complex task than had been expected. The chapters, once written, had to be reviewed by DOE/NV staff and a peer review group consisting of some fifty prominent scientists and key test participants. Once all the comments had been received, Dr. Hacker then had to resolve any conflicts. The entire process consumed much time but was vital if the product was to be the most accurate historical account possible.

By 1984, although ten of the fifteen chapters were at some stage of completion, it was evident that at least some of the completed chapters had to be made available to the public soon. Since the late 1970s many legal claims had been placed against the government in connection with the nuclear weapons atmospheric testing program. Information contained in this manuscript could provide both plaintiff and defense counsels an accurate perspective on radiological safety practices in the early testing years. It was decided that the conclusion of the Manhattan Project would make a good cutoff point, and efforts proceeded to complete the final review process of the history of radiation safety from 1942 through 1946. That process consisted of a final technical review on December 5 and 6, 1984, by a select panel of scientists and historians.

A special note of acknowledgment and appreciation is extended to those individuals who have given of their time to be interviewed and to those who reviewed the manuscript. The continued support from the management of the Nevada Operations Office and DOE Headquarters program officials has been vital to this task and is acknowledged. The program supervision extended by members of the Health Physics Division staff has been critical and the efforts of Messrs. Michael A. Marelli and Marshall Page, Jr., are specially noted. The extensive effort of Dr. Barton C. Hacker is also acknowledged. Without the dedication he has displayed, it is doubtful that such work as this would have been possible. It is my hope that the development of both manuscripts will provide the information to remove much of the speculation and wonderment often expressed about the radiological safety program for the testing of nuclear weapons.

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Preface

This volume benefits from the institutional and financial support of the United States Department of Energy, successor to the Atomic Energy Commission and the Energy Research and Development Administration. In 1977 officials from DOE's Nevada Operations Office conceived the need for a complete and reliable historical account of radiological safety in nuclear weapons testing. Reynolds Electrical & Engineering Co., Inc. (REECo), the support firm that has operated the Nevada Test Site for the Atomic Energy Commission and its successors for more than three decades, hired me in 1978 to write that history. It has grown into a far larger project than any of us anticipated, this volume having become but the first of two. The second, which is well under way, traces the history of radiation safety in testing nuclear weapons from the formation of the AEC after World War II until the present.

I have received much guidance from participants in the events I describe, not only in Nevada but everywhere in the country. Many individuals have allowed me to interview them, have read and commented on all or part of the manuscript, and have encouraged or otherwise aided me in this work. The names of those I have interviewed, many of whom also commented on draft chapters, appear in the list of interviews at the back of the book, but I here wish to extend my heartfelt thanks for their help.

For reading the manuscript and otherwise contributing to the endeavor, the following members of REECo's Environmental Sciences Department deserve acknowledgment: Arden E. Bicker, Department Manager; B. Lee Brown, former Dosimetry Research Project Manager; Bernard F. Eubank, Technical Information Officer; Linda K. Jensen, Dosimetry Research Project Staff Assistant; Linda M. Rakow, Dosimetry Research Project Manager; Roger C. Thompson, former Laboratory Analysis Superintendent; and Ira. J. Wells, Senior Health Physicist.

Special thanks must go to William J. Brady, Department Technical Advisor, who shared with me his knowledge of nuclear weapons testing and critically reviewed every one of my drafts; he saved me from more mistakes than I care to contemplate.

Mr. Brady also chaired the review panel, all of whose members I wish to thank for their painstaking and detailed examination of the final draft of *The Dragon's Tail* for accuracy, integrity, and readability. Other members of the review panel were Robley D. Evans, Professor Emeritus of Physics, Massachusetts Institute of Technology; Louis H. Hempelmann, Jr., M.D., Professor of Radiology, University of Rochester, and former Health Group Leader, Los Alamos National Laboratory; Richard G. Hewlett, History Associates Incorporated, and former AEC and DOE Chief Historian; John S. Malik, Scientific Advisor for underground testing, Los Alamos National Laboratory, and Test Panel member, Nevada Test Site; and William H. McNeill, Robert A. Millikin Distinguished Service Professor of History, University of Chicago.

Many other current and former members of DOE, the Defense Nuclear Agency, and their contractors have also assisted me in various ways. So, too, have the many scholars and interested laypersons from whose comments and other help I have further profited. All are included in the list of reviewers. I wish to thank them, as well as those named in the list of interviews.

Last and most important, I thank Sally L. Hacker, although thanks seems too inadequate a word. Professional responsibilities, hers and mine alike, have separated us physically, but distance has never diminished her support—emotional, spiritual, and intellectual—for a project that more than once might otherwise have seemed discouragingly endless and thankless.

Whatever virtues this book may attain owes much to those who have given so freely of their time and knowledge. Its flaws reflect, in part, my difficulty in taking full advantage of all the advice I have received. In the final analysis, I bear full responsibility for what I have written, but no one knows better than I that it could not have been done unaided.

Las Vegas, 1984 B. C. H.

Introduction

RADIATION SAFETY IN WORLD WAR II

The central Pacific morning of 25 July 1946 dawned bright and clearing over Bikini atoll. Scientists finished checking gear aboard barge LSM-60 and left the lagoon just after six o'clock. Ninety feet below the barge hung a watertight caisson holding an atomic bomb; it was the fifth such device ever used, all in little more than a year, but the last for many months to come. Above the barge towered a radio antenna to receive the coded firing signal at How hour, 8:35 A.M., two and a half hours later. As the moment neared, only a few low-lying clouds and scattered high cumulus lingered as reminders of predawn rain squalls and lightning. On the lagoon's calm surface floated a mighty fleet, seventy-four vessels ranging from aircraft carrier and battleship to concrete barge and landing craft. The vessels carried stores, munitions, and fuel, but no voice broke the stillness, no human being stirred. It was called the ghost fleet: an anchored armada arrayed to show the effects of a shallow underwater atomic explosion. A cautious distance away at sea, Joint Army-Navy Task Force One awaited Baker, the second test of Operation Crossroads.

Caution proved well advised. The bomb performed as expected, not surprising for the same plutonium-fission model already tried near Alamogordo and over Nagasaki the year before, and in Crossroads Able earlier that July. The surprise came in what followed. As thousands upon thousands of tons of water collapsed back into the lagoon, a surging wall of radioactive mist blanketed the ghost fleet. "These contaminated ships became radioactive stoves," observed the military committee assigned to evaluate the test. Dismayed salvage teams could scarcely approach most of the target vessels for days; some ships remained off limits much longer. Worse than aborted salvage plans, spreading contamination began to threaten the task force's own support ships and crews. Vigorous efforts by the radiological safety section forestalled apparent harm to any member of the task force, but many safety experts saw too close a call for comfort.

Bombs bursting in air—like the one over Bikini lagoon in the first Crossroads test—caused few radiological safety problems. Radioactive debris (little enough in any case) rose too high, stayed aloft too long, and scattered too widely to pose any danger when falling finally to earth. These results may have helped obscure the warning implicit in the first test of an atomic bomb, Trinity, in July 1945, a warning already muted by good luck and wartime secrecy. Detonated atop a hundred-foot tower and sucking huge amounts of earth and other debris into the rising fireball, it produced enough fallout to alarm those in charge. Superficially burned livestock, however, suffered the only certain damage. As the danger passed, urgent wartime demands discouraged dwelling on might-have-beens. Crossroads Baker left no such easy exit. Testing nuclear weapons clearly posed hazards more severe than even the most expert scientists had fully anticipated.

Radiation safety had been recognized fifty years earlier as a far more modest problem. Before World War II, those chiefly at risk were limited numbers of doctors and technicians working with X-ray machines or radium. Safety centered on the concept of tolerance, the amount of radiation living systems could absorb without irreparable damage. Tolerance doses measured in roentgens became the formal basis for self-imposed X-ray safety codes by the mid-1930s. Concern aroused by the fate of dial painters and other victims led to such codes being extended to radium, then to radon. Standards for tolerable body burdens of radium and for air concentrations of active gases were published in 1941. These three basic standards—for X rays and gamma rays, for ingested radium, and for airborne radon—framed the structure of safety in the fission-bomb project. But much remained unknown or uncertain as the United States launched what the postwar world learned to call the Manhattan Project, the bold venture to design and produce the first atomic bombs.

When the project began in 1941, some basic properties even of the natural radioelements remained question marks; their effects on living things were still less clear. Yet they were well known compared with properties of the active materials used in the bomb project—plutonium, enriched uranium, the products of fission—materials that would require handling in amounts vastly larger than all the radium ever used. Special concerns centered on making plutonium and culling it from fission products. Piles that converted uranium to plutonium produced radiation levels far higher than any met in the past. Plutonium itself, discovered only in 1941, was a complete unknown. And danger might now threaten not merely doctors and technicians by the hundreds, but workers of all kinds by the tens of thousands. Most would know little about the dangers, and few could be told much in a highly secret project. Possible risks to the public compounded the problem, as larger numbers of potential victims offset the presumably lesser danger to any single person.

The bomb makers foresaw these problems. Knowing the hazards, they accepted the need to protect workers and the public against undue exposure. Soon after starting work on plutonium, therefore, the Metallurgical Laboratory of the University of Chicago formed a health division as full partner to its Physics, Chemistry, and Engineering divisions. The Health Division first adapted existing standards and practices to safeguard Chicago project workers. It also launched research programs to learn more about the hazards and the means of coping with them. Ultimately, the entire Manhattan Project modeled its health and safety effort on Chicago practice and research. Chapter 1 surveys the base upon which the Health Division built, the half century of attempts before World War II to counter the hazards of X rays and radium and to devise workable standards for their safe use.

Health Division experts believed they could hold radiation risks, the "special hazards" in project usage, to tolerable levels. By and large they did, but whether they did or not might have mattered little. Health hazards did not rank highest among the risks of gambling large amounts of money, men, and scarce resources on the effort to convert untested theories into working weapons. Early in World War II, no risk outweighed the threat of a Nazi bomb. A German laboratory was the scene of the first recognized nuclear fission in 1939. After the war began, Allied intelligence believed Germany was backing further research. The prospect of seeing Nazi Germany first to make so awesome a weapon was a horror against which almost any risk seemed worth taking.

Health and safety, in fact, may well have posed some of the least baffling problems to confront the Manhattan Project. Routine industrial safety proved to require the more intensive effort, though deeper concern centered on the special hazards. In the event, prewar standards broadly sufficed, despite the host of new and exotic active substances produced in the piles. Although applied on a vastly larger scale, the trial-and-error methods devised over four decades to protect radiation workers mostly met the need. Radiation sources were shielded, careful work habits instilled, workplaces closely watched, workers screened to detect early signs of damage. Setting standards and seeing them enforced were the first tasks of the Health Division.

Those responsible for project health and safety had other concerns as well. Much Health Division research addressed urgent questions about handling and using the many unfamiliar substances the project required. Researchers also explored problems more likely to matter in the longer run. How valid were extant standards? Were all the risks, toxicological as well as radiological, fully perceived? Did new and strange substances pose unknown risks? Were there better ways to detect radiation? Could radiation-caused damage be treated if not prevented? Such questions evoked a wide-ranging research program that sometimes threatened to overshadow more routine work in clinical medicine, health physics, and industrial safety. Health Division opinion was itself divided about the wisdom of spending scarce resources on basic research while war raged; army officers running a crash program showed even less enthusiasm. Although research produced results—better instruments, enhanced knowledge, even new protection concepts—safety remained closely modeled on prewar theory and practice. The main difference was the vastly larger scale of the wartime work, which meant vastly enlarged hazards. Chapter 2 recounts Chicago Health Division efforts to balance wartime demands against long-term safety.

Throughout the Manhattan Project, radiological safety began with good housekeeping. Careful handling of active subtances and proper shielding against radiation largely protected workers from dangerously high levels of contamination or exposure. But turning fissile metals into bombs posed new, and sometimes greater, dangers. The people assigned to the weapons laboratory at Los Alamos in northern New Mexico first faced the unprecedented hazards of making a nuclear bomb. Starting from scratch under intense wartime pressures, they struggled

to devise techniques for treating, purifying, and shaping plutonium, a metal neither they nor anyone else knew very much about. What dangers they might face, what safeguards they needed, were matters of guesswork, informed only by extant radium experience and standards. Protecting laboratory workers became the first task of the small Los Alamos Health Group.

