion might have affected the outcome of the five-point test as to leukemia injuries.

[80] In *Allen*, the court did not explain any special test for determining liability; however, the court seemed to adopt a "substantial factor" test, shifting the burden to the defendant to prove that he had not caused the injury to these five plaintiffs. Instead of comparing the probabilities that the injuries resulted from alternative causes, the court said, "Where the factual connections between radiation exposure and injury are as strong as the ones here, other largely hypothetical alternatives carry little force." *Id.* at 441 n.201.

On the other hand, if the proposed five-point test were applied in *Allen*, five of nine successful plaintiffs did not satisfy step 5: they failed to prove that their injury was more likely than not caused by radiation exposure. *See* 588 F. Supp. 247.

each strike blows sufficient to break the leg of the plaintiff, neither should escape liability by claiming the injury would have resulted even without his own blow. That situation, however, differs from late radiation injury cases. Unlike the broken leg scenario, the injury in radiation cases is likely even without the actions of some defendant; cancer and leukemia commonly occur through sources other than radiation.[81] In these cases, a defendant is not usually joined with other identifiable defendants who may have also contributed to the alleged injury. Also, a "more likely than not" test is possible in radiation cases which assures that the defendant will not escape liability based solely on the "but for" test.

Moreover, shifting the burden in radiation injury cases does not follow from the doctrine presented in *Summers v. Tice*[82] or *Sindell v. Abbott Laboratories*.[83] In *Summers* and *Sindell*, the plaintiffs suffered injury which was unlikely without the negligence of some, though indeterminate, defendant. In the adjudication of late radiation injury, it is the cause itself which is indeterminate. Cancer and leukemia incidence is a fact of life with or without a radiation insult. The injury suffered by the alleged victim may occur regardless of the activities of the defendant. The inequities which shifting the burden seeks to remedy in the indeterminate defendant cases do not apply in the radiation cases.

4. *Injury*

Normally, it should not be difficult to establish injury in radiation cases. Although late injuries are characterized by long latency periods, they still manifest themselves as recognizable and diagnosable disorders such as cancer and leukemia. Courts should consider the nature of radiation injury as they seek to do justice. Any amount of radiation always causes cell damage, but cell damage does not mean that there will be a recognizable in-

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[81] The requisite insult to a plaintiff alleging cancer injury, if one exists, may result from many sources. *See, e.g.*, Miller & Miller, *Mechanisms of Chemical Carcinogenesis*, 47 CANCER 1055, 1055 (1981) ("Of the known carcinogenic agents (viruses, ultraviolet and ionizing radiation, and chemicals), chemicals appear to be of major importance in the induction of human cancers.").

[82] 33 Cal. 2d 80, 199 P.2d 1 (1948).

[83] 26 Cal. 3d 588, 607 P.2d 924, 163 Cal. Rptr. 132, *cert. denied*, 449 U.S. 912 (1980).

jury to the organism.[84] There are medical tests which can detect cell damage at higher radiation exposures (above approximately twenty-five rems) if the tests are performed within a short time after exposure.[85] However, it is not cell damage that tort law seeks to compensate. Tort law compensates injury to the organism.[86] Such injury need not be manifested as physical symptoms in the plaintiff, but it must, at least, be manifested in some medically or scientifically recognizable fashion.[87]

B. *Strict Liability*

In addition to negligence torts, a defendant might be held strictly liable for radiation injury. In the Price-Anderson Act, Congress stated that "nuclear facilities" would stand strictly liable for an "extraordinary nuclear occurrence."[88] Although not expressly stated, it can be argued that this section bars strict liability actions against defendants who are not nuclear facilities

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[84] In this regard, courts must exercise care not to give overly broad jury instructions concerning injury. For example, in *Silkwood*, the court instructed the jury as follows: "You are instructed that if you find from a preponderance of the evidence that prior to her death [in an automobile accident] Karen Silkwood suffered any mental pain or anguish by reason of any physical injury suffered [due to radiation], then plaintiff is entitled to recover [damages] . . . ." 485 F. Supp. 566, 602 (W.D. Okla. 1979), *aff'd in part*, 667 F.2d 908 (10th Cir. 1981), *rev'd*, 464 U.S. 238 (1984). In response, the jury asked the court, "[W]hat does physical injury mean?" *Id.* The court responded, "Certainly physical injury can include a non-visible or non-detectable injury, and may include injury to bone, tissue or *cells*." *Id.* (emphasis added). The court's instruction may have gone too far, considering that cell damage may not result in damage to the organism.

[85] Microscopy tests can be performed to determine chromosome breaks caused by radiation. Since these breaks also occur naturally without radiation, exposures must be high enough (above 25 rems) to show effects above the natural occurrence. The tests are complicated, and reliable results are available only at specific scientific centers, *e.g.*, Oak Ridge National Laboratory. The tests have been available for over 10 years, but have not been extensively used for medical or radiation safety purposes.

The chromosome breaks test is not specific to cell damage that will manifest injury in the organism. Thus, at the present scientific state, the chromosome breaks test can only demonstrate exposure to radiation and estimate exposure levels. For alleged stochastic injury litigation, the test is of no value because the time elapsed since the radiation insult is too great.

[86] Allen v. United States, 588 F. Supp. 247, 430 (D. Utah 1984), *rev'd*, 816 F.2d 1417 (10th Cir. 1987), *cert. denied*, 484 U.S. 1004 (1988). To establish the element of injury, the *Allen* court properly required that the injury "took effect in actual somatic injury to the plaintiffs . . . ." *Id.*

[87] A microscopic determination of cancer by a pathologist certainly satisfies the requirement that the injury be manifested in a recognizable fashion. A microscopic determination will show characteristics of cancer in tissue, such as the clustering of cells. The cancer process observed is not likely to reverse itself.

[88] Price-Anderson Act, 42 U.S.C. § 2210(n) (1982).

or for accidents which are not extraordinary nuclear occurrences. The Supreme Court has not addressed the issue, but *Silkwood* suggests that states may apply their own strict liability standards in radiation injury cases.[89] Applying state standards may allow the use of the "highly dangerous" or "ultrahazardous" test. This test is far too severe for the radiation industry, which has an excellent safety record in its normal operation.[90] In its ordinary operation, the radiation industry is neither highly dangerous nor ultrahazardous.

