

Los Alamos Radiation Detectors

In 1940, Otto Frisch and Rudolph Peierls wrote a memorandum to the British government warning of the possibility of a German atomic bomb. In it, they impressed upon the British government the importance of determining, in the aftermath of the explosion of an atomic bomb, “the exact extent of the danger area, by means of ionizing measurements, so that people can be warned from entering it.” Even as Frisch and Peierls made the first serious consideration of an atomic bomb, they were mindful of the need for radiation detectors to define the boundaries between hazard and health. This concern for radiation protection, which was articulated well before the Manhattan Project was even conceived, was inherited by the workers who built the atomic bomb.



Figure 1. Supersnoop

This early alpha-particle detector, called Supersnoop, was produced at the Chicago Metallurgical Laboratory and distributed to places such as Los Alamos for the detection of plutonium, uranium, and polonium in the work environment. However, because of the shortage of instruments like this one, Los Alamos began a detector development program of its own. By 1945, the program yielded a sensitive light hand-held alpha detector called Pee Wee.

Radiation detectors were needed at Los Alamos to delimit safe and dangerous areas and, even more challenging, to monitor internal exposures to plutonium and other radioisotopes. In 1943, when Los Alamos first opened, Los Alamos scientists were preoccupied with research on the atomic bomb and, therefore, relied upon the Chicago Metallurgical Laboratory to supply the radiation detectors needed to monitor uranium and plutonium in the work environment. Yet, despite heated correspondence between Los Alamos and the Met Lab, the detectors were not forthcoming. Los Alamos suffered an acute shortage of radiation detectors well into 1944 and, in the interest of the workers, began a detector development program of its own. At the forefront of this work was Richard Watts of the Electronics Group in the Physics Division who developed a number of alpha-particle detectors—culminating in the portable “Pee Wee”—named for its mere 19 pounds, to detect uranium and plutonium in the work environment. This work initiated detector development at Los Alamos and set the stage for later work. After the war, Los Alamos began the development of some very special radiation detectors for monitoring internal exposure to radioisotopes. Wright Langham, the leader of the Radiobiology Group of the Health Division, organized a group of scientists of diverse and complementary talents to produce detectors that not only provided radiation protection but also had a great impact in the fields of biology and nuclear medicine.

During the late 1940s, while Los Alamos was busy maintaining its newly acquired nuclear capability, a number of discoveries led to the rebirth of a promising class of detectors called scintillation counters. In 1903, scintillation counting was first used by Sir William Crookes to detect alpha particles emitted by radium. Every time an alpha particle struck the scintillator, zinc sulphide, the scintillator would emit a flash of light. With his eye, Crookes counted the flashes and, with a pen, he recorded the tally. Because this technique was so laborious and uncertain, scintillation counters fell into disuse in the 1930s as Geiger-Müller counters and ion chambers, which produced electronic output, took their place. Two events revived scintillation counting in the forties and fifties: the development of the photomultiplier tube (an instrument that converts light into an electrical pulse) and the discovery of a variety of new types of scintillators, liquid and solid, organic and inorganic, each with their particular advantage. Scintillation counting developed through the 1950s to produce the most versatile, sensitive, and convenient detectors of the time.

Los Alamos scientists became involved in these developments in the early 1950s

for Biology and Medicine

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as they began intensified research on the hydrogen bomb and boosted fission bombs. This work involved tritium, the radioactive isotope of hydrogen. As a result the Los Alamos Health Division began to develop techniques to monitor internal exposures to this low-energy beta-emitting isotope. Unlike gamma rays, low-energy beta particles cannot penetrate the body, and therefore internal tritium exposures must be monitored by measuring the tritium in samples of body fluids such as blood and urine. The beta particles are hard to detect even in the body fluids because they tend to be “self-absorbed” before they reach the detector. Consequently each sample had to be prepared in many tedious steps, including complete distillation or combustion followed by vaporization and reduction (see “Tracer Studies at Los Alamos”), before its tritium content could be measured with a standard detector, either an ion chamber or Geiger-Müller counter. Furthermore, those standard detectors were fairly inefficient at measuring the very low-energy (less than 18 keV) beta particles emitted by tritium.