Laboratory crises, however, paled before other strains on Health Group resources when the first plutonium-bomb design proved unworkable in mid-1944. Developing new designs entailed a series of hazardous open-air experiments in the canyons around Los Alamos during the next six months. A young scientist likened one of those experiments to "tickling the tail of a sleeping dragon." Probably no more than a casual quip, the comment nonetheless tapped a deep vein of meaning. In the lore of dragon hunting, the reptile's potent tail posed a special danger: Its thrashing might inflict unexpected damage on the unwary hero even after the animal itself had received its death wound. Metaphorically, the dragon's tail aptly symbolizes the "special hazards" of the Manhattan Project and, perhaps even more aptly, the key process of testing nuclear weapons.

The experimental findings in late 1944 and early 1945 resolved some doubts, but not all. Bomb makers felt compelled to test their gadget. "Gadget" was the word they used. One reason, of course, was secrecy. Perhaps so homely a word also eased the minds of men and women facing a monstrous unknown. In any event, testing the first bomb posed safety problems far more serious than even the broadest meaning of good housekeeping might span. Planning had been under way for a year when the decision for a full-scale field test, code-named Trinity, was made in March 1945. Although the desert site in southern New Mexico was chosen, in part, for the sparsity of its nearby population, the most violent man-made explosion in history would still pose public danger. Radioactivity might pose even more serious hazards, and workers at the test site might not be the only ones at risk. Clouds of plutonium dust or fission products could threaten health and lives miles downwind from the blast. When they decided to conduct the test, planners judged other factors to outweigh the potential dangers. Minimizing the risks fell to the Health Group. Chapter 3 describes how the group planned to do so, and how it coped with the other challenges that carried Los Alamos to the brink of Trinity.

Initially at least, testing the gadget seemed a difficult but straight-

2

ROLE OF THE CHICAGO HEALTH DIVISION

FIRST TASKS

The Health Division issued its first report on 15 August 1942, little more than a week after Robert Stone arrived. It merely noted the need for radiation safety.[1] Serious discourse on what needed to be done and how it should be done appeared only a month later. Simeon Cantril and Kenneth Cole opened the second report with a statement stressing the division's dual role. Part of the job was project health and safety. These concerns were clinically focused; the division bore "direct responsibility for the health of the personnel and the public." The other part was research on "the effects of physical and chemical hazards . . . to provide both a basis for clinical measures and fundamental understanding of the phenomena." These statements in essence defined the goals of Cantril's medical section and Cole's biological research section.[2]

The health physics section supported these efforts. Within the division it measured, analyzed, and computed "the factors involved in the clinical and experimental aspects." Outside the division it had two main jobs: first, to judge and measure future as well as present hazards throughout "the project—research and development, plants and production, and military"; second, to design and oversee safety measures.[3] In practice these statements did not draw sharp limits for the sections; rather they defined centers of concern. Each section did research, just as each became involved in health and safety, guided by the central aim "to eliminate physical and chemical hazards before they reach clinically detectable proportions."[4]

"The first tasks," however, Cantril and Colé noted, centered on "immediate surveys of the hazards to personnel on the Project as a

whole."[5] Two especially seemed to require prompt action. Uranium handling was one. Suspected of being highly toxic in animals, the metal was feared so in humans as well. No proven case of a worker poisoned by uranium had yet appeared at Chicago or in plants that supplied fuel for the pile. Yet the Health Division had to assume uranium to be as toxic as other heavy metals, and so it altered handling routines to reduce dust workers might breathe or swallow. At the same time it sponsored research to find how toxic ingested uranium really was. Albert E. Tannenbaum, a cancer expert at Michael Reese Hospital in Chicago, received a contract and began work in September 1942. His findings proved most reassuring. Uranium toxicology later became the subject of independent research at the University of Rochester.[6]

Uranium was not regarded as a radiological hazard. The half-life of uranium 238 was measured in billions of years, of uranium 235, in hundreds of millions. Radioactivity of neither was thus high or intense enough to pose much threat, even if ingested. This points up an aspect of Manhattan Project safety problems easy to miss. As it became a large industrial project using a host of new techniques and substances, most hazards had little or nothing to do with radiation. Workers may well have faced more serious risks over the course of the project in handling toxic chemicals than they ever did from gamma rays, neutrons, or active substances. Radiation was nonetheless the "special hazard." It was the other one of the two earmarked for prompt action in the September report.[7]

Even before heading the health physics section, Ernest Wollan had begun to survey the laboratory for radiation hazards. Leon Jacobson had likewise taken a health role in the project since early 1942. Both believed "some radical changes must be made at once in working conditions to avoid unnecessary exposure to radiation."[8] Cantril began a systematic survey of the health status of project workers. Aided by the staff of the University of Chicago clinics, he began examining several workers a day. They hoped to correlate their findings with each person's past and current work on the project and thus perhaps devise standard blood and urine tests to detect early signs of radiation damage. They were disappointed. Although routine screening of project workers persisted throughout the war, it proved of little use, for normal results varied too widely and were affected by too many factors. Routine testing simply provided no basis for early warning.[9]

Meanwhile, all workers in areas where gamma radiation levels might be troublesome received pocket ionization chambers. Readings were taken and recorded daily.[10] Although a decade old, pocket chambers remained neither handy to use nor easy to buy. A prewar market for radiation detection or monitoring devices of any kind scarcely existed. Ordinarily, users made their own or did without, but pocket chambers were modest exceptions. Victoreen Instrument Co. of Cleveland, Ohio, offered the first commercial model in 1940. It was a simplified version of the well-known Victoreen R-Meter, widely used during the 1930s in X-ray therapy. Victoreen called the new system the Minometer. Commonly, however, workers used the name only for the separate instrument required to charge and read the pocket chamber.[11]

The chamber itself was an air-filled tube the size of a fountain pen. It worked as a capacitor. A thin wire running through the center of the tube and insulated from its walls stored an applied electrical charge. Ions produced in air by radiation neutralized the charge; the difference between initial and final charge indicated how much radiation the chamber had been exposed to. Requiring both charging and reading on a separate device, the chamber was awkward to use. It was also none too reliable because other factors, like shock or moisture, might affect results. Problems in volume manufacturing to Health Division specifications were also slow to be resolved. To sidestep these drawbacks, Herbert Parker suggested giving each worker two chambers. Using them in pairs became standard practice, sharply reducing the ratio of bad readings. Since all errors increased apparent exposure, the lower reading was taken as correct. By 1945 the pocket dosimeter was far more convenient than the chamber. Basically similar to the simple chamber, it still required charging, but its wearer could read a built-in dose scale directly through a system of magnifying lenses. Instruments of this kind became one mainstay of personnel dosimetry throughout the Manhattan Project.[12]

Photographic film was the other mainstay of personnel dosimetry. Pocket dosimeters provided direct monitoring of individual exposures. Wearers could read them at any time and they were recharged daily. Film served a different purpose. It recorded cumulative exposure over days or weeks, although film, too, might be processed on a daily schedule. In September 1942 the use of film was still only in the planning stage for the Metallurgical Project. Dental X-ray film packets had been on the market for two decades; for nearly as long, they had been used to warn workers against pending overexposure. By 1942 the technique

was well known if not widespread. Standardization presented problems, as did questions about how photographic emulsions responded to different kinds of rays.[13] Film's value thus remained chiefly qualitative, as one dosimetry pioneer suggested in 1939: "If after a week of exposure and standard development, none of the films is so dark that, when it is put on a printed page in good light, the letters cannot be distinguished through it, then protection is adequate."[14]

Quantification of film-recorded doses, however, made progress. The greatly increased demands and resources of the wartime project promoted still more. Film had drawbacks. Heat or moisture could distort readings. It was more sensitive to some kinds of rays than to others. It could not provide immediate readings, as it had to be processed. But it also promised a simple, cheap, and reasonably reliable way to check the very large numbers of workers who might be exposed.[15] Wollan planned to issue film packets "to all those for which there is any possibility of a radiation hazard existing." He also intended "to have these attached to the back of the badge." All workers in the highly secret project had to wear and display security badges. The union of film and badge, he noted, increased "the probability of the film and the individual being together."[16] It has remained a common practice ever since.

Wollan's plans took unexpectedly long to mature. The key problem was that film response varied with energy of X- or gamma radiation. Lower-energy rays produced more ions in emulsions than higher-energy rays. The same number of roentgens, in other words, at lower energies produced darker developed film. The answer was to use filters to flatten the response curve. The right choice of film and filter could give fairly even results over a useful range of energies. Finding the right mix took time. A year of research on films, filter materials, and filter thicknesses preceded the decision on an acceptable design. The choice was a cadmium filter 1 millimeter thick packaged with two types of film. One of the films carried a very sensitive emulsion which allowed darkness to be measured with reasonable reliability over a range from 0.03 to 3 roentgens. The second covered 1 to 20 roentgens. Only late in 1943 did film begin to join pocket chambers in tracking the X- and gamma-ray exposures of project workers.[17]

At the outset the most urgent question facing the Health Division was the most basic one from a safety standpoint. To how much radiation might workers safely be exposed? In one sense, setting protection standards was easy. The widely accepted prewar standards were ready to hand. Confronted with work well under way and workers already at risk, Wollan stated the division's clear choice. The radiation to which workers were exposed should be "less than what is agreed on as being safe (at present 0.1 r per day)."[18] In another sense, however, the problem was not so easy to resolve. What was agreed to be safe in the fall of 1942 could be regarded as only a stopgap. "Established tolerance doses" for X and gamma rays when the project began, Stone later explained, "rested on rather poor experimental evidence."[19]

Unreliable though their basis might be, X-ray and gamma-ray standards existed; the Health Division at least had a body of accepted usage for coping with the danger. For other hazards, even that was lacking. Little or nothing was known about tolerance for neutrons or for alpha and beta particles. For internal emitters—active substances swallowed, inhaled, or otherwise taken into the body and retained—the problem was more complex. The well-known hazards of radium and radon led to the first published standards in 1941. Less was known about radiophosphorus and radiostrontium, nothing at all about tolerance for other active nuclides. A tolerable burden of some active substance was the amount lodged in the body which could be borne without seeming harm. Measuring body burdens in living subjects was tricky, and then it provided only an after-the-fact notice that something had gone wrong. The best measure of body burden, in any event, revealed nothing about intake when metabolic pathways remained question marks. Intake, not burden, was the crucial safety problem, but no one knew much about the relation of amounts taken in to amounts retained. As intake was almost always inadvertent, measured data scarcely existed. The very meaning of tolerance dose for internal emitters was unclear. Repeatedly Stone insisted that the only safe practice was to try to avoid any intake at all.[20]

Enough was known in 1942 to provide, in Cantril's phrase, "base levels on which to build."[21] That was vital. Time pressed, and plans to produce plutonium had to proceed from "calculation of hazards based on such knowledge as already existed," Stone recalled. Yet no one questioned the need, he added, to check the assumed biological effects "by experimentation as rapidly as possible."[22] Other steps also could be taken. One seemed merely semantic. Although "tolerance dose" remained in use well into the postwar era, the preferred term changed during World War II. The new usage, "maximum permissible exposure," had begun to challenge the older term after the mid-1930s. In one sense, changing new words for old meant little. Numbers at first stayed the same. Maximum permissible gamma exposure was the same 0.1 roentgen per day the tolerance dose had been. In other ways, however, the shift was crucial. As the words themselves suggest, the new term connoted a ceiling, an upper limit to exposure, in contrast with the looser notion of tolerability implied by the term it replaced.[23]

At the outset, no new findings supported the change. It was rather a response to the clouded issue of radiation effects on living systems. Biological intuition and medical experience, in fact, suggested that persons exposed below some level would suffer no lasting damage. Given the large number of workers and the huge scope of the project, however, Stone and most of his colleagues preferred the prudent course. They acted almost as if they believed any exposure could be harmful, as if no threshold existed, as if any body burden might cause damage. They hoped research would provide better data than they had in 1942, but the project was too urgent to wait upon final results. Time enough later to raise the limits if research findings permitted. This course undoubtedly kept worker exposures well below what they might otherwise have been.