As the radiation industry continues to grow, courts can expect plaintiffs to bring actions against small radiation users for alleged injury.[91] The general fear of radiation and the possible passion against radiation users subject the highly dangerous or ultrahazardous test to significant abuse. For personal injury caused outside the extraordinary nuclear occurrence, the defendant should stand liable only for actions in negligence.

The demarcation between an extraordinary nuclear occurrence and a negligent accident may be shadowy indeed, but the four dissenting Justices in *Silkwood* thought that Congress intended strict liability to apply only to the extraordinary occurrence.[92] A possible test for the extraordinary nuclear occurrence addresses the following questions:

1. Is this accident of the type and magnitude which would subject other industries using toxic materials to strict liability?
2. Does the plaintiff have "clean hands?" Such a determination is made depending upon whether or not the plaintiff contributed to the accident by his intentional or negligent actions.
3. Did many potential plaintiffs result from the accident? An extraordinary occurrence involving radiation will produce many potential plaintiffs.
4. Did the accident have the potential to cause significant injury to the organism?

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[89] *See* Silkwood v. Kerr-McGee Corp., 464 U.S. 238, 252-55 (1984). In this decision the Supreme Court held that states could impose their own punitive damage standards even though the NRC had a federal remedial scheme of civil penalties and fines in place. *Id.* at 258. Further, the Supreme Court said that "a state may . . . award damages based on its own law of liability." *Id.* at 256. Presumably this includes a state's strict liability standards.

[90] *See id.* at 282 n.12 (Powell, J., dissenting).

[91] The NRC has licensed thousands of radiation users, including universities, hospitals, industrial radiographers, well loggers, *etc.* Each user is a potential defendant for radiation litigation.

[92] *Silkwood*, 464 U.S. at 278-79.

5. Did the source of radiation actually escape the defendant's control? For example, the user of sealed radioactive sources should not stand strictly liable if "escape" from the sealed sources does not occur.[93] Loss of an intact sealed radioactive source may be prima facie evidence of negligence, but it should not trigger strict liability.

An answer of "no" to any of these questions should bar an action in strict liability.

The reason the strict liability test must be applied so carefully derives from two facts. First, as stated earlier, radiation is not "highly dangerous" in its normal use. Second, late radiation injury varies fundamentally from the injury caused by other highly dangerous activities which trigger strict liability. Injury from explosives or their projectiles, from vast amounts of escaped water, or from the attack of an escaped lion,[94] are identifiable and unlikely without the actions of the defendant. If the plaintiff can identify the specific defendant responsible for the injury, liability is properly imposed. On the other hand, late radiation injury cannot be exclusively identified in the plaintiff. Cancer or leukemia occur with or without the actions of the defendant. The inequities which strict liability seeks to remedy do not attach to radiation injury outside the extraordinary nuclear occurrence.

C. *Evidence*

Radiation injury cases are trials about numbers, yet the numbers of radiation physics and radiation injury can be confusing. An understanding of how scientists handle very large and very small numbers is fundamental to understanding radiation cases. The two primary methods of manipulating extreme and otherwise awkward numbers are scientific notation[95] and mathe-

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[93] Sealed sources of radioactive materials describe a specific physical state of radiation sources. The production of sealed sources is a mature industry. Radioactive material is usually double-encapsulated in stainless steel or similar material. Radiation emitted from the sources is used for both medicine and industry. The sealed sources are designed to preclude the actual escape of the radioactive material.

[94] In *Silkwood*, plaintiff's attorney wrote on a blackboard before the jury, "IF THE LION GETS AWAY, KERR-McGEE HAS TO PAY." G. SPENCE, WITH JUSTICE FOR NONE: DESTROYING AN AMERICAN MYTH 76 (1989). It was obviously effective, but in reality had nothing to do with the questions which *should* have been before the court in this matter.

[95] For an example of scientific notation, suppose the annual U.S. budget is $1,100,000,000,000. In scientific notation, this is written as $\$1.10 \times 10^{12}$: the superscript

matical prefixes.[96] In addition, litigators should know the "nature" of the expected numbers (*i.e.*, statistical, estimated, inferred, recreated, *etc.*) to avoid surprises from their experts and to properly attack the experts of the opposing party.[97]

For the elements of duty, breach and injury, the type of evidence in the adjudication of alleged radiation injury will not vary in nature from traditional negligent tort actions. Problems in these three elements arise as matters of law rather than matters of fact. If the courts can formulate proper standards, tests and instructions at law, juries can adequately resolve issues of facts. In contrast, evidence regarding causation for alleged late radiation injury is far more problematic. Evidence here must include statistical data regarding late injury versus radiation exposure, statistical data regarding the specific injury alleged without the alleged radiation insult, and expert witnesses to interpret and give opinions regarding these data. Expert witnesses are the touchstone of the litigation of alleged radiation injury. Judges need to be wary of "expert" witnesses who present a viewpoint which is outside the generally accepted opinion held by most experts in the field. Sometimes such experts can have impressive credentials and display a court presence which bespeaks credibility. It can be difficult to identify witnesses who represent views contrary to sound scientific principles. However, testimony which differs significantly from recognized national and international standards should raise considerable suspicion.[98]

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12 denotes how many times the prefix *1.10* is multiplied by 10 (*i.e.*, \$1.10 x 10^{12} is equal to \$1.10 x 10 x 10 x 10 x 10 x 10 x 10 x 10 x 10 x 10 x 10 x 10 x 10). Scientific notation handles small numbers similarly. In scientific notation, the number 0.0000013 is written 1.3 x 10^{-6}. The negative superscript *-6* indicates how many times the prefix *1.3* is divided by 10 (*i.e.*, 1.3 x 10^{-6} is equal to 1.3 x 10÷10÷10÷10÷10÷10).

[96] Table 1, *infra*, presents common prefixes and their values. Using this system, 0.017 grams of material is the same as 17 milligrams and 14,300,000 tons is the same as 14.3 megatons.