Once discovered, it was immediately clear that liquid organic scintillators would eliminate many of the problems associated with tritium detection in biological samples. Self-absorption would not be a problem because the blood or urine was directly mixed into the liquid scintillator such that the tritium beta particles would immediately collide with scintillator molecules. Depending on the energy, the beta particles would excite thousands or possibly millions of scintillator molecules. The excited molecules would quickly re-emit the absorbed energy in the form of photons, which would travel freely through the transparent scintillator to a photomultiplier tube where they would be converted into an electrical pulse. The scintillation counter was also highly efficient.

Wright Langham, who had been an investigator in the tritium human studies, was well aware of the advantages of liquid scintillation and decided to put the exceptional talents of his scientific staff to work on a liquid scintillation counter. F. Newton Hayes—a brilliant organic chemist who discovered the “*p*-terphenyls,” a family of organic chemicals which yielded many of the best liquid scintillators ever known—produced the scintillator. Ernest C. Anderson, Robert Schuch, and Jim Perrings—who were familiar with the difficulties of low-energy beta detection from their work with Willard Libby and Jim Arnold at the University of Chicago on radiocarbon dating—did the instrumentation.

Even the earliest liquid scintillation counters were several times more efficient than the ion chamber and very convenient, requiring minimal preparation. Yet, for all these advantages, there was one serious problem: the false signal, or “noise,” produced by the photomultiplier tube. This noise was so large that it could easily overwhelm the signal from a typical biological sample. Richard Hiebert and Watts, the experienced detector physicist who developed the much needed alpha detectors during World War II, were the first to rectify this problem. Instead of using only one photomultiplier tube to detect the light emitted by the scintillator, they used two and created a “coincidence circuit” to eliminate background noise. Signals that appeared in both photomultiplier tubes at the same time were counted, whereas signals that occurred in only one photomultiplier tube were thrown away. Of course, occasionally the false signal from the two photomultiplier tubes would occur at the same time and be counted in the



Figure 2. The Early Version . . .
As big as a refrigerator, the early Packard TriCarb Liquid Scintillation Counter of 1954 was a marked improvement on existing techniques for the detection of tritium and other beta-emitting radioisotopes, such as the biologically important carbon-14 and phosphorus-32.



Figure 3. . . . and the New Version
Sleek and computerized, the modern Packard Liquid Scintillation Counter still uses the original basic design developed at Los Alamos. This detector, or a detector like it, can be found in virtually every biochemistry or genetics laboratory around the world.

data. However, this technique immediately reduced the noise from 10,000 to 20,000 counts per minute to only 10 counts per minute in the Los Alamos Coincidence-Anticoincidence Model 530 Liquid Scintillation Counter. As has so often been the case, once the basic design was worked out, industry began to produce commercially successful models of the liquid scintillation counter. In 1953, Gordon Gould was collaborating with George LeRoy at the University of Chicago on a study of the role of cholesterol in atherosclerosis, or hardening of the arteries. Cholesterol and one of its building blocks, acetate, were labelled at Los Alamos with tritium and carbon-14, both low-energy beta emitters. Although they did not use the liquid scintillation counter in this study, Gould in-

formed LeRoy about the work done at Los Alamos on the Model 530. LeRoy was so enthusiastic about the detector that he went to Lyle Packard and asked him to build him one of these detectors. This interaction resulted in the first commercially successful version of the Los Alamos Tritium Counter, called the Packard Tricarb. The value of this detector extended well into the fields of biochemistry and nuclear medicine and, in fact, a modern equivalent is found in every biochemistry or genetics laboratory to this day (see “DNA Repair and the Scintillation Counter” for examples of how these counters were used to make major discoveries in molecular biology).