HEALTH DIVISION RESEARCH

Much Health Division research was more applied than basic: testing and proving the tools and methods required to meet the project's immediate health and safety needs. Typical was health physics work on film badges and pocket ionization chambers. But research was not limited to finding ways to measure individual doses. Instruments were needed to detect and monitor the whole range of particles and rays produced in nuclear reactions. The problems were challenging. Each radionuclide had its own characteristic decay mode. Each kind of radiation presented its own problems and hazards. Each workplace imposed its own special demands. Principles were all known before the war, but few had been reduced to the kind of rugged, standard, and reasonably easy-to-use instruments the project needed. The hard and complex task of turning theory into working tools lasted throughout the war and after.[24]

This effort was crucial to the entire project. Instruments were not only designed and tested at the Met Lab, but in many instances they were also produced in large numbers for use throughout the project.

They also served many purposes beyond health and safety. Health physics, in fact, worked closely with William P. Jesse's instrument group in the Met Lab's Physics Division. Jesse had received his Ph.D. in physics from Yale in 1924 and joined the University of Chicago a decade later. His research centered on X-ray crystallography, cosmic rays, and the ionization of gases. Like others engaged in such research, he learned a great deal about making instruments. He was among the first members of the Chicago faculty tapped for the Metallurgical Project.[25]

Ionization of gases, Jesse's specialty, was by far the most common basis for instruments. Nuclear radiation can be detected only through some effect of its interaction with matter. Of such effects, ions produced in gas are often the most useful. A device like the pocket chamber described above works electrostatically; the ions neutralize the charge. Connecting a power supply—normally a battery—attracts ions to the electrodes and allows the ion charges to flow in a circuit. This current flow can be precisely measured even at very low levels. This process in turn provides a measure of the radiation intensity that caused the ionization. Ionization chambers were one of the two main classes of instruments used at the Met Lab. They had been widely employed before the war in X-ray work. Commercial models were on the market and could be adapted without too much trouble to measure gamma rays, and they could also serve for beta radiation.[26]

The second class of instruments comprised proportional and Geiger-Müller counters. At voltages higher than those used by ionization chambers, freed electrons acquire enough energy to create new ions. The effect is called gas amplification. Over a certain voltage range, it increases current flow in proportion to initial ionization events. Devices working in this range are called proportional counters. At still higher voltages, proportionality fails. A single ionizing event may trigger an avalanche of electrons throughout the detector gas and produce a large electrical pulse. This is the working region of Geiger-Müller counters, named for the two German scientists who perfected the first such device in 1928. Proportional counters were, for the most part, still handmade laboratory devices when the war began.[27] The Manhattan Project changed that because their major use was alpha detection, a special project concern. Plutonium is chiefly an alpha emitter. Massive and highly charged, alpha particles present little threat outside the body; even a sheet of paper will block them. But plutonium, like radium, proved to be a bone seeker. It might produce the same "horrible results . . . [as] radium salts taken into the body."[28] Alpha counters became the subject of intense work throughout the war. The result was an array of devices to check workers and to survey workplaces: hand, face, and foot counters, air samplers, and survey meters with nicknames like Pluto, Sneezy, Poppy, Zeus, and Juno.

Neutrons presented the most difficult problem for the instrument makers. Electrically neutral, their effects on matter differed widely from those of charged particles. From a safety standpoint, the hazard also depended closely on their speed and energy, which vary over a wide range. Monitoring high-speed neutrons in the presence of gamma rays presented special problems. One answer was a device called Chang and Eng, named after the famous Siamese twins because of its twin chambers; the first chamber measured the combined neutron-gamma effect, the second, gamma only. The current from the gamma-only chamber subtracted from the other chamber's current gave the neutron reading. Slow (low-energy) neutrons required a different technique, based on their reaction with boron to form lithium and alpha particles. Filled with a gaseous boron compound or lined with boron, alpha counters could thus be adapted to count neutrons.[29]

In a sense, instruments themselves might define the hazards. The Health Division adopted a tolerance dose for neutrons of 0.01 neutron unit per day. The unit was "that quantity of fast neutron radiations which will produce a reading of one roentgen on a Victoreen condenser r meter when using the 100 r chamber."[30] Exposure levels were often expressed as instrument readings. Thus the maximum permitted alpha level on work surfaces became 50 units on Pluto, the first alpha survey meter produced at the Met Lab. Five units on an alpha hand counter defined the limit for hands, 50 counts per minute on another device, that for faces. In the health physics section, research fell chiefly to Herbert Parker's protection measurements group. Instruments were not the sole concern. Parker also faced the old problem of finding satisfactory units to relate the physics of ionization to biological effects.[31]

The roentgen was defined only for X and gamma rays, but the project faced, Parker noted, the "practical problem of adding the doses received by a large group of workers from quantum radiation, alpha, beta, and neutron radiation."[32] The answer was a common unit. The key choice was to base it on energy absorbed rather than on ions produced. The "rep" (roentgen equivalent physical) measured dose as energy absorbed per unit mass (ergs per gram) equivalent at a point in the body to exposure in roentgens. Since biological effects varied with kind of ray, Parker derived a second unit that included a biological factor. Termed RBE (Relative Biological Effectiveness), it was found by experiment for each kind of radiation. The measure of biological dose was then the product of rep times RBE. Parker called it the "rem" (roentgen equivalent mammal or man). "Roentgen equivalent biological" might have made better logic; he rejected that term when he learned that hearers might confuse rep and reb.[33] Parker completed the new system in early 1944. Stone proposed it for the project at a Met Lab meeting on 7 March.[34] Simple, thoughtful, and convenient, Parker's system won many users during the war. Security prevented its public dissemination until 1948, but not until the late 1950s did rem, the dose unit, fully displace roentgen, the exposure unit, as the basic measure in radiological safety.[35]

The Health Division's medical section provided health services, but like the health physics section it conducted research as well. Clinical needs directed research chiefly in response to the project's direct health and safety demands. Leon Jacobson's blood studies and Albert Tannenbaum's toxicological work were typical. The research program also included other contracted studies on human subjects. Participating were Memorial Hospital in New York, the Chicago Tumor Institute, and the University of California Hospital in San Francisco. The subjects were patients not expected to survive more than a year or two. They received massive single, repeated, or continuous X-ray doses.[36] These studies, as Cantril explained,

> will give some useful information which we do not have on the effects of whole body irradiation. They may permit an appraisal of the effects after . . . at most 1–2 years. . . . They also serve to judge the magnitude of an exposure to which a man could be subjected in an emergency and the length of time before restoration (as well as can be judged from present laboratory methods).[37]

Researchers sometimes used themselves as guinea pigs; in one study of the effects of external radiation on white blood cell counts, four volunteers received up to 50 roentgens whole-body X-irradiation.[38]

Other research was pursued outside the Chicago laboratories. The Health Division sponsored or supported such efforts from the outset. Some of these emerged as major programs in their own right. At the National Cancer Institute in Washington, Egon Lorenz and his colleagues began a small-scale study in the spring of 1941. They exposed mice and other animals to relatively low levels of gamma rays over extended periods of time. Shortly after he joined the Health Division, Stone visited Lorenz. Cooperation between the two groups followed. Met Lab support allowed Lorenz and his co-workers to expand their studies with a much more elaborate experimental facility. Early in 1943 they could begin a new series of experiments using far larger numbers of animals.[39]

The project at the University of California in Berkeley also had prewar roots. Joseph G. Hamilton had worked with Stone on studies of cyclotron-produced active nuclides, later found to be fission products as well. After Stone went to Chicago, Hamilton pursued the work under Health Division auspices. Such studies were badly needed, as Hamilton observed in his first report: "Of the 17 or more elements . . . produced by uranium fission, only a few have been studied with regard to their biological disposition."[40] Little was known about the fate of fission products once they entered an animal's body. One question had special bearing on tolerance. Did other radioelements share iodine's well-known trait of concentrating in a single organ or tissue? Biochemistry ignored radioactivity and thyroids collected all isotopes of iodine indiscriminately. Many fission products, however, were isotopes of rare elements with unknown biochemistry. What impact an active nuclide might have remained guesswork. Using micrograms of radioelements from the Berkeley cyclotron, Hamilton began tracing metabolic pathways of the products and their compounds.[41]

The line between applied and basic research often blurred. As Stone observed, "the clinical study of the personnel is one vast experiment. Never before has so large a collection of individuals been exposed to so much irradiation."[42] Kenneth Cole's experimental biology section, however, was clearly intended to focus the division's basic research. Stone was not the only one who believed that "beneath all observable effects was the mechanism by which radiations, no matter what their origin, caused the changes in biological material. If this mechanism could have been discovered, many of the problems would have been simpler."[43] Whether a full-scale basic research program could have been designed in 1942 must remain an open question. The dearth of sure knowledge may have been too large a handicap.

In any event, wartime pressures precluded such an approach. As, Cantril and Cole noted early, "work directly connected with immediate not a bone seeker. Polonium was very quickly absorbed by the body but also quickly excreted. Other factors promoted the picture of a lesser hazard: smaller amounts used, simpler technical operations. The availability of a quick, easy test for polonium in urine, something achieved for plutonium only after strenuous efforts, also permitted routine checking of workers from the outset. Yet even at war's end much remained unknown about the way both polonium and plutonium behaved in the body and about the full extent of the hazard.[24]

SAFETY AND RESEARCH

Meanwhile, however, safety demanded prompter action. With other project doctors, Hempelmann visited a radium-dial firm in Boston for a firsthand look at hazard controls. His report guided Kennedy to set up three committees to begin work on the problems, one of which was assigned to devise guidelines for the Chicago instrument makers. The pressing need was for portable alpha counters and air samplers.[25] Once again Oppenheimer stressed how much Los Alamos relied on Chicago. Experience and resources put "your laboratory," he noted, "in a far better position than ours to undertake [this work]."[26] The second committee began working on designs for plutonium-handling equipment; the third, on setting rules for working with active substances. At the same time Kennedy formed the monitoring and decontamination group under Richard A. Popham. Trained as a botanist but diverted into other channels by the war, Popham's new job was to head the Chemistry-Metallurgy Division's "central office for the control of the special radioactive health hazard." The first task was to begin "regular monitoring for activity of the dust in all laboratories." Then, as soon as he could, Popham would enlist specialists "for clean-up of rooms in which the hazard has gotten out of hand."[27]

Knowledge about plutonium and proper means to detect it were both in short supply. Popham worked closely with Hempelmann to devise expedients. One was the so-called swipe method of rubbing a 1-square-inch piece of oiled filter paper across a working surface and then testing the paper in a fixed alpha counter. Recorded counts per minute served as a rough index of concentration. Both men would have preferred more direct survey methods to this crude makeshift, but lack of portable alpha counters limited options. Swipes also ignored the key problem: airborne active dust workers might breathe. Chicago work on air samplers had as yet produced no results. That meant a second stopgap, nose counts. This technique involved swabbing inside a worker's nostrils with filter paper, again measured in the fixed counter. Readings higher than 100 counts per minute were somewhat arbitrarily deemed to require action, such as warning the worker to improve his technique or perhaps shifting him to a plutonium-free job. Nasal swabs provided at best only a rough index of how much dust might have been inhaled. The real problem, however, remained too little knowledge about the ways plutonium behaved in the lungs and elsewhere in the body.[28]

William Jesse's Chicago instrument group was neither recalcitrant nor incompetent. Radiological safety had not demanded alpha monitoring before the war. Although an alpha source, radium also emitted much-easier-to-measure strong gamma rays. Fission products, too, tended toward strong gamma emission. As pile radiations and fission products seemed the most urgent problems during the project's first years, the instrument group focused its limited resources on these areas. Plutonium posed the first major hazard that could be detected, essentially, only through its alpha activity. Methods existed, but largely in the form of clumsy and touchy laboratory devices. Without commercial sources to draw on, the Chicago group had not only to design and develop, but also to produce, what was needed. Los Alamos stood last in line. Chicago itself, the pilot plant in Tennessee, the production plant at Hanford—all required instruments. Both more closely linked to Chicago than Site Y, Sites X and W might well make demands easier to hear. Their demands also came sooner. It was, after all, only when plutonium began to arrive from Tennessee and Hanford that Los Alamos called for help.[29]

Shortages, however, accounted for only part of the problem. Each site had special needs. Even when developed, the large, fixed alpha counters and air samplers suited for production plants seemed too clumsy for Los Alamos. At Site Y concern centered on laboratory monitoring which required, above all, good portable survey meters. The only one yet available early in 1944 was the Met Lab's Pluto, an ionization chamber adapted for alpha counting. From Los Alamos it looked far too insensitive. Pluto shortages thus only partly explained why Site Y monitors persisted with the swipe method. For all the slow and spotty results, swipes could detect much lower alpha levels.[30] Los Alamos electronics experts strove to fill the gap. Their first effort produced a new hand counter. Installed in Building D—where pluto-

Radiologic History Exhibit

Wrong Turns on Radiology's Road of Progress[1]

David J. DiSantis, MD • Denise M. DiSantis, BS

■ INTRODUCTION

Radiology has been blessed with remarkably insightful proponents and practitioners since its inception. Consequently, the first century of radiologic practice has been one of unparalleled advance. Not unexpectedly, given this rapid ascent, American radiology has occasionally suffered a mild case of the intellectual "bends." Chronicled herein are some of the missteps along the way.