[97] Experts are called upon to generate and evaluate many numbers in the litigation of radiation injury. These numbers should be sound in their scientific derivation but courts and juries must know that they will rarely, if ever, be absolutely true numbers. Most numbers are generated from scientific or statistical formulas. Attorneys can lay proper foundations for the numbers of their experts and attack the numbers of the opposing party only if they know how numbers are scientifically produced. Consultation with the experts in this regard is important.

[98] *See, e.g.*, Johnston v. United States, 597 F. Supp. 374 (D. Kan. 1984). In *Johnston*, four plaintiffs sued the United States for alleged injury caused by radiation exposure to luminous dials and other aircraft instrument parts. The plaintiffs' experts were the same as those who successfully testified at trial in Silkwood v. Kerr-McGee Corp., 485 F. Supp. 566 (W.D. Okla. 1979), *aff'd in part*, 667 F.2d 908 (10th Cir. 1981), *rev'd*, 464 U.S. 238 (1984), and Allen v. United States, 588 F. Supp. 247 (D. Utah 1984), *rev'd*,

Judges must also be on the alert for expert witness' misuse of "significant" figures and the jury confusion which it engenders. An expert's number of say 2.20 x 10^5 might appear quite precise when, in fact, it may vary by a factor of 2, 10, 100 or more.[99] In radiation injury cases, few, if any, numbers will be exact or precise within the general meanings of the words.

In addition to the problem of witness credibility, the sheer volume of evidence associated with alleged radiation injury litigation can present problems. In a recent radiation case, there were more than 7,000 pages of trial transcript, 54,000 pages of written evidence, an estimated 2,500 pages of depositions, and judicial notice of thousands of additional pages of other written material.[100] It is difficult for courts and juries to assimilate this volume of evidence within the trial process. This does not mean that justice cannot be done; it does mean, however, that it is

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816 F.2d 1417 (10th Cir. 1987), *cert. denied*, 484 U.S. 1004 (1988). In *Johnston*, the trial court identified what the scientific community had long known about these alleged experts, but which escaped the trial courts in *Silkwood* and *Allen*. Regarding the plaintiff's witnesses, the court in *Johnston* stated:

> As to Dr. Morgan's procedures, if this man were reporting his test results for anyone other than a jury or this Court, he would become an immediate laughing stock! In the Court's view, Dr. Morgan is perhaps an esteemed scientist of yesterday trying to hold on to whatever reputation remains. He has baffled his old friends and those far better trained. He is, in the Court's view, a pathetic figure who can better serve the field by simply "going home." Dr. Morgan's testimony is stricken from this case as totally unreliable.
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> . . . In light of all that has been said here, the Court disagrees with the basis on which Dr. Gofman has made his opinion and will ignore it in its entirety. Doubtless this will offend the sensitivities of this most confident witness; notwithstanding that, the Court knows now that no matter what esteem he claims, he is *not* a certified health physicist, and while a physician, he does *not* examine or treat patients. He enjoys emeritus status at the University of California at Berkeley, but has *no* office, nor access to any laboratory or library, and he teaches *no one*! From what this Court can garner, it appears that his principal activities are writing books and testifying in the courtroom.
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> . . . .
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> . . . Dr. Morgan and Dr. Gofman represent the views of an extreme minority of scientists. This is not a situation where the scientific community is equally divided between two respected schools of thought. It is a case where there is a very small, but yet very vocal group of scientists, including Drs. Morgan and Gofman, that holds views which are not considered credible by the experts in the field.

Johnston, 597 F. Supp. at 410-11 (emphasis in original). Recognized national and international standards are described *supra* text accompanying notes 38-42.

[99] *See, e.g.*, Allen v. United States, 588 F. Supp. 247, 436-37 (D. Utah 1984), *rev'd*, 816 F.2d 1417 (10th Cir. 1987), *cert. denied*, 484 U.S. 1004 (1988) (the court observed that the "significant figures" in an expert's estimate of radiation dose to plaintiff might be misleading).

[100] *Id.* at 258 n.3.

complicated. When the volume of evidence is great, it is human nature to seize upon that evidence which satisfies preconceived notions and to discount everything else.

The quality of written documents such as scientific papers is also at issue here. While there are many publications addressing radiation and resulting injury, there is little information to show a court whether or not a particular published work has withstood the test of time or whether it has been discounted by the scientific community. Notwithstanding their development for non-judicial purposes, the major contemporary documents of the recognized authorities such as BEIR, ICRP, ICRU and NCRP represent by far the best sources of guidance for the courts.[101]

D. Defenses

The United States has successfully argued the affirmative defenses of the "discretionary function doctrine"[102] and the "*Feres* doctrine"[103] in radiation injury cases. The primary af-

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[101] *See supra* text accompanying notes 38-42.

[102] In *Allen*, the Tenth Circuit reversed a judgment for plaintiffs arising out of the early 1950s and 1960s atmospheric testing of nuclear weapons, holding that the government's actions were protected as a discretionary function:

> On appeal, plaintiffs contend that the AEC [Atomic Energy Commission], in planning and conducting its monitoring and information programs, was not making the kind of policy judgments protected by § 2680(a). They point to the general statutory provisions instructing the AEC to consider public health and safety, and claim that these broad congressional directives leave no further room for discretion. We disagree.
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> . . . .
>
> Government liability cannot logically be predicated on the failure of test-site personnel to go beyond what the operational plans specifically required them to do. If, as the plaintiffs maintain, the AEC delegated "unfettered authority" to a Test Manager and his subordinates to implement public safety programs, this simply compels the conclusion that those officers exercised considerable discretion. Their actions, accordingly, also fall within the discretionary function exception.

Allen, 816 F.2d at 1421.