At more or less the same time that the Model 530 scintillation counter was being developed, an elusive particle called the neutrino brought about the development of a second branch of liquid scintillation counters at Los Alamos: the whole-body counters, HUMCO I and II. The existence of the neutrino had been hypothesized by Wolfgang Pauli as early as 1930, but the particle had never been “observed,” and Fred Reines and Clyde Cowan of the Los Alamos Physics Division decided to

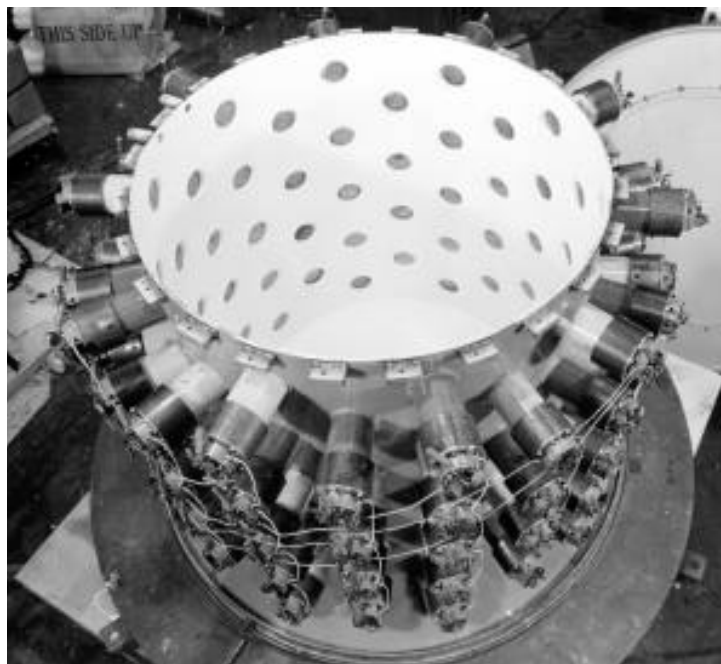


Figure 4. The Neutrino Detector

This top view of the giant Hanford neutrino detector shows the interior of the ten-cubic-foot vat for the liquid scintillator and the 90 photomultiplier tubes peering inside. This detector was the first step toward the discovery of the neutrino, work for which Fred Reines (see Figure 5) earned the 1995 Nobel Prize in physics.

test Pauli's theory. Because neutrinos interact extremely weakly with other matter, they needed to build a colossal, high-density detector and put it near a nuclear reactor, where the flux of neutrinos was expected to be high. Liquid scintillators, which are quite dense and can be produced in large quantities, were perfect for the job. Reines and Cowan approached Wright Langham with their idea and were apparently so persuasive that Langham “loaned” them Hayes, Anderson, and Schuch. They built a cylindrical vat, 10 cubic feet in volume, and filled it with liquid scintillator. They surrounded the vat with 90 photomultiplier tubes, connected them to a coincidence circuit, and placed the detector beside the Hanford nuclear reactor. This work produced a tentative confirmation of Pauli's neutrino in 1953 and in 1956, after some modifications on the original detector, the first positive observation of the neutrino (see Figure 4).

The neutrino detector was developed out of pure academic interest, yet it yielded the practical rewards of HUMCO I and II. In the course of their work on the neutrino detector, Reines and Cowan decided to determine the degree to which the natural gamma ray activity of the materials used to shield the neutrino detector would add noise to the experiment. They built a large “top hat” about 23 centimeters in diameter and 75 centimeters high and inserted it, top down, into the cylindrical vat of scintillator. The shielding materials were placed in the concavity of the top hat. Most of the gamma rays emitted by the materials would penetrate the top hat, enter the scintillating material, produce photons, and be detected.

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DNA Repair and the Scintillation Counter

Before the invention of the liquid scintillation counter, there seemed to be a conspiracy in nature against the biochemist, that tritium and carbon-14, two of the most important radioisotopes to the study of biology, were also some of the hardest to measure. The scintillation counter, which was developed in the 1950s, made the detection of these low-energy beta-emitters simple and efficient. Consequently, tritium and carbon-14, along with phosphorus-32, soon became the backbone of biomedical research. A few of the contributions to our understanding of DNA repair of radiation damage that were made possible by the scintillation counter are given below.