■ AMERICA LEARNS OF X RAYS

Even the introduction of the new science to Americans was a bit off-key. The *New York Sun* touted the mysterious "light that never was" on January 6, 1896 (Fig 1), crediting its discovery to Professor Routgen [sic]. "Roentgen ray fever" promptly became an American epidemic. With nearly 1,000 presentations and articles dealing with x rays appearing within the first year (2), it was obvious that both the medical community and lay public were thoroughly enamored of the new marvel. Extended (unshielded) fluoroscopy became de rigueur during physical examinations (Fig 2). Long lines formed at public exhibitions where subjects underwent fluoroscopy for hours (Fig 3) to amuse the customers (4). Advertisements for ladies' x-ray-proof underwear appeared, as did a (perhaps tongue-in-cheek) bill in the New Jersey legislature banning incorporation of x rays into opera glasses (5).

The popularity of x rays can be traced in part to the efforts of Thomas Edison. Edison's entrepreneurial interest in x rays was aimed at increasing their public availability, and so in 1896 he introduced a recreational home fluoroscopy unit (4) (Fig 4). He anticipated even wider appeal for his new type of light bulb—an x-ray tube coated with fluorescent paint (4) (Fig 5).

■ ARE THESE RAYS SAFE?

Reports of skin damage after exposure to x rays began to appear as early as 1896. But the controversy regarding the injurious effect could not have been more heated. Nikola Tesla blamed ozone for the damage (3), while others thought it was some sort of electrical burn. Dogmatic wrong-headed pronouncements did much to muddy the issue (Fig 6). But danger lurked on both sides of the fluoroscopy screen.

After his assistant, Clarence Dally, became the first American x-ray casualty, Thomas Edison observed, "Experimental work with x-rays will be but slightly affected by

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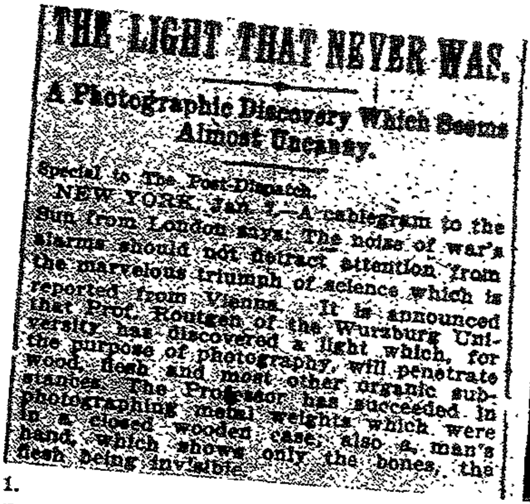
Index terms: Radiations, injurious effects • Radiology and radiologists, history

RadioGraphics 1991; 11:1121–1138

[1] From the Department of Radiology, DePaul Medical Center, Eastern Virginia Medical School, 150 Kingsley Ln, Norfolk, VA 23505. Recipient of a Certificate of Merit for a scientific exhibit at the 1990 RSNA scientific assembly. Received August 7, 1991; accepted August 22. Address reprint requests to D.J.D.

See also the article by Sirr (p 1068) in this issue.



THE LIGHT THAT NEVER WAS,

A Photographic Discovery Which Seems Almost Uncanny.

Special to The Post-Dispatch.

NEW YORK, Jan. 7.—A cablegram to the Sun from London says: The noise of war's alarms should not distract attention from the marvelous triumph of science which is reported from Vienna. It is announced that Prof. Routgen of the Wurzburg University has discovered a light which, for the purpose of photography, will penetrate wood, flesh and most other organic substances. The Professor has succeeded in photographing metal weights which were in a closed wooden case; also a man's hand, which shows only the bones, the flesh being invisible.

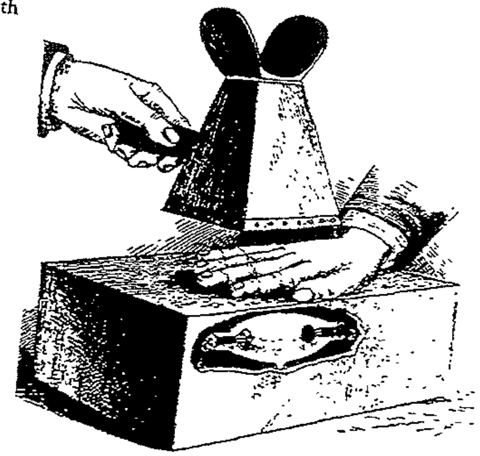
1.

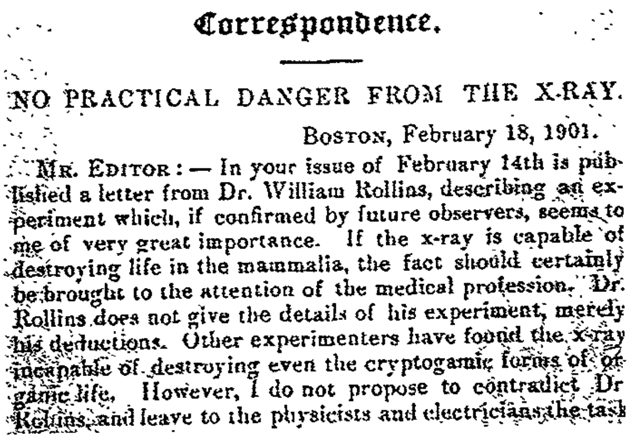
2.

Figures 1–3. (1) "Routgen's" amazing rays, announced by the *St Louis Post Dispatch* on January 7, 1896. (Reproduced, with permission, from reference 1.) (2) Unshielded patients, operators, and tubes were the rule for fluoroscopic examinations in 1896. Little did they suspect that the test was worse than the disease. (Reproduced, with permission, from reference 2.) (3) Exhibitions did indeed expose the public to "the new marvel." (Reproduced, with permission, from reference 3.)

3.

Figure 4. Drawing of the Edison Vitascope, intended for recreational home fluoroscopy. (Reproduced, with permission, from reference 4.)





Correſpondence.

NO PRACTICAL DANGER FROM THE X-RAY.

Boston, February 18, 1901.

Mr. Editor: — In your issue of February 14th is published a letter from Dr. William Rollins, describing an experiment which, if confirmed by future observers, seems to me of very great importance. If the x-ray is capable of destroying life in the mammalia, the fact should certainly be brought to the attention of the medical profession. Dr. Rollins does not give the details of his experiment, merely his deductions. Other experimenters have found the x-ray incapable of destroying even the cryptogamic forms of organic life. However, I do not propose to contradict Dr Rollins, and leave to the physicists and electricians the task

Figure 6. Venerable radiology pioneer E. A. Codman reassures readers of the *New England Journal of Medicine* (then known as the *Boston Medical and Surgical Journal*) that fears of x rays are overblown. (Reproduced, with permission, from reference 7.)

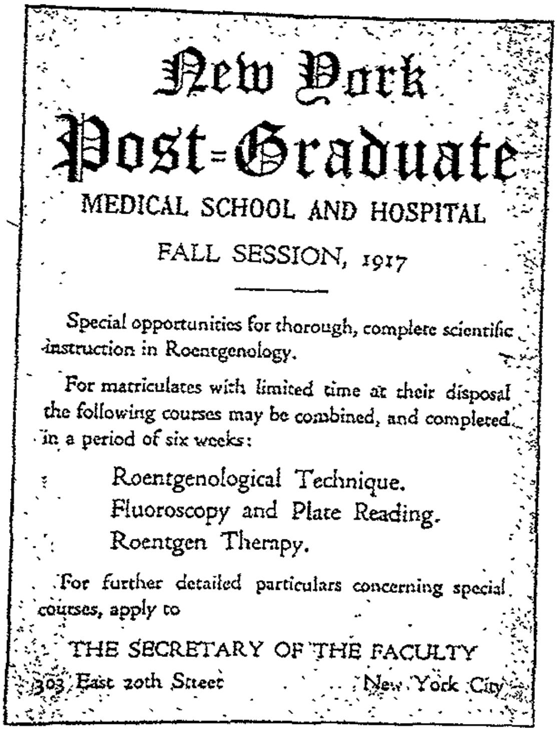
Figure 5. Edison, photographed by the light of his x-ray tube light bulb. (Reproduced with permission, from reference 6.)

my discovery of their harmful effects. I have a [lead] screen one-half inch thick in my laboratory, and would continue the experiments, but my wife won't let me" (8). With the consensus regarding the potential danger slow to grow and bolstered by early successes in tumor treatment, x rays were applied to an amazingly wide range of maladies, from ringworm to frostbite.

Training for physicians who used x-ray equipment was cursory at best (Fig 7), rarely stressing safety. Consequently, gross overexposures by inexperienced practitioners continued well into this century (Fig 8). X-ray physicians were in no less jeopardy than their patients. A 1948 study of the hands of radiologists revealed radiation damage in 48% (10) (Fig 9).

■ X RAYS IN THE MARKETPLACE

American business was even more liberal in its use of x rays. Beginning in the 1920s, x-ray units were used in beauty parlors to remove unwanted facial and body hair (Fig 10). The largest operation, known as the Tricho Sys-



New York
Post-Graduate
MEDICAL SCHOOL AND HOSPITAL
FALL SESSION, 1917

Special opportunities for thorough, complete scientific instruction in Roentgenology.

For matriculates with limited time at their disposal the following courses may be combined, and completed in a period of six weeks:

- Roentgenological Technique.
- Fluoroscopy and Plate Reading.
- Roentgen Therapy.

For further detailed particulars concerning special courses, apply to

THE SECRETARY OF THE FACULTY
303 East 20th Street New York City

Figure 7. Cram course or sham course? One could become a radiologist, radiographer, and radiation therapist in just 6 weeks. (Advertisement from AJR 1917; 4:XVIII.)

Figure 8. Photograph shows lower back scar caused by an x-ray burn from a single gastrointestinal tract fluoroscopic examination. The fluoroscopist burned three more patients that same day (9). (Reproduced, with permission, from reference 9.)