[103] In Heilman v. United States, the Third Circuit held that, under the *Feres* doctrine, the government was not liable to a plaintiff who claimed radiation injury resulting from exposure which he received while he was in the military:

> We address first whether damages arising out of Heilman's military service are actionable in the courts. The liability of the United States for injuries received by members of the armed forces has been the subject of numerous judicial opinions, all of which stem from the seminal case of Feres v. United States, 340 U.S. 135, 71 S.Ct. 153, 95 L.Ed. 152 (1950). In *Feres*, the Supreme Court held that the Federal Tort Claims Act did not waive the sovereign immunity of the United States for injuries suffered incident to military service, and therefore

firmative defenses for non-government defendants are contributory or comparative negligence and the statute of limitations. The adjudication of contributory or comparative negligence issues in radiation actions should not vary from traditional personal injury cases. However, the statute of limitations issue may differ.

Statutes of limitations were created to avoid lost evidence, fading memories, staleness caused by the passage of time, and to free the defendant from the threat of suit after some length of time. In traditional common law torts, the clock began to run on the statute of limitations from the time of defendant's tortuous act. But this would effectively bar actions for most, if not all, late radiation injury (as distinguished from acute injury). This is true because of the long latency period between the radiation insult and the observable injury in the organism.

The statute of limitations proved to be an effective bar to late radiation injury actions when these cases first appeared in the courts.[104] Now, few plaintiffs are barred from their day in court on the basis of the latency period.[105] This policy benefits both the plaintiff and the defendant. Without a liberal statute of limitations providing a right of action to the plaintiff when a bona fide injury is manifest, actions which have not matured

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the courts had no jurisdiction to entertain the suit.

731 F.2d 1104, 1106 (3d Cir. 1984).

[104] *See, e.g.*, LaPorte v. United States Radium Corp., 13 F. Supp. 263 (D. N.J. 1935). *LaPorte* involved radiation injury to the painters of luminous dial faces in the 1920s. The painters would "tip" their brushes with their lips. This caused radioactive radium to be ingested and many painters developed bone cancer of the jaw. One painter developed the disease twelve years after leaving her employment and subsequently died. Her representative brought an action to enjoin the defendant from pleading the two-year statute of limitations; nevertheless, the action was dismissed because of the limitations period had run. *Id.* at 277.

[105] In United States v. Kubrick, The Supreme Court held that, for a cause of action under the Federal Tort Claims Act, 28 U.S.C. § 2401(b) (1982), the statute of limitations begins to accrue when the plaintiff knows of the facts of his injury and its cause. 444 U.S. 111 (1979). Relying upon *Kubrick*, the trial court in *Allen* construed the § 2401(b) limitations period liberally in favor of the plaintiff, stating that "[g]enuine concern about lost evidence, fading memories and the passage of time are subordinated to a greater concern that legal wrongs be remedied at the first practical opportunity." 588 F. Supp. at 341.

State legislatures have also addressed this problem. The statute of limitations for several states begins to accrue when a victim discovers both his injury and the potential relationship to a cause. Others begin when the victim knew or reasonably should have known of his injury and its cause. In states most favorable to the plaintiff, the limitations period begins to run when the plaintiff knew or should have known of his injury, its cause, and his cause of action.

would be brought by those who have only a fear that they have suffered injury. Injustice to defendants seems probable since these actions would lend themselves to jury and even court passion for the unknowable future of the plaintiff. *Silkwood* was such a case. In *Silkwood*, the jury awarded $10.5 million dollars even though there was no evidence that Ms. Silkwood suffered any injury other than a short period of mental distress.[106]

Although not an affirmative defense, the defendant who has substantially complied with federal regulations may successfully argue that an injury resulting despite his compliance with federal standards was not "foreseeable," and was therefore beyond his duty. This defendant could certainly make the argument that within compliance he did not foresee injury for which liability would attach. The defendant should not have a duty to protect against an unforeseeable injury. Radiation safety regulations have been in place for more than thirty years. Perhaps naively, the radiation industry has come to feel that compliance with applicable regulations acts as a shield against liability since manifest radiation injury to the organism has never been identified at or below regulated exposure limits. A "foreseeability defense" might be successfully argued before a court that understands radiation injury and applicable regulatory standards, but it is unlikely that a court with this understanding would find a breach of duty in the first place, so long as there was substantial compliance with federal regulations.

E. Suggestions

The adjudication of radiation injury is technically and legally complicated. Because of fear and a lack of understanding of radiation injury, it is an area of tort law which is subject to abuse and passion. The courts are in some disarray regarding how to handle these complicated actions, leaving the radiation industry to question the standards by which it will be judged. This situation could be improved through the following suggestions:

First, Congress should clarify its position regarding its intent to occupy or not occupy, either in part or in total, the field of radiation safety. Clarification is needed regarding how compliance with federal regulations will affect the legal analysis for breach of duty, causation, and wanton, willful or reckless con-

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[106] 464 U.S. 238, 275 (1984) (Powell, J., dissenting).

duct. Clarification is also needed regarding standards for imposing strict liability. The courts would benefit greatly from such clarification as they attempt to resolve radiation injury cases.

Second, courts should seek judicial, scholarly, and/or legislative forums for direction in determining the causation issue. The courts should consider formalized guidelines or a grid to decide causation. A respected group of scientists, physicians and judges could be assembled to create such a grid. Once created, the judge would enter the grid using parameters determined by the fact finder. These parameters include the type of injury, amount of radiation exposure, external or internal exposure, and time from insult to manifest injury. From these determinable facts, the grid would provide the best measure of causation based on available scientific data and medical knowledge. Using this measure, the judge could determine as a matter of law if the "more likely than not" standard was met.

The grid is not at odds with tort law. It leaves in the hands of the fact finder those facts which are determinable and reserves for the court the "reasonableness of inference" as to an element which is indeterminate. Grids are not unknown to the law,[107] but they have not been used in an area as traditionally the province of the fact finder as this. The purpose of the fact finder, however, is to promote justice and to minimize bias. In this case, a grid better satisfies both purposes. Moreover, a grid of this type is already in existence. The grid is the result of Senator Orrin Hatch's attempt to compensate the victims in *Allen*[108] after the court of appeals denied compensation. So far, Senator Hatch has been unsuccessful in gaining passage of a law to compensate his constituents, but he did attach a provision to the Orphan Drug Act[109] directing the Secretary of Health and Human Services to "devise and publish radioepidemiological tables that estimate the likelihood that persons who have or have had any of the radiation-related cancers and who have received specific doses [of radiation] prior to the onset of such diseases

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[107] Guideline grids have been formulated under the Social Security Act to determine a claimant's rights to disability benefits. *See* 20 C.F.R. pt. 404, subpt. P (1982). Guidelines have also been implemented under the Sentencing Reform Act of 1984 to determine sentencing. *See* 42 U.S.C. §§ 991-98 (Supp. IV 1984). The Supreme Court upheld the "disability grid" as constitutional in Heckler v. Campbell, 461 U.S. 458 (1983), and upheld the "sentencing grid" as constitutional in Mistretta v. United States, 109 S. Ct. 647 (1989).