In 1964, R. B. Setlow and W. L. Carrier at Oak Ridge National Laboratory used a scintillation counter to produce some of the first biochemical evidence that cells repair ultraviolet damage to DNA. Earlier in the 1960s it had been demonstrated that ultraviolet radiation induces chemical bonds between two neighboring pyrimidine DNA bases (thymine and cytosine), forming pyrimidine "dimers." Those dimers distort the normal helical shape DNA, stop DNA synthesis, and prevent cells from replicating. Setlow and Carrier examined the cellular response to pyrimidine dimers in a culture of bacterial cells.

The cells were grown in a medium containing tritium-labeled thymidine, which was incorporated into their DNA. After irradiation, the DNA was degraded into single bases, dimers, and other DNA fragments,

which were analyzed by process called "paper chromatography." In this process, bases and dimers separate onto different locations on a piece of paper by virtue of their different solubilities. The paper was cut into segments containing single bases and others containing dimers, and the segments were tossed directly into a scintillation counter. Fortunately, because of its broad range of sensitivity, the scintillation counter was able to measure the activity of both the bases and the dimers, even though they may differ by as much as a factor of one hundred thousand.

Setlow and Carrier observed fewer dimers in the DNA of cells that were allowed to incubate, indicating that those cells somehow repaired the dimers, and they also demonstrated that the cells cut the dimers out of the DNA, the first step in a type of genetic repair called "nucleotide excision repair."

In 1964, David Pettijohn and Philip Hanawalt at Stanford University demonstrated the second step of the repair, the replacement of the excised piece of DNA. In this experiment, two labels were used: carbon-14-labeled thymine and a higher-density, tritium-labeled thymine analog. The cells were grown in the presence of the first label, irradiated, and allowed to incubate in the presence of the second label. The DNA was broken into fragments of similar length and separated in a centrifuge by density. Then the DNA was dried on filter paper and put it into a scintillation counter. They observed that

the higher-density thymine analog was incorporated into the DNA in the small quantities that demonstrated the replacement of the excised piece of DNA.

In 1966, R. A. McGrath and R. W. Williams of Oak Ridge National Laboratory used the scintillation counter to produce the first evidence that cells repair "single-strand breaks," or breaks in one side of the DNA double-helix, caused by ionizing radiation. The cells were grown in tritium-labeled thymidine and irradiated with x rays. The cells were divided into batches and allowed to incubate for different amounts of time. The DNA from the cells was then divided into its two single strands, such that it fell into pieces at the single-strand breaks. Using a centrifuge, they separated the long molecules of DNA from the short molecules. The DNA was dried on small disks of filter paper which were then thrown into the scintillation counter. McGrath and Williams observed that the DNA from the cells that were allowed to incubate was in large pieces, not very unlike the DNA of unirradiated cells, while the DNA from the cells that were not allowed to incubate was in short pieces. Clearly, the DNA had been significantly repaired during incubation.

The scintillation counter has continued to produce breakthroughs in the study of cellular repair of radiation damage since then and remains as important today as when it first became available in the 1950s. ■

Figure 5. Getting Down to Work
Wearing his characteristic tie, Wright Langham was the only one small enough to be lowered into the “top hat” inside the neutrino detector. Fred Reines (left) and Kiko Harrison do the honors.



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Schuch was the one who suggested making a larger insert, 51 centimeters in diameter, so that they could put a small person inside and use the detector to measure the gamma activity of people. Before trying it out with a person, a dog was lowered into the insert and counted before and after injection of a solution containing 10^{-7} curies of radium. It was concluded that a radium body burden of about 5×10^{-9} curies could be detected, an immediate improvement by a factor of about 100 on the sensitivity of Robley Evans' early instrument for measuring the body burden of the radium dial painters (see “Radium—the Benchmark for Alpha Emitters”).



Figure 6. A Captive Audience
Wright Langham lectures on the uses of Remab (left) and Remcal in the calibration of the whole-body counters, HUMCO I and II. These plastic “phantoms” enabled the researchers to perform “human” experiments to determine the efficiency of the detectors.

given the ten per cent efficiency of the detector, these measurements agreed well with expected results.