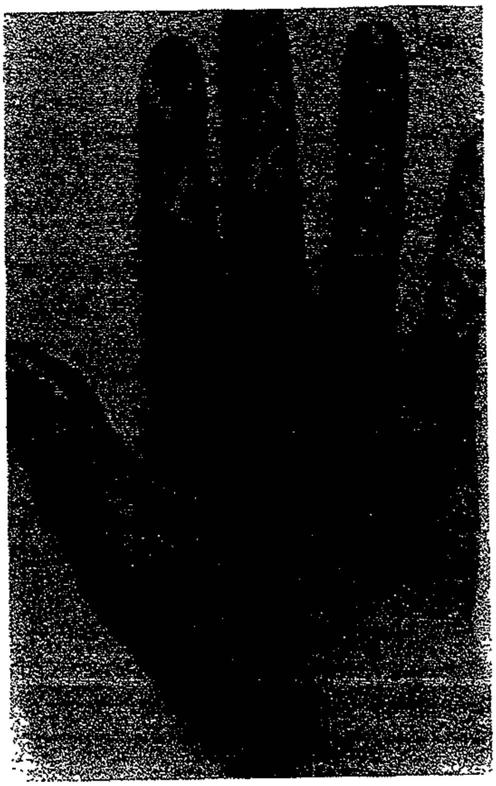
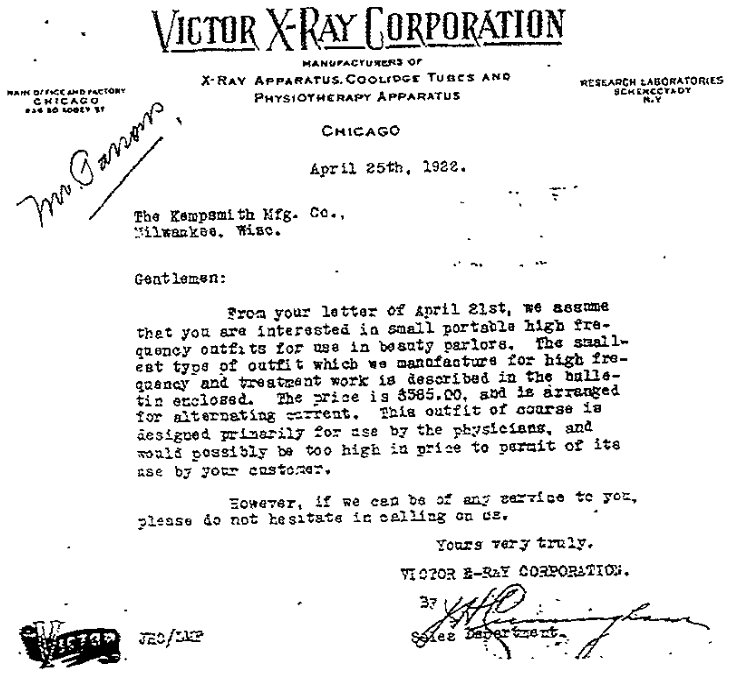


Figure 9. Photograph shows multiple, ulcerating squamous cell carcinomas on the hand of an early radiologist. (Reproduced, with permission, from reference 3.)



VICTOR X-RAY CORPORATION

MANUFACTURERS OF
X-RAY APPARATUS. COOLIDGE TUBES AND
PHYSIOTHERAPY APPARATUS

MAIN OFFICE AND FACTORY
CHICAGO
236 SO ROBEY ST

RESEARCH LABORATORIES
SCHENECTADY
N.Y

CHICAGO

April 25th, 1922.

Mr Gannon

The Kempsmith Mfg. Co.,
Milwaukee, Wisc.

Gentlemen:

From your letter of April 21st, we assume that you are interested in small portable high frequency outfits for use in beauty parlors. The smallest type of outfit which we manufacture for high frequency and treatment work is described in the bulletin enclosed. The price is $385.00, and is arranged for alternating current. This outfit of course is designed primarily for use by the physicians, and would possibly be too high in price to permit of its use by your customer.

However, if we can be of any service to you, please do not hesitate in calling on us.

Yours very truly.

VICTOR X-RAY CORPORATION.

By
Sales Department.

JRC/LMP

Figure 10. What price beauty? According to the Victor X-Ray Corporation, just $385. (Reproduced, with permission, from the Hammer Collection, Archives Center, National Museum of American History, Smithsonian Institution.)

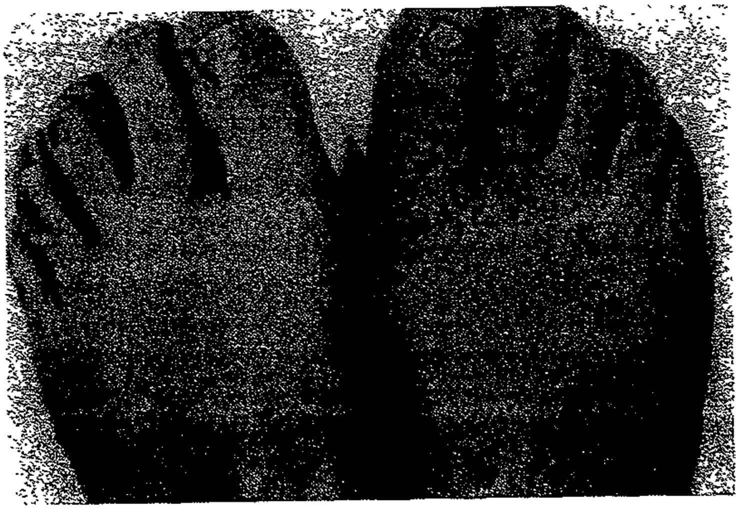
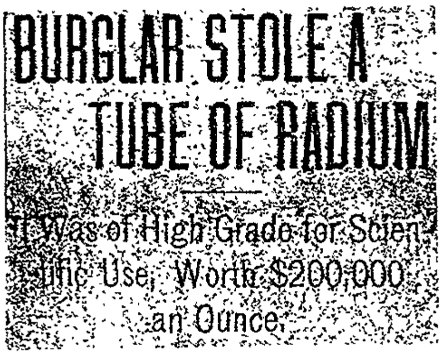


Figure 13. Photograph shows severe radiodermatitis of the feet of a shoe store employee whose fitting fluoroscope had faulty shielding. (Reproduced, with permission, from reference 14.)



BURGLAR STOLE A TUBE OF RADIUM

It Was of High Grade for Scientific Use, Worth $200,000 an Ounce.

Figure 14. The explosive popularity of radium made it a "hot" commodity in more than one sense. (From the *New York American*, May 8, 1904. Reproduced, with permission, from the Hammer Collection, Archives Center, National Museum of American History, Smithsonian Institution.)

■ ENTER RADIUM

Marie and Pierre Curie's discovery of radium in 1898 touched off a new round of "ray mania." The mystery and romance of a new element (one discovered by a woman, no less) that produced constant abundant radiation without the cumbersome apparatus needed to generate x rays electrified the scientific community and lay public as well. The mystique was enhanced when it was revealed that radium actually changed into other elements—alchemy come true. Despite the scarcity of radium and the resultant spectacular cost (Fig 14), public fascination prompted the incorporation of radium into everything, from chocolate to contraceptive jelly (5) to cleansers (Fig 15).

To say that radium was viewed early on as a godsend panacea is to understate the prevalent perceptions (Fig 16). Spectacular accounts of radium-induced tumor shrinkage prompted physicians to try it for maladies ranging from hypertension to schizophrenia. There seemed to be no reason for caution, since, as the journal *Radium* declared in 1916, "Radium has absolutely no toxic effects, it being accepted as harmoniously by the human system as is sunlight by the plant" (Radium 1916; 7:24). According to some, radium might even be the source of life itself (Fig 17)!

There were many people disappointed in not being able to obtain a Radium Eclipse Sprayer on our first offer, because of the overwhelming demand from nearly every State in the Union. As a result, we have decided to offer another special lot of

250 Radium Eclipse Sprayers

Absolutely Free

With Every Gallon Can ($2.50) of Radium Cleanser

Radium Cleanser is the greatest cleaning proposition of modern times. It quickly kills all Flies, Mosquitoes, Roaches, Bed Bugs, Germs, Microbes, etc. Radium Cleanser has no equal as a cleaner of Furniture, Paintwork, Porcelain, Tile, etc.

It is harmless to humans and easy to use. Radium Cleanser is now being used by all the warring European nations in trenches, barracks, camps, hospitals with [illegible]

For Sale at All Leading Department, Drug, Grocery and Hardware Stores or Direct From

Radium Chemical Co.

[illegible] Bailey Bldg. 1218 Chestnut St.

COUPON

Radium Chemical Co.
[illegible] Bailey Building,
1218 Chestnut St., Phila.

Figure 15. Advertisement for a combination radium insecticide and furniture polish Virtually no potential market escaped the assault of the radium entrepreneurs. (Reproduced, with permission, from the Hammer Collection, Archives Center, National Museum of American History, Smithsonian Institution.)

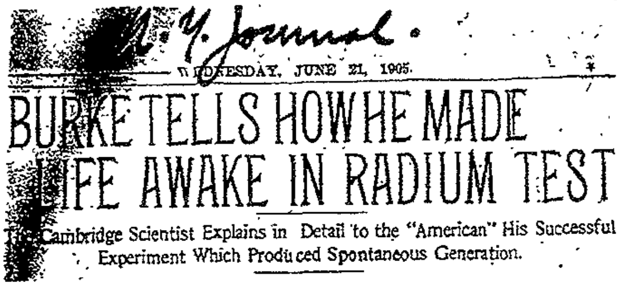
RADIUM AS A SUBSTITUTE FOR GAS, ELECTRICITY
AND AS A POSITIVE CURE FOR EVERY DISEAS

Wonderful Things Learned About the New Metal by W. J. Hammer, Formerly Associated With Edison.

As Difficult to Obtain
Would Be a Spoonful
Flavoring Extract Fr
the Waters of the Pla

WILLIAM J. HAMMER
Who Probably Knows More About Radium Than Any Man in the United States.

Figure 16. When radium could do no wrong. (Article appeared in 1904; reproduced, with permission, from the Hammer Collection, Archives Center, National Museum of American History, Smithsonian Institution.)



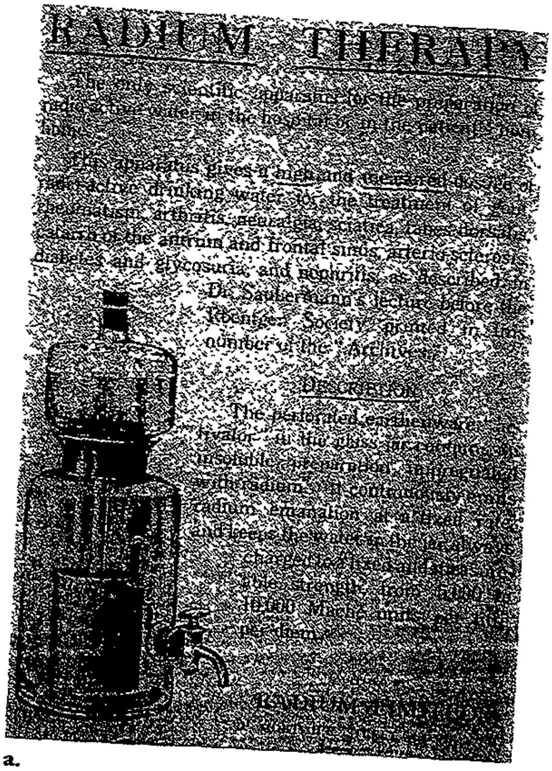
N. Y. Journal.

WEDNESDAY, JUNE 21, 1905.

BURKE TELLS HOW HE MADE LIFE AWAKE IN RADIUM TEST

The Cambridge Scientist Explains in Detail to the "American" His Successful Experiment Which Produced Spontaneous Generation.

Figure 17. The most amazing claim of all. In fact, quite the opposite was to prove true. (From the *New York Journal*, June 21, 1905. Reproduced, with permission, from the Hammer Collection, Archives Center, National Museum of American History, Smithsonian Institution.)



RADIUM THERAPY

The only scientific apparatus for the preparation of radio-active water in the hospital or in the patient's home.