[108] 588 F. Supp. 247.

[109] 42 U.S.C. § 241 (1982).

developed cancer as a result of these [radiation] doses."[110] This directive resulted in the Report of the National Institute of Health Ad Hoc Working Group to Develop Radioepidemiological Tables (NIH Report).[111]

The NIH Report, like BEIR III, will probably be pressed into the service of the courts, but the courts should be cautioned that the report was prepared rather quickly with only a small budget.[112] It may or may not accurately reflect scientific consensus. The document claims that about half of its risk coefficients were taken from BEIR III and the rest from more recent sources.[113] Despite its possible weaknesses, the NIH Report is certainly a step toward the creation of a judicially useful grid.[114]

Third, as an alternative to the second suggestion, special courts and masters with specific training and expertise in this area of the law should be considered. Courts should consider withholding trial by jury in highly technical and complex cases because of due process considerations.[115] If the practice was ever

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[110] Director Nat'l Institute of Health, Pub. No. 85-2748, Report of Ad Hoc Working Group to Develop Radioepidemiological Tables at i (Jan. 4, 1985).

[111] *See supra* note 110.

[112] *Id.* at 4.

[113] *Id.* at i.

[114] *See* Comment, *supra* note 64. The author of the comment recommends that the NIH Report be used not as a method of evaluating the "more likely than not" test, but as a tool for deciding an ambiguous "casual linkage" test, *id.* at 503, and apportioning defendant liability. *Id.* at 505-08. These suggested uses indicate a poor understanding of radiation injury and unfairly make the radiation industry a prorated insurer of the prevalent diseases of cancer and leukemia. Any use of grids in this fashion properly belongs in the hands of the legislature, not the courts.

[115] A trial by jury is constitutionally preserved in legal actions. However, some courts have held that a trial before a jury may be denied for unusually complex cases under the constitutional guarantee of due process. In *In re* Japanese Ele. Prod. Antitrust Litig., the Third Circuit stated:

> The due process objections to a jury trial of a complex case implicate values of fundamental importance. If judicial decisions are not based on factual determinations bearing some reliable degree of accuracy, legal remedies will not be applied consistently with the purposes of the laws. There is a danger that jury verdicts will be erratic and completely unpredictable, which would be inconsistent with evenhanded justice. Finally, unless the jury can understand the evidence and the legal rules sufficiently so as to rest its decision on them, the objective of most rules of evidence and the procedure in promoting a fair trial will be lost entirely. We believe that when a jury is unable to perform its decisionmaking task with a reasonable understanding of the evidence and legal rules, it undermines the ability of a district court to render basic justice.

631 F.2d 1069, 1084 (3d Cir. 1980).

> For the unusually complex case, the district court can take a fairly objective measure of its complexity by examining three factors which contribute to a jury's inability to understand the evidence and legal rules: first, the overall size

merited, it is merited for these complex actions of alleged radiation injury.

Fourth, the volume of written evidence in radiation injury litigation ought to be reduced through several methods. First, judicial notice would reduce the volume of evidence. Notice of specific, credible scientific authority would alleviate attorneys' fears that certain evidence would not be available at trial or on appeal.[116] It would also create standards with which to measure other evidence.

The courageous use of the Federal Rules of Evidence (FRE), Rules 402 and 403 can also control the volume of evidence. Attorneys can be required to show that evidence is relevant under FRE 402. Under FRE 403 even relevant evidence can be excluded if its probative value is substantially outweighed by the danger of unfair prejudice, confusion of issues, deception of the jury, or undue delay, waste of time, or needless presentation of cumulative evidence. Greater use of FRE 402 and 403 will undoubtedly follow as judges become more familiar with the intricacies of the adjudication of radiation injury cases.

> of the suit, the primary indicia of which are the estimated length of trial, the amount of evidence to be introduced and the number of issues that will require individual consideration; second, the conceptual difficulties in the legal issues, which are likely to be reflected in the amount of expert testimony to be submitted and the probable length and detail of jury instructions; and third, the difficulty of segregating distinct aspects of the case, as indicated by the number of separately disputed issues related to single transactions or items of proof.

Id. at 1088-89.

The Supreme Court has not ruled directly on the right to withhold a jury trial based on the unusual complexity of the case, but it has noted that "the practical abilities and limitations of juries" may be a factor in determining the "legal" nature of cases, and therefore whether or not a jury is mandated. Ross v. Bernhard, 396 U.S. 531, 538 n.10 (1970). This suggests that the Supreme Court has left the door open to withholding jury trials in unusually complex cases.

[116] Judicial notice of scientific truths is not uncommon in the law. When radar gun readings were first introduced for speeding violations, courts required expert testimony on the principles of radar and required a showing by a preponderance of the evidence that radar worked. Now most courts take judicial notice of radar's principles and its ability to determine speed. All that is now required is a showing that the device was used in a proper fashion by a competent individual.

Courts could take judicial notice of scientific knowledge such as that reported in BEIR III. *Supra* note 32. This would show prejudice to neither the plaintiff nor the defendant. BEIR III faithfully points out its own inadequacies. Like radar, judicial notice of BEIR III would still require that the data be used in a proper fashion by competent experts.