This preliminary work was rapidly brought to fruition. By September 1954, a collaboration between Schuch and Anderson at Los Alamos and Marvin van Dilla at the University of Utah resulted in the development of the K-9, otherwise known as the “dog counter.” This detector was used to perform radiation experiments on animal subjects, and it also served as an intermediate step before the development of a whole-body detector for humans. In January 1956, Anderson, Schuch, Perings, and Langham developed the Human Counter or HUMCO I, a whole-body gamma detector for people. Because it was highly sensitive, this detector made it possible to measure the amount of potassium-40 in a person in only a minute and 40 seconds with a 5 per cent error.

Immediately, the detector was put to practical use. By 1959, the potassium-40 concentration had been measured in 1590 men and women from the ages of 1 to 79. Because potassium-40 resides largely in muscle, the amount of potassium-40 in

By crouching, a small person could also fit into the top hat and Langham, as the smallest one around, was the first person to try (see Figure 5). He was counted twice, once with an external 0.1 millicurie radium source and once without. Later, a water “human phantom” (see Figure 6) was made and radioactive potassium salt was dissolved in it. With this phantom, the scientists determined that the detector efficiency for potassium-40 was 10 per cent. That was very useful because potassium-40 is a naturally-occurring gamma-emitting radioisotope which is found in humans. A number of people were counted to determine the amount of potassium-40 in their bodies, and

the body is proportional to the body's lean mass. The measurements were mainly for the benefit of the public, but they also revealed the fundamental facts about the evolution of muscle mass with age for men and women (see "Tracer Studies at Los Alamos," page 270). At the same time, under Project Sunshine, HUMCO was used to study the worldwide distribution of fallout and the change of fallout with time. The concentration of gamma-emitting fallout radionuclides was measured in dried milk from three New Mexico dairies as well as in New Mexico residents and laboratory visitors. The sensitivity of the whole-body counter not only made those measurements quick and accurate, it also enabled medical tests and biological experiments to be performed on people using very small amounts of radionuclide—so small in fact that diagnostic tests could be performed safely even on newborns. In 1962, HUMCO I was superseded by HUMCO II, which had nearly ten-fold greater sensitivity and therefore made measurements that much safer and quicker.

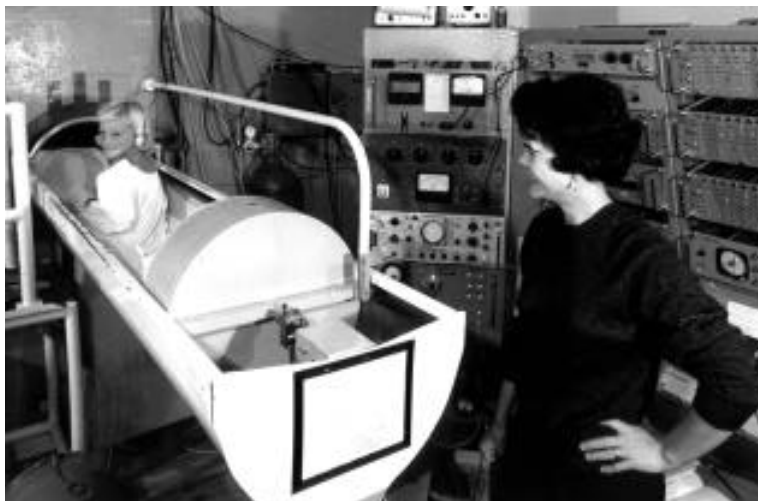


Figure 7. A Young Volunteer
Many New Mexican residents were monitored for the level of fallout radionuclides in their body. Here, a young resident enters the cylindrical opening of HUMCO I under the supervision of the attendant, Annie Hargett. Several young volunteers were counted weekly to determine their cesium-137 body burden.

This story is a good illustration of the benefits of the interdisciplinary approach to problem solving that was common at Los Alamos at the time. If an investigator had an interesting idea, he was not required to seek permission from his superior or consult him to see if the idea was worthwhile. He would simply talk to scientists in the fields that related to his idea, perhaps perform a preliminary experiment, and then, if the idea seemed promising, he would begin research. That approach to problem solving was in stark contrast to the strong disciplinary segregation that was the fashion in academic institutions, and, in light of stories such as this one about the Los Alamos liquid scintillation counters, it proved quite successful. ■

Further Reading

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