This apparatus gives a high and measured dosage of radio-active drinking water for the treatment of gout, rheumatism, arthritis, neuralgia, sciatica, tabes dorsalis, catarrh of the antrum and frontal sinus, arterio-sclerosis, diabetes and glycosuria, and nephritis, as described in Dr. Saubermann's lecture before the Roentgen Society printed in this number of the "Archives."

DESCRIPTION

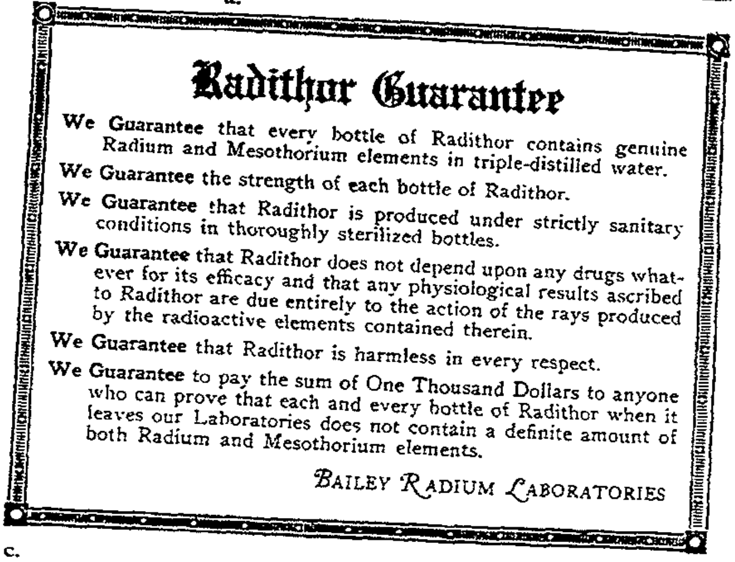
The perforated earthenware activator in the glass jar contains an insoluble preparation impregnated with radium. It continuously emits radium emanation at a fixed rate and keeps the water in the jar always charged to a fixed [illegible] strength, from 5,000 to 10,000 Mache units per litre per diem.

RADIUM [illegible]

Figure 18. (a) Treatment with liquid sunshine was made easy with a home radium water dispenser. (Reproduced, with permission, from reference 15.) (b) Radithor was a 1920s radium tonic and contained more than 2 μCi (74 kBq) of radium per bottle. (c) This guarantee assured Radithor customers that they were getting the real thing. Ironically, it was the manufacturers whose tonics contained too little radium that ran afoul of the law. (Figs 18b and 18c reprinted, with permission, from reference 16.)

a.

b.



Radithor Guarantee

We Guarantee that every bottle of Radithor contains genuine Radium and Mesothorium elements in triple-distilled water.

We Guarantee the strength of each bottle of Radithor.

We Guarantee that Radithor is produced under strictly sanitary conditions in thoroughly sterilized bottles.

We Guarantee that Radithor does not depend upon any drugs whatever for its efficacy and that any physiological results ascribed to Radithor are due entirely to the action of the rays produced by the radioactive elements contained therein.

We Guarantee that Radithor is harmless in every respect.

We Guarantee to pay the sum of One Thousand Dollars to anyone who can prove that each and every bottle of Radithor when it leaves our Laboratories does not contain a definite amount of both Radium and Mesothorium elements.

BAILEY RADIUM LABORATORIES

c.

a.

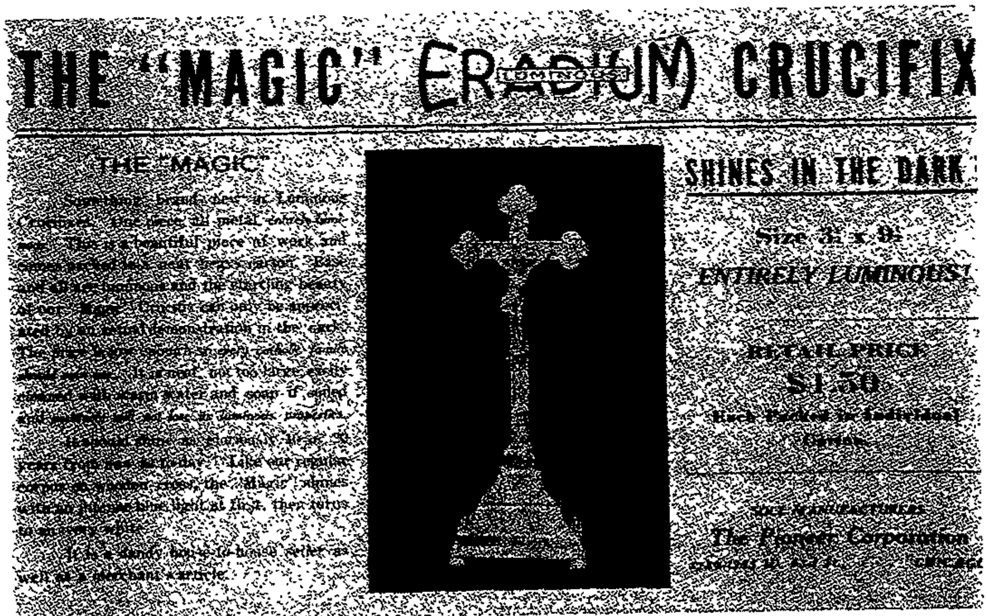
Recipe for "Liquid Sunshine."
To Be Used at the Technology Club Banquet.
One part of sulphate of quinine.
Fifty thousand parts of water.
Stir until dissolved in a glass.
Insert a tube of radium until sufficient radioactivity is developed to cause the water to throw off violet or ultra violet rays.
Drink it as you would sauterne or champagne.

c.

b.

Figure 19. (a, b) "Let us 'rays' our glasses." Toasting with liquid sunshine cocktails at the 1904 banquet of the New York Technology Club (c) Recipe for the radium cocktail. (Reproduced, with permission, from the Hammer Collection, Archives Center, National Museum of American History, Smithsonian Institution.)

A favorite means of gaining the much-touted health benefits was to ingest radium-impregnated water, known bucolically as "liquid sunshine." Hailed not only as salubrious tonics (Fig 18), radium beverages were an instant hit as fluorescent cocktails on the banquet circuit (Fig 19). Dinner could be served on radioactive china (Fig 20), then cleansed away with radium toothpaste (Fig 21). After-dinner entertainment might include a glowing game of radium roulette (Fig 22) or perhaps just evening prayers before an ever luminous crucifix (Fig 23). American business loved radium (Fig 24).



THE "MAGIC" ERADIUM CRUCIFIX

LUMINOUS

THE "MAGIC"

SHINES IN THE DARK

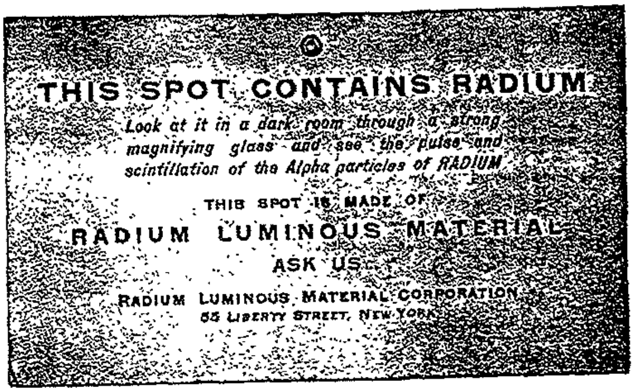
Size 3½ x 9½

ENTIRELY LUMINOUS!

RETAIL PRICE
$1.50
Each Packed in Individual
Carton

SOLE MANUFACTURERS
The Pioneer Corporation
CHICAGO

Figure 23. Advertisement for a crucifix with a decidedly unheavenly glow. (Reproduced, with permission, from the Hammer Collection, Archives Center, National Museum of American History, Smithsonian Institution.)



THIS SPOT CONTAINS RADIUM

Look at it in a dark room through a strong magnifying glass and see the pulse and scintillation of the Alpha particles of RADIUM

THIS SPOT IS MADE OF

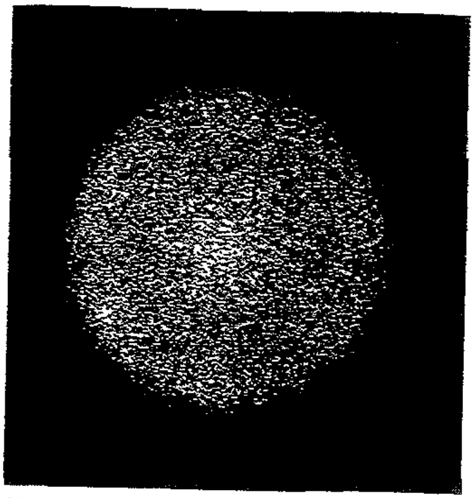
RADIUM LUMINOUS MATERIAL

ASK US

RADIUM LUMINOUS MATERIAL CORPORATION
55 LIBERTY STREET, NEW YORK

Figure 24. A business card not conducive for maintaining long-term customers. (Reproduced, with permission, from the Hammer Collection, Archives Center, National Museum of American History, Smithsonian Institution.)

Figures 20–22. (20) "Hot" plate. Scintigram of a Fiestaware dessert dish. These uranium-glazed dishes were produced from 1935 to 1971. Acidic foods can leach traces of uranium out of the glaze (5). (Courtesy of Claude Hesselman, DePaul Medical Center, Norfolk, Va.) (21) A perky German advertisement (ca 1935) for radioactive toothpaste. The rays were said to provide a "healthful massaging of the gums." (Courtesy of Ben Z. Swanson, Jr, MD, Baltimore.) (22) Participants gambled with higher stakes than they imagined. The wheel, balls, and chips were coated with luminescent radium paint. (Article appeared in 1904; reproduced, with permission, from the Hammer Collection, Archives Center, National Museum of American History, Smithsonian Institution.)



20.

Wußten Sie schon ...?

daß man durch regelmäßige, leichteste Massage des Zahnfleisches die Zähne länger gesund und dauernd ganz weiß erhalten kann?

Jeder kennt die wohltuende Wirkung einer Massage für den Körper. Die Massage des Zahnfleisches besorgt ganz selbsttätig „Doramad", die biologisch wirksame Zahnpaste mit der radioaktiven Strahlung, die beim Zähneputzen mit „Doramad" frei wird. Die Strahlen prallen, ohne daß Sie es wahrnehmen, auf das Zahnfleisch und massieren noch stundenlang nach dem Putzen die Mundorgane. Das bedeutet schnellere Durchblutung, Stärkung der natürlichen Abwehrkräfte und somit sichere Vernichtung der schädlichen Bakterien.

„Doramad" wirkt biologisch, ihr regelmäßiger Gebrauch sichert Ihnen dauernd gesunde und weiße Zähne.

Doramad-Zahnpaste erzeugt natürliche Frische!

21.

UM ROULETTE

A NEW YORK RAGE

IS PLAYED IN THE DARK, AND GHASTLY SILENCE.

A GAME OF "RADIUM ROULETTE."

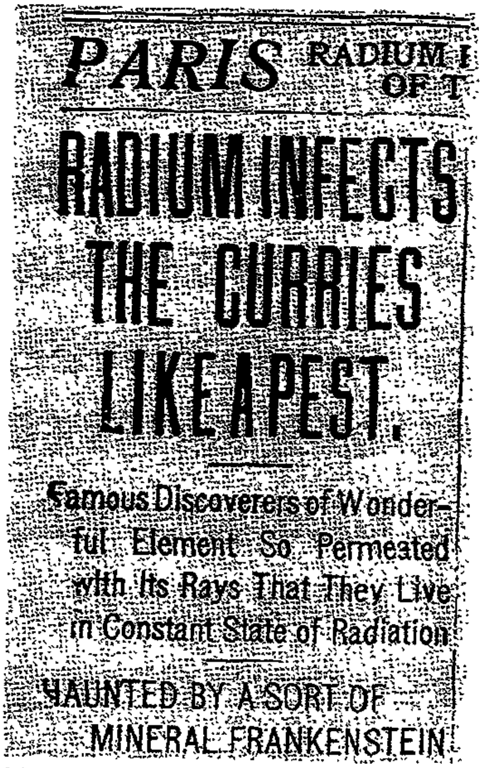
The roulette outfit is immersed in a solution of radium, and the game is played in the dark.