CONCLUSION

The adjudication of late radiation injury is one of the most complicated and difficult actions in tort law. The complications arise from the highly complex biological and physical mechanisms of radiation injury, the long latency period between insult and injury, the indeterminacy of causation, and the problems of formulating proper legal tests for elements such as breach of duty. Most of the actions to date were brought against the United States and its defense contractors. Here defenses not available to the private radiation user have generally provided a shield against liability. In the future, more actions will be brought against private radiation users. The proper analysis of radiation cases requires a basic knowledge of radiation, the way in which radiation causes injury, and how this knowledge affects tort law theory. Although there is no way to remove all the complexities and difficulties for radiation injury adjudication, the methods proposed in this article will minimize bias to either the plaintiff or to the defendant and facilitate the court's ability to do justice in this complex and problematic area of the law.

APPENDIX

TABLE 1. SCIENTIFIC PREFIXES

Prefix	Symbol	Power	Prefix	Symbol	Power
tera	T	10^{12}	deci	d	10^{-1} or 1/10
giga	G	10^{9}	centi	c	10^{-2}
mega	M	10^{6}	milli	m	10^{-3}
kilo	K	10^{3}	micro	u	10^{-6}
lecto	L	10^{2}	nano	n	10^{-9}
deka	da	10^{1}	pico	p	10^{-12}
			femto	f	10^{-15}
			atto	a	10^{-18}

TABLE 2. The Elements

Atomic Number	Element Name	Chemical Symbol	Atomic Number	Element Name	Chemical Symbol	Atomic Number	Element Name	Chemical Symbol
1	Hydrogen	H	36	Krypton	Kr	71	Lutettium	Yb
2	Helium	He	37	Rubidium	Rb	72	Hafnium	Hf
3	Lithium	Li	38	Strontium	Sr	73	Tantalum	Ta
4	Beryllium	Be	39	Yttrium	Y	74	Tungsten	W
5	Boron	B	40	Zicronium	Zr	75	Rhenium	Re
6	Carbon	C	41	Niobium	Nb	76	Osmium	Os
7	Nitrogen	N	42	Molybdenum	Mo	77	Iridium	Ir
8	Oxygen	O	43	Technetium	Tc	78	Platinum	Pt
9	Flourine	F	44	Ruthenium	Ru	79	Gold	Au
10	Neon	Ne	45	Rhodium	Rh	80	Mercury	Hg
11	Sodium	Na	46	Palladium	Pd	81	Thallium	Tl
12	Magnesium	Mg	47	Silver	Ag	82	Lead	Pb
13	Aluminum	Al	48	Cadmium	Cd	83	Bismuth	Bi
14	Silicon	Si	49	Indium	In	84	Polonium	Po
15	Phosphorus	P	50	Tin	Sn	85	Astatine	At
16	Sulfur	S	51	Antimony	Sb	86	Radon	Rn
17	Chlorine	Cl	52	Tellurium	Te	87	Francium	Fr
18	Argon	Ar	53	Iodine	I	88	Radium	Ra
19	Potassium	K	54	Xenon	Xe	89	Actinium	Ac
20	Calcium	Ca	55	Cesium	Cs	90	Thorium	Th
21	Scandium	Sc	56	Barium	Ba	91	Protactinium	Pa
22	Titanium	Ti	57	Lanthanum	La	92	Uranium	U
23	Vanadium	V	58	Cerium	Ce	93	Neptunium	Np
24	Chromium	Cr	59	Praseodymium	Pr	94	Plutonium	Pu
25	Manganese	Mn	60	Neodymium	Nd	95	Americium	Am
26	Iron	Fe	61	Promethium	Pm	96	Curium	Cm
27	Cobalt	Co	62	Samarium	Sm	97	Berkelium	Bk
28	Nickel	Ni	63	Europium	Eu	98	Californium	Cf
29	Copper	Cu	64	Gadolinium	Gd	99	Einsteinium	Es
30	Zinc	Zn	65	Terbium	Tb	100	Fermium	Fm
31	Gallium	Ga	66	Dysprosium	Dy	101	Mendelevium	Md
32	Germanium	Ge	67	Holmium	Ho	102	Nobelium	No
33	Arsenic	As	68	Erbium	Er	103	Lawrencium	Lw
34	Selenium	Se	69	Thulium	Tm	104	(Kurchatovium)	Ku
35	Bromine	Br	70	Ytterbium	Yb	105	(Hahnium)	Ha

TABLE 3. RELATION OF THE TYPE OF RADIATION TO QUALITY FACTOR (Q)*

Type of Radiation	Quality Factor
X-rays, gamma rays, beta particles	1
Neutrons (Low Energy)	3
Neutrons (High Energy)	10
Protons	1-10
Alpha Particles	1-20
Fission Fragments, Recoil Nuclei	20

* F. WHICKER & V. SCHULTZ, RADIOECOLOGY: NUCLEAR ENERGY AND THE ENVIRONMENT 92, 107 (1982).

TABLE 4. HALF-LIVES FOR SELECTED RADIOACTIVE ISOTOPES

Isotope	Half-life	Isotope	Half-life	Isotope	Half-life
^{3}H	12.5 years	^{55}Fe	2.9 years	^{226}Ra	1,622 years
^{14}C	5,600 years	^{59}Fe	40 days	^{233}U	$1.62 \text{x} 10^{5}$ years
^{39}Ar	260 years	^{60}Co	5.3 years	^{235}U	$7.1 \text{x} 10^{8}$ years
^{24}Na	15 hours	^{90}Sr	28.1 years	^{238}U	$4.51 \text{x} 10^{9}$ years
^{32}p	14 days	^{131}I	8 days	^{238}Pu	86 years
^{42}K	12 hours	^{137}Cs	30.3 years	^{239}Pu	24,400 years
^{45}Ca	52 days	^{192}Ir	74.5 days	^{240}Pu	6,580 years
^{56}Mn	16 hours	^{198}Au	2.7 days	^{241}Pu	13.2 years

TABLE 5. SUMMARY OF CLINICAL EFFECT OF ACUTE IONIZING RADIATION EXPOSURE*

Range	0 to 100 Rems Subclinical Range	100 to 200 Rems Clinical Surveillance
Incidence of Vomiting	None	100 Rems Infrequent 200 Rems Common
Initial Phase		
Onset	—	3 to 6 Hours
Duration	—	≤ 1 Day
Latent Phase		
Onset	—	≤ 1 Day
Duration	—	≤ 2 Weeks
Final Phase		
Onset	—	10 to 14 Days
Duration	—	4 Weeks
Leading Organ		Hematopoietic Tissue
Characteristic Signs	None Below 50 Rems	Moderate Leukopenia
Critical Period Posi-exposure	—	—
Therapy	Reassurance	Reassurance, Hematologic Surveillance
Prognosis	Excellent	Excellent
Convalescent Period	None	Several Weeks
Incidence of Death	None	None
Death Occurs Within	—	—
Cause of Death	—	—

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* S. GLASSTONE & P. DOLAN, THE EFFECTS OF NUCLEAR WEAPONS 580-81 (3d ed. 1977).