22.

Was radium a panacea or Pandora's box? Its discoverers found they could not escape it (Fig 25), and its proponents and partakers came to rue its advent (Fig 26). In the 1920s, the popularity of radium was unabated, with glowing radium paint particularly ubiquitous in products from fish bait to doll eyes. As Dr Sabin von Sochocky, developer of "Undark" radium-based paint observed in 1921, "The time will doubtless come when you will have in your own house a room lighted entirely by radium . . . like soft moonlight" (5).

The rapid fall of radium from grace began with the deaths of several young women, painters of luminous watch dials (Fig 27). Their mysterious osteonecrosis and profound anemia prompted a search of their workplace, the U.S. Radium Company. The unshielded work area and the painters themselves were so thoroughly spattered with radioactive paint that even the workers' undergarments glowed (5). Safety was such a nonissue that the women painters sometimes applied the glowing radium paint to their fingernails and teeth for special occasions (5). To get the finest point on the brush, the painters passed their brushes between their lips and thus swallowed minute amounts of radium-based paint (Fig 28). So permeated with radioactivity were the dial painters that they could light a fluoroscopy screen with their breath, and yet an autopsy revealed that the lethal dose had been less than 70 cents worth of radium. Amazingly, because of the long latency between exposure and disease, the U.S. Radium Company nearly evaded culpability by invoking the statute of limitations (5).

The deaths of the dial painters plus the burgeoning casualty list of early x-ray workers tolled the close of America's uninhibited love affair with radiation. But by then, some "ray-vangelists" had already given in to temptation. Heady with newfound power thanks to



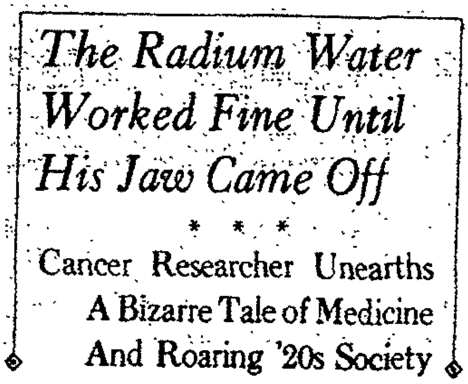
PARIS RADIUM I
OF T

RADIUM INFECTS THE CURRIES LIKE A PEST.

Famous Discoverers of Wonderful Element So Permeated with Its Rays That They Live in Constant State of Radiation

HAUNTED BY A SORT OF MINERAL FRANKENSTEIN

25.



The Radium Water Worked Fine Until His Jaw Came Off

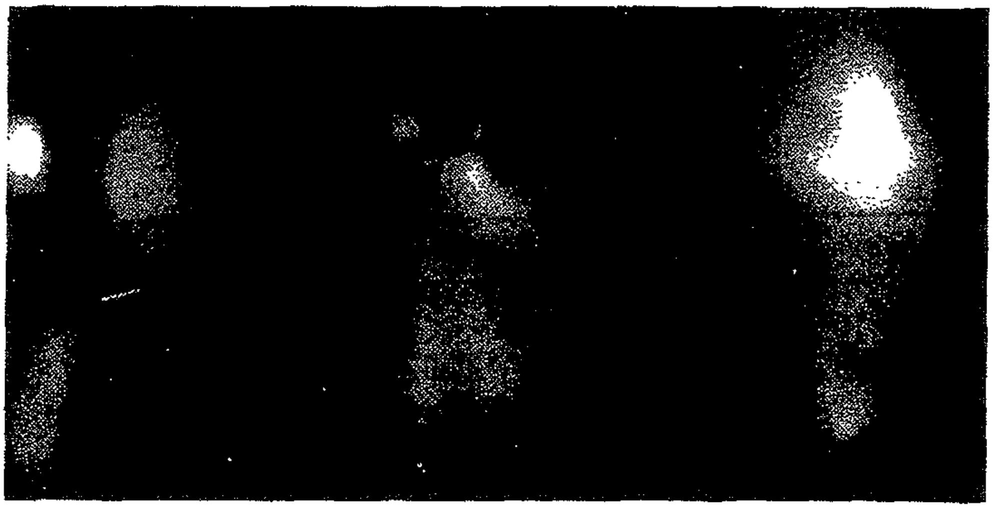
* * *

Cancer Researcher Unearths A Bizarre Tale of Medicine And Roaring '20s Society

26.

Figures 25, 26. (25) The Curies were to suffer more than misspelling. Marie Curie died of radiation-induced aplastic anemia. (From the *New York Journal*, April 30, 1905. Reproduced, with permission, from the Hammer Collection, Archives Center, National Museum of American History, Smithsonian Institution.) (26) The debt begins to come due, as seen in the headline from a story detailing the demise of a radium tonic user. (From the *Wall Street Journal*, August 1, 1990.)

27.



28.

Figures 27, 28. (27) Photograph shows the work area of the radium dial painters. Note the street clothes and the complete absence of shielding. (Reproduced, with permission, from reference 17.) (**28**) Autoradiograph obtained by placing the teeth of a radium poisoning victim atop photographic film. (Reproduced, with permission, from reference 18.)

Figure 29. The self-righteous employ the new science in attempts to foist dubious blessings. (Reproduced, with permission, from the Hammer Collection, Archives Center, National Museum of American History, Smithsonian Institution.)

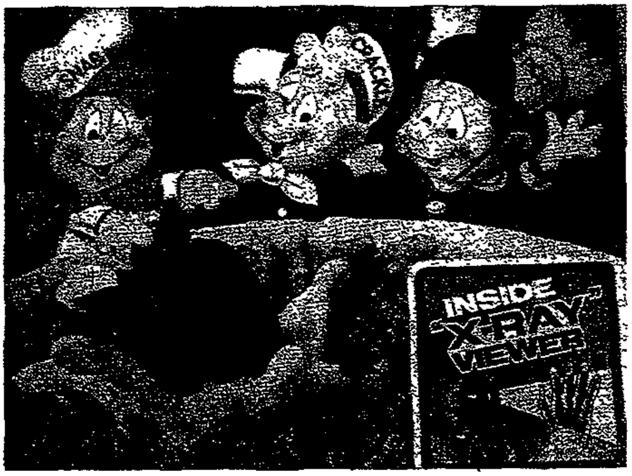
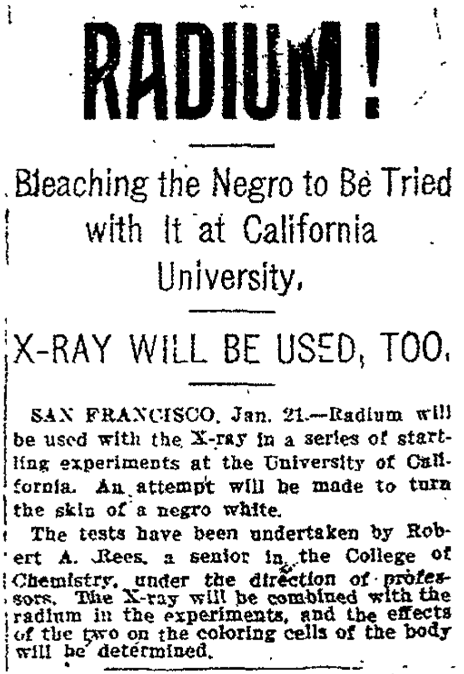


Figure 31. As this photograph of a 1990 cereal box attests, radiation *remains fully assimilated* into current culture. A careful look at the hands of this famous threesome, however, reminds us of the hazards of "x-ray" viewer overuse. (Courtesy of Kellogg Corporation.)



RADIUM!

Bleaching the Negro to Be Tried with It at California University.

X-RAY WILL BE USED, TOO.

SAN FRANCISCO, Jan. 21.—Radium will be used with the X-ray in a series of startling experiments at the University of California. An attempt will be made to turn the skin of a negro white.

The tests have been undertaken by Robert A. Rees, a senior in the College of Chemistry, under the direction of professors. The X-ray will be combined with the radium in the experiments, and the effects of the two on the coloring cells of the body will be determined.

Figure 30. More experiments in human "betterment." (Article appeared in 1904, reproduced, with permission, from the Hammer Collection, Archives Center, National Museum of American History, Smithsonian Institution.)

radiation, they sought to reshape society more to their liking (Figs 29, 30). Even William Rollins, the patron saint of early radiation safety, succumbed briefly to the dark side of the force, as evidenced by his article titled "On the importance of treating the generative organs of degenerates by X light to prevent *their increase*" (19). Happily, the period was brief when radiology journals' pages were sullied with titles such as "Sterilization in the interests of race betterment" (20).

■ CONCLUSION

Only the benefit of the "retrospectoscope" permits a smug review such as this one. The giants who piloted radiology through the groping, formative years stand no less tall for these brief detours from the true path. And though the applause for the blessings of radiation has been tempered by recognition of its perils, the sheer fascination with it remains undiminished (Fig 31).

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NO DOSE TOO LOW

Contents

A high-stakes battle rages over the risks of low-level ***radiation***.

IS THERE A SAFE LEVEL OF ***RADIATION***? Is there some standard belong which exposure is harmless? Maybe even "good for you?" Years ago, many ***radiation*** scientists believed just that. Very low doses of ***radiation*** were harmless to human health, they said, and some argued that very small exposures actually had a positive effect.

Over time, however, those views have lost favor, and they are now aired mainly by those who appear to have a pro-nuclear bias. Today, most of the world's ***radiation*** scientists believe that even very small doses of ***radiation***--those that are well below background levels and whose effects are difficult to detect--increase the risk of developing cancer, however slightly.

That view was officially endorsed in 1991, when the International Commission on ***Radiation*** Protection (ICRP) adopted the "linear-no-threshold" model, a theory that had been around, in various forms, for decades. A wide variety of studies--of Japanese A-bomb survivors, nuclear workers, and children who had been exposed with medical equipment--are often cited in support of the no-threshold theory, as well as recent studies that implicate "natural" or background ***radiation*** as the cause of many cancers.

Although the no-threshold theory is now widely accepted by every major international organization concerned with ***radiation*** risks, it continues to be a matter of controversy because a significant number of ***radiation*** scientists, particularly in the United States and France, still hold to the earlier view that low doses are harmless. And the views of American scientists in particular remain influential in setting ***radiation*** standards in the U.S. nuclear industry.

In part, the growing acceptance of the no-threshold theory reflects the latest understanding of biologists of how cancers originate. Their recent findings of ***radiation's*** effects on a cellular level raises new and serious questions about what level of ***radiation*** exposures should be permitted, both for workers in the nuclear industry and for the public at large. But tighter standards requiring lower emissions are likely to have serious cost implications for the nuclear industry, and they could have implications in lawsuits over ***radiation*** overdoses.

The current controversy

When the ICRP, a voluntary international commission that makes recommendations on ***radiation dosimetry*** and limits, issued Publication 60, 1990 Recommendations of the ICRP, calling for lower limits, it set off considerable controversy.(n1) The ICRP proposed that ***radiation*** doses to the general population and to workers in the nuclear industry should be kept to very low levels below background. The proposal was significant, because most countries, excluding the United States and Russia, follow the commission's recommendations in setting national standards.

Publication 60 recommended reducing ***radiation*** limits for workers from 50 milliSieverts (5 rem) to an average of 20 per year, and limiting permissible exposures to the general public from 5 milliSieverts to one. These standards have now been adopted by a variety of other organizations, including the U.N. Scientific Committee on the Effects of Atomic ***Radiation***, the International Atomic Energy Agency, the World Health Organization, Britain's National Radiological Protection Board, and the European Union.

In the United States, the National ***Radiation*** Protection Committee, the National Research Council's Committee on Biological Effects of Ionizing ***Radiation***, and the Environmental Protection Agency have all endorsed the no-threshold theory, but the Nuclear Regulatory Commission has yet to adopt the ICRP'S recommended exposure limit. The current U.S. standard for workers remains at 50 milliSieverts per year. However, the Nuclear Regulatory Commission's standard for the public is already 1 milliSievert.