TABLE 5 (continued)

	100 to 1,000 Rems Therapeutic Range	
Range	200 to 600 Rems	600 to 1,000 Rems
	Therapy Effective	Therapy Promising
Incidence of Vomiting	300 Rems 100%	100%
Initial Phase		
Onset	½ to 6 Hours	¼ to ½ hour
Duration	1 to 2 Days	$\leq$ 2 Days
Latent Phase		
Onset	1 to 2 Days	$\leq$ 2 Days
Duration	1 to 4 Weeks	5 to 10 Days
Final Phase		
Onset	1 to 4 Weeks	5 to 10 Days
Duration	1 to 8 Weeks	1 to 4 Weeks
Leading Organ	Hematopoietic Tissue	
Characteristic Signs	Severe Leukopenia Purpura, Hemorrhage. Infection Epilation above 300 Rems.	
Critical Period Posi-exposure	1 to 6 Weeks	
Therapy	Blood Transfusion, Antibiotics	Consider Bone Marrow Transplant
Prognosis	Guarded	Guarded
Convalescent Period	1 to 12 Months	Long
Incidence of Death	0 to 90%	90 to 100%
Death Occurs Within	2 to 12 Weeks	1 to 6 Weeks
Cause of Death	Hemorrhage, Infection	

TABLE 5 (continued)

	Over 1,000 Rems Lethal Range	
Range	1,000 to 5,000 Rems	Over 5,000 Rems
	Therapy Palliative	
Incidence of Vomiting	100%	
Initial Phase		
Onset	5 to 30 minutes	Almost Immediately**
Duration	0 to 1 Days*	
Latent Phase		
Onset	≤ 1 Day*	Almost Immediately**
Duration	≤ 1 Day	
Final Phase		
Onset	0 to 10 Days	Almost Immediately**
Duration	2 to 10 Days	
Leading Organ	Gastrointestinal Tract	Central Nervous System
Characteristic Signs	Diarrhea, Fever, Disturbance of Electrolyte Bal.	Convulsions, Tremor; Ataxia; Lethargy
Critical Period Posi-exposure	2 to 14 Days	1 to 48 Hours
Therapy	Maintenance of Electrolyte Bal.	Sedatives
Prognosis	Guarded	Hopeless
Convalescent Period	—	
Incidence of Death	100%	
Death Occurs Within	2 to 14 Days	< 1 to 2 Days
Cause of Death	Circulatory Collapse	Respiratory Failure Brain Edema

* At the higher doses within this range there may be no latent phase

** Initial phase merges into final phase, death usually occuring from a few hours to about 2 days. This chronology is possibly interrupted by a very short latent phase.

TABLE 6. SENSITIVITY OF VARIOUS TISSUES TO ONCOGENIC INFLUENCE OF RADIATION*

Site or Type of Cancer	Spontaneous Incidence of Cancer	Relative Sensitivity to Radiation Induction of Cancer	Remarks
Major Radiation-Induced Cancers			
Female breast	Very High	High	Puberty increases sensitivity
Thyroid	Low	Very high, esp. females	Low mortality rate
Lung (bronchus)	Very High	Moderate	Quantitative effect of smoking uncertain
Leukemia	Moderate	Very high	Especially myeloid leukemia
Alimentary tract	High	Moderate-low	Occurs especially in colon
Minor Radiation-Induced Cancers			
Pharynx	Low	Moderate	--
Liver and biliary tract	Low	Moderate	--
Pancreas	Moderate	Moderate	--
Lymphomas	Moderate	Moderate	Lymphosarcoma and multiple myeloma, but not Hodgkin's
Kidney/bladder	Moderate	Low	--
Brain/nervous system	Low	Low	--
Salivary glands	Very low	Low	--
Bone	Very low	Low	--
Skin	High	Low	Low mortality. High dose necessary?

TABLE 6 (CONTINUED)

Site or Tissues in Which Magnitude of Radiation-Induced Cancer is Uncertain

Larynx	Moderate	Low	--
Nasal sinuses	Very low	Low	--
Parathyroid	Very low	Low	--
Ovary	Moderate	Low	--
Connective tissue	Very low	Low	--

Sites or Tissues in Which Radiation-Induced Cancer has not been Observed

Prostate	Very high	Absent?	--
Uterus/cervix	Very high	Absent?	--
Testis	Low	Absent?	--
Mesentery and mesothelium	Very low	Absent?	--
Chronic lymphatic leukemia	Low	Absent?	--

Latency 1: Leukemia and some bone cancers show delay from radiation insult to manifest injury of about 3-30 years.

2: Other cancers rarely appear earlier than 10 years after the radiation insult and appear to have no upper limit after which the incidence returns to normal.

* Prepared from BEIR III, *supra* note 32, at 266-67.