Meanwhile, the lower limits--and the no-threshold theory behind them--have provoked a heated debate in some quarters--in professional associations, ***radiation*** and nuclear industry conferences, ***radiation*** journals, and on various e-mail listservers. The controversy, which has continued for more than six years, shows few signs of abating.

French complaints

Initial complaints about the recommendations in Publication 60 came mainly from ***radiation*** authorities in countries whose governments were strongly pro-nuclear--France, Canada, and Japan.

France is committed to nuclear power, with about 75 percent of its electricity capacity derived from nuclear plants. The French government was particularly concerned about the effect that tighter limits would have on domestic uranium mining; however, a slump in world uranium prices has since shut that industry down.

Then, in 1995, the French Academie des Sciences issued a report criticizing the new standards, consistent with the views of the powerful French nuclear industry and research establishment.

The Academie's own report was heavily criticized, however, and the French government's Institute of Nuclear Safety and Protection sided instead with the ICRP. Even more remarkable, the institute asked Britain's National Radiological Protection Board to review the Academie's report for the French parliament.(n2) Although the Academie opposed the conclusions of that review, the Academie itself refused to make recommendations one way or the other. As a result, the French government has now agreed to implement the recommendations in Publication 60.

The United States

In January 1996, the Health Physics Society, a professional association of ***radiation*** protection personnel and scientists working in the U.S. nuclear power industry, weapons laboratories, and nuclear research establishments, issued a statement opposing the no-threshold theory.(n3) The society asserted that no adverse effects had been observed in humans exposed to less than 100 milliSieverts, and further, that below such a dose, ***radiation*** risks were either nonexistent or too small to be observed. Estimating the risk of doses below 50 milliSieverts, the society said, was too speculative. The society also asserted that applying the no-threshold theory without accounting for biological mechanisms like "cellular repair" resulted in overstatements of risk.

It was soon clear that many of the society's members disagreed. The society's May 1996 newsletter contained many dissents from that January statement. One member pointed out that the society's statement that low doses had no health effects was in conflict with the society's simultaneous recommendation that risk estimates not be used for low doses. Another member pointed out that the society's position sounded "more political than scientific". And a third correspondent predicted that the statement "will harm the credibility of the [Society] as a ***radiation*** protection organization."

Meanwhile, the American nuclear waste industry also became concerned. In July 1996, the Nuclear Regulatory Commission was petitioned by its own advisory committee on nuclear waste, most of whose members are representatives of industry, warning that there would be significant "societal" costs if the no-threshold positron was adopted.(n4) In addition, the petition argued strongly against the idea of "collective" or population-wide dose estimates when calculating risks.

The scientific debate

Epidemiological studies. Both sides agree that studies of Japanese bomb survivors show strong evidence of adverse effects at a dose of 200 milliSieverts for adult survivors and 100 milliSieverts in the case of children. Below that, the Health Physics Society says, there is an "inability to detect any increased health detriment."

But most others disagree. They cite Alice Stewart's pioneering Oxford studies, which revealed that children whose in utero exposures were as little as 10 to 20 milliSieverts had 40 percent more childhood leukemias than those who were not exposed--a statistically significant increase in risk at low doses.(n5) Although Stewart's work, published in 1970, was long attacked by nuclear industry proponents, subsequent studies have supported its main findings and government ***radiation*** authorities now quote the Oxford studies without caveat.(n6)

In addition to Stewart's work, a 1995 study that pooled the results of seven epidemiological investigations showed a statistically significant increase in the incidence of human thyroid cancer in groups that received doses of between 10 and 100 milliSieverts.(n7)

Carcinogenesis. Perhaps more important than epidemiological studies, where there is always room for argument, are recent advances in understanding how cancers are triggered. Radiobiologists now agree that cancer can be initiated as a result of a single ***radiation*** track passing through a single cell nucleus.(n8) Most damage to cellular genetic material is corrected by repair enzymes. When cellular DNA is misrepaired, however, it can result in a mutation that, years later, may develop into cancer.

And if a single track through a single nucleus--the lowest possible ***radiation*** dose--can cause cancer, then any exposure to ***radiation*** is hazardous. Of course, the odds that a particular individual will develop cancer from a particular exposure are extremely low. Still, it means that one can no longer speak of a "safe" dose level. A more troubling problem arises if one calculates the chance that some members of a large population--not a particular individual--will develop cancer (calculated by adding all the individual risks).

Background *radiation*. Everyone in the United States is exposed to 4 to 5 milliSieverts per year of natural, or background, ***radiation*** from a variety of sources--radon, cosmic rays, and the nuclides found in soil, diet, and in the body. Individuals may also be exposed to additional ***radiation*** through medical diagnostic and treatment programs.

No-threshold opponents argue that because emissions from nuclear installations are already well below background levels, there is no reason to worry. But this argument has always assumed that natural ***radiation*** is safe, an assumption that is no longer tenable, given what we now know about carcinogenesis at the cellular level. Background ***radiation*** has already been calculated to cause some 4-5 percent of Britain's cancer deaths.(n9) Similar rates occur in the United States and other countries. The International Committee on ***Radiation*** Protection does not use background ***radiation*** as a criterion for acceptable radiological practices.

DNA damage. The integrity of a cell's DNA is constantly under assault, mostly by thermodynamic instabilities or attacks by chemical radicals. Because almost all of the resulting DNA breaks are repaired with great fidelity, those who adhere to the idea of a safety threshold claim that a few more breaks pose an insignificant risk.

But this claim ignores the nature of repair. Damage caused by heat instability or chemical radicals affects only one of the two strands that make up the DNA; in repairing the break in a single strand, the other strand is used as a template. ***Radiation***, however, is more likely to cause double-strand DNA breaks, which have a greater risk of misrepair.

"Adaptive response." Many nuclear proponents point to research findings that appear to show that cells given small doses of ***radiation*** suffer less damage when subsequently given larger doses than cells that received no preliminary dose.(n10) In other words, they say that cells benefit from low doses in some circumstances.

They postulate that a low priming dose of ***radiation*** may increase the number of enzymes available to repair subsequent ***radiation*** damage. But this argument ignores the enormous capacity already available for repair, and the fact that it is fidelity of repair, not the number of repairs, that is critical. The U.N. Scientific Committee on the Effects of Atomic ***Radiation*** examined the notion of "adaptive response" in 1993, and concluded that while it was an interesting phenomenon that occurs in some cell systems at various stages of development, it had little relevance in ***radiation*** protection.(n11)

The latest word

In 1996, the latest mortality data from the continuing study of Japanese A-bomb survivors was published, revealing a statistically significant upward trend of risk with doses in the region of 50 milliSieverts.(n12) Warren Sinclair, president emeritus of the U.S. National Committee for ***Radiation*** Protection, concluded that these new results vindicated the position the ICRP took in 1991.(n13) The results are another blow to the Health Physics Society's claim that there is no scientific proof of negative effects at exposures below 100 milliSieverts. The Academie des Sciences has concluded that these new results require it to reconsider its position on the no-threshold theory.

Three important findings come out of the latest study of survivors: on effects at low exposures, on the shape of the dose-response curve, and on gender and age differences in response to ***radiation***. The increased statistical power of the study, with five added years (to 1990) and 10,000 additional subjects, allowed the authors to divide the population that received lower exposures into three groups that received estimated doses of no more than 20, 50, or 100 milliSieverts.

Excess cancers occurred in each group, and the authors conclude that the "data do not suggest the existence of a threshold below which there is no excess risk." Their results are also consistent both with Stewart's study on fetal exposures, and Thomas Mancuso's study of workers exposed at Hanford, both of which involved low exposures. Indeed, Stewart's study of pregnant women showed a linear relationship down to 10 milliSieverts.(n14) (It should be noted that all the subjects in these studies were exposed to similar rates of background ***radiation***.)

Although the latest survivor study suggests a straight dose-response curve the authors also raise the possibility of a "superlinear" relationship--that is, that the incidence of some solid cancers increases more steeply at lower doses.

The latest survivor study also found important cancer mortality differences by gender and age at the time of the bombing: Generally, risk dropped as age at exposure increased. Women were at twice the risk as men when exposed at the same age, and children under 10 were at greatest risk.

Collective dose

The ICRP'S adoption of a no-threshold model for ***radiation*** effects has stimulated renewed interest in calculating collective dose. Until recently, this concept was used mainly for collating occupational doses or doses to small populations living near nuclear facilities.

Two reports in the mid-1980s provide theoretical underpinning to the concept of collective dose. Both reports recommended that, since ***radiation*** protection practices are concerned with the protection of the population as whole, potential collective as well as individual harm should be calculated.(n15) The ICRP has also endorsed the use of collective dose: "***Radiation*** detriment should be explicitly included," and "collective effective dose is an adequate representation of the collective detriment." The ICRP is also concerned that collective dose be kept "as low as reasonably achievable," as the regulations of most European countries require.

Death and money

If the practice of calculating collective dose is adopted, there will be great controversies over attempts to translate from dose to detriment--that is, to calculate damages in terms of deaths or their money equivalents. For instance, one can predict that the collective doses from Britain's Sellafield fuel reprocessing plant will cause 200 excess cancer deaths worldwide each year (over all future time) for every year that Sellafield's emissions remain at the present level.

Cost-benefit studies may use collective dose to calculate whether it is worthwhile to carry out remedial work or to end certain processes. For instance, if the ICRP's per-Sievert risk factor and an estimated value of $3 million for each loss of life were used, the global cost of Sellafield's annual estimated emissions would be $615 million.(n16)

Despite their uncertainty, the global effects of collective doses and their monetary costs should be calculated for discharges from military and civilian nuclear facilities, and they should be included in environmental impact statements for proposed nuclear facilities, nuclear waste dumps, and final repositories.

Such calculations will undoubtedly raise questions about the environmental costs of proposed nuclear facilities. This concern is reflected in the opposition to collective dose measurements expressed by the Health Physics Society and the Nuclear Regulatory Commission's nuclear waste advisory committee.

The inescapable problem for the Health Physics Society and the nuclear industry is that, as knowledge of ***radiation's*** effects continues to increase, it becomes more and more apparent that those effects must be taken more seriously than once thought.

Over the past 100 years, exposure limits steadily have been tightened as more knowledge has been acquired about ***radiation*** effects. Whether they like it or not, global collective dose estimates will increasingly become a part of the language of both environmental agencies and pressure groups, and they will make their way into environmental impact statements and other assessments of nuclear operations.

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(n16.) For example, see "Estimating Externalities of the Nuclear Fuel Cycle," Oak Ridge National Laboratories and Resources for the Future (Washington, D.C.: McGraw-Hill, 1994); C.F. Guenther and C. Thein, "Estimated Cost of Person-Sv Exposure," Health Physics, 1997, vol. 72, pp. 204-221.

MAJOR SOURCES

(in person-Sieverts)

All bomb tests conducted in the atmosphere worldwide	30,000,000
The Chernobyl accident	600,000
Worldwide nuclear power production (to 1989)	400,000
Worldwide radioisotope production and use (to 1989)	80,000
Nuclear weapons fabrication (to 1989)	60,000
Ten years of reprocessing at Sellafield	40,000

Ten years of reprocessing at La Hague	30,000
The Kyshtum accident,1957	2,500
The Windscale (Sellafield) accident, 1957	2,000
All underground nuclear tests worldwide	200
The Three Mile Island accident, 1979	40

(*) Using a conventional risk factor of 5 percent per Sievert, it has been predicted that the nuclear tests that were conducted in the atmosphere will--over the next 10,000 years--cause 1.5 million people to contract potentially fatal cancers.

The authors suggest that reprocessing at Sellafield, on Britain's northwest coast, will cause 200 excess cancer deaths yearly.

Following the Windscale (Sellafield) accident in 1957, a researchers, uses a modified household vacuum cleaner samples of air- and wind-borne dust.

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By Ian Fairlie & Marvin Resnikoff

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Top of Page

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