TABLE 7. ANNUAL DOSE RATES FROM SOURCES OF RADIATION EXPOSURE IN THE UNITED STATES*

	Average Dose Rate, mrems/yr.		
Source	Body portion Exposed	Exposed Grp.	Prorated over tot pop
Natural Background			
Cosmic radiation	Whole body	28	28
Terrestrial radiation	Whole body	26	26
Internal sources	Gonads	28	28
	Bone marrow	24	24
Medical X-rays			
Medical diagnosis	Bone marrow	103	77
Medical personnel	Whole body	300-350[a]	0.3
Dental diagnosis	Bone marrow	3	1.4
Dental personnel	Whole body	50-125[a]	0.05
Radiopharmaceuticals			
Medical diagnosis	Bone marrow	300	13.6
Medical personnel	Whole body	260-350	
Atmospheric weapons tests	Whole body	4-5	
Nuclear Industry			
Commercial nuclear power plants (effluent releases)	Whole body	<<10	<<1
Commercial nuclear power plants (occupational)	Whole body	400[b]	0.1
Industrial radiography (occupational)	Whole body	320	0.02
Fuel processing and fabrication (occupational)	Whole body	160	0.01

	Exposed Group	
Source	Description	No. Exposed
Natural Background		
Cosmic radiation	Total population	220x10^{6}
Terrestrial radiation	Total population	220x10^{6}
Internal sources	Total population	220x10^{6}
Medical X-rays		
Medical diagnosis	Adult patients	105x10^{6}/yr
Medical personnel	Occupational	195,000
Dental diagnosis	Adult patients	105x10^{6}/yr
Dental personnel	Occupational	171,000
Radiopharmaceuticals		
Medical diagnosis	Patients	10x10^{6} to 12x10^{6}/yr
Medical personnel	Occupational	100,000
Atmospheric weapons tests	Total population	220x10^{6}
Nuclear Industry		
Commercial nuclear power plants (effluent releases)	Population within 10 mi.	<10x10^{6}
Commercial nuclear power plants (occupational)	Workers	67,000
Industrial radiography (occupational)	Workers	11,250
Fuel processing and fabrication (occupational)	Workers	11,250
Handling byproduct materials	Workers	3,500

(occupational)		
Federal contractors (occupational)	Workers	88,500
Naval nuclear propulsion program (occupational)	Workers	36,000
Research activities		
Particle accelerators (occupational)	Workers	10,000
X-ray diffraction units	Workers	10,000-20,000
Electron microscopes (occupational)	Workers	4,400
Neutron generators (occupational)	Workers	1,000-2,000
Consumer products		
Building materials	Population in brick and masonry bldgs.	110x10^6
Television receivers	Viewing populations	100x10^6
Miscellaneous		
Airline Travel	Passengers	35x10^6[c]
(cosmic radiation)	Crew members and flight attendants	40,000
Airline transport of	Passengers	7x10^6[d]
radioactive materials	Crew members and flight attendants	40,000

	Average Dose Rate, mrems/yr.		
Source	Body portion Exposed	Exposed Grp.	Prorated over tot pop
Handling byproduct materials (occupational)	Whole body	350	0.01
Federal contractors (occupational)	Whole body	≈250	0.1
Naval nuclear propulsion program (occupational)	Whole body	220	0.04
Research activities			
Particle accelerators (occupational)	Whole body	Unknown	<<1
X-ray diffraction units (occupational)	Extremeties and whole body	Unknown	<<1
Electron microscopes (occupational)	Whole body	50-200	0.003
Neutron generators (occupational)	Whole body	Unknown	<<1
Consumer products			
Building materials	Whole body	7	3-4
Television receivers	Gonads	0.2-1.5	0.5
Miscellaneous			
Airline Travel	Whole body	3	0.5
(cosmic radiation)	Whole body	160	0.03
Airline transport of	Whole body	≈0.3	0.01
radioactive materials	Whole body	≈3	<0.001

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* Prepared from BEIR III, *supra* note 32, at 66.

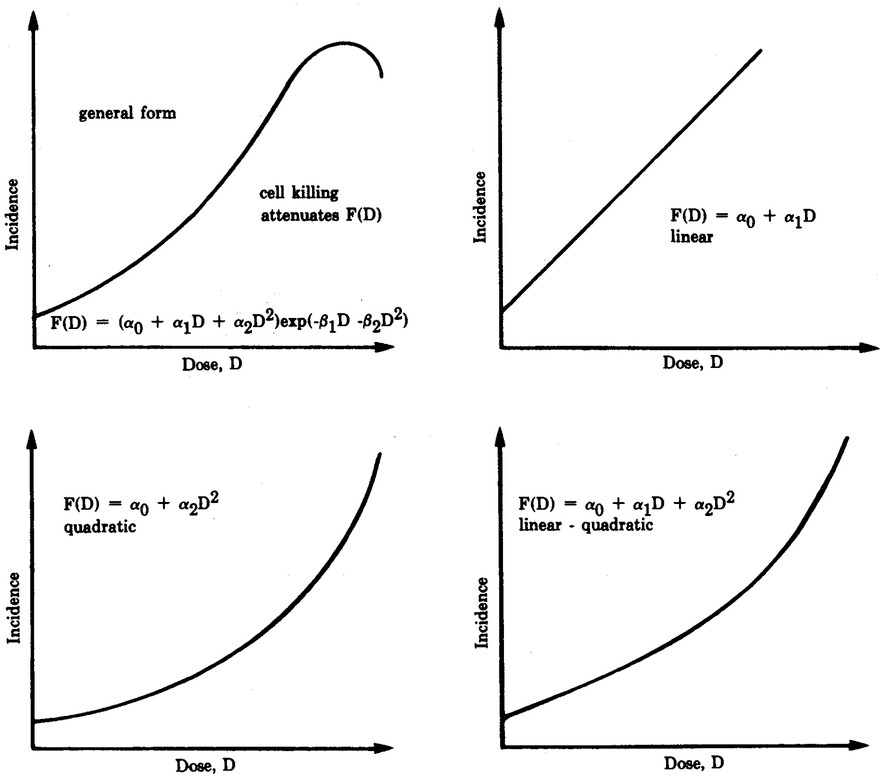
[a] Based on personnel dosimeter readings; because of relatively low energy of medical x-rays, actual whole-body doses are probably less.

[b] Average dose rate to the approximately 40,000 workers who received measurable exposures was 600-800 mrems/yr.

[c] Total number of revenue passengers per year is 210 x 10^6; however, many of these are repeat airline travelers.

[d] About one in every 30 airline flights includes the transportation of radioactive materials; assuming 210 x 10^6 passengers per year (total), approximately 7 x 10^6 would be on flights carrying radioactive materials.

FIGURE 1. MATHEMATICAL MODELS*



* Reproduced from BEIR III, *supra* note 32, at 23.