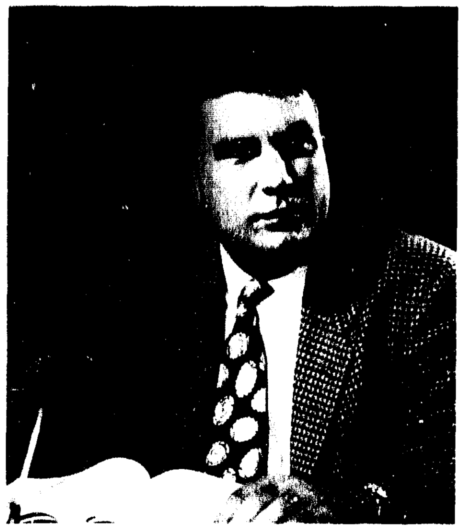
Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price codes: printed copy A03, microfiche A01

UCRL-52000-93-6
Distribution Category UC-700
June 1993

Energy & Technology Review

Herbert F. York:
The Legacy of E. O. Lawrence and the Role of the Laboratory in the Future



As part of LLNL's 40th anniversary observances held during 1992, the six former Directors were asked to participate in a lecture series. Each of these men contributed in important ways to making the Laboratory what it is today. They were asked to comment on their years at Livermore, their view of the changing world, and their vision of the Laboratory's role in the future. This article is based on Dr. York's talk of September 2, 1992.

I'D like to talk about a mixture of things, many of them having to do with the transition from the past to the future. Most of what I'll be saying about the past is designed to extract some lessons for the future. I'll begin by talking about Ernest O. Lawrence. Of all the principals involved in getting the Laboratory started, he's the one who's no longer here and the one who has been forgotten by so many because they never knew him. He died 34 years ago. Thirty-four years isn't 40, but it's a long way back, so I'll accept the obligation of talking more about him than others might.

To understand how a second weapons laboratory came to be and Lawrence's role in the process, it's important to recall how the world looked in those days. America had only recently emerged victorious from World War II. Along with our western allies, we promptly demobilized our armies and drastically reduced the efforts at our defense-oriented laboratories. Then, in a one-year period, from 1949 to 1950, three major events changed all that.

The first was in August of 1949, when the Soviet Union exploded its first atomic bomb. Contrary to some views, it was quite expected. The intelligence authorities had estimated that it would take the Soviets about four years, and it did. Several well-informed people, including Vannevar Bush and General Groves, thought it would take much longer. After about two years, however, as the predicted event got closer, people were still thinking in terms of several more years, maybe four more years. As a result, when it really happened, it came as a bad surprise. And the nature of the surprise made it worse still.

Within the next month or so, the People's Liberation Army marched into Beijing, and Mao Ze-Dong proclaimed the People's Republic of China. In January (1950), Mao went to Moscow, where he spent two months closeted with Stalin. Nobody to this day knows where they found so much to talk about, but at the end they issued some joint proclamations that the West found thoroughly menacing. They said that the tide of history had changed and now favored the Socialist camp, and that the imperialists—meaning the United States and its allies—would soon be put in their place.

In June of the same year (1950), North Korean armies invaded South Korea. At that point, it looked to anyone with any sense at all as if the fat was in the fire. It was clear that the West was facing some really serious international problems, and there was a national consensus that to cope with them, extraordinary measures would be needed.

Mobilizing Science

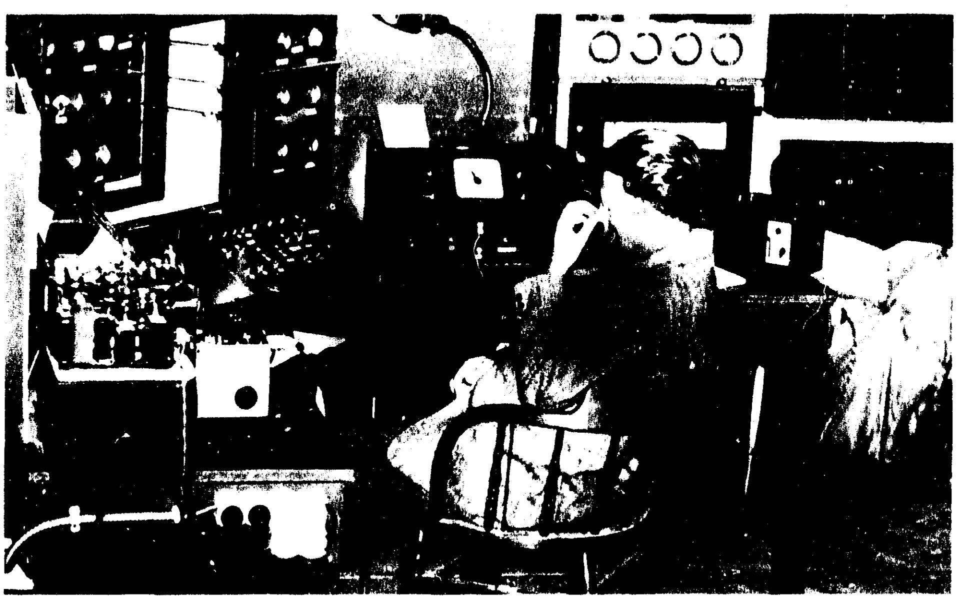
From the earliest days of that period, E. O. Lawrence was looking for a way to mobilize his Berkeley laboratory to advance the cause of national security. He was aware of the work going on at Los Alamos, and, in the spring of 1950, he sent Hugh Bradner and me down there to meet with Edward Teller, whom I'd not yet met, and others. Our mission was to find out whether there was something Lawrence's group could do to help with the forthcoming nuclear test series at Enewetak atoll in the Pacific.

We found a niche in the activities and set up a project at Berkeley. We were charged with making some diagnostic measurements to check out preshot calculations for the George shot. That was the test that produced the first manmade thermonuclear reactions ever. In the course of our work, we used some storage space out at the old naval air station in Livermore.

Ernest continued to look for other involvements. He was aware of the interest in starting a second weapons laboratory, especially Edward Teller's enthusiasm for the idea. But the issue wasn't just about starting a second laboratory; there was general interest in expanding the country's nuclear weapons program. For instance, an intensified effort to find uranium ore had led to the discovery of large deposits on the Colorado plateau. Also as a result, the production of plutonium and tritium was increased considerably. Establishing the Livermore laboratory was part of that overall expansion.

Lawrence eventually came to see establishing a second weapons laboratory as being perhaps the best way to get his people involved in science for national defense. In January of 1952, I ran into Lawrence at a New Year's party, and he asked me to come and see him as soon as I could. I was very attached to him, so I went the very next day to see what he had in mind. He asked me to help find out whether we needed a second weapons laboratory.

I wasn't aware of all the exploratory activities that had already taken place, but I agreed and soon went to talk with people at Los



E. O. Lawrence at the Calutron Controls (1944). According to York, people used to call Lawrence "clockwise Lawrence" because of his habit of sitting down at the Calutron console and turning all the control knobs to the right, as far as they would go.

Alamos, with Edward, who was then at the University of Chicago, and with people in the Air Force and the Atomic Energy Commission (AEC) and others.

Ernest was already ill with the disease that was to kill him, so there were long periods during which he wasn't around, and I carried on with these activities more or less on my own. By the beginning of the new fiscal year, the decisions necessary to establish a second laboratory had been made. During the summer, we visited the Livermore site often and held a number of meetings about what we might be doing there. On September 2, 1952, we opened shop here on site.

Lawrence's Legacy

Lawrence had a number of special characteristics that played a role in all these activities. They were what made this operation different from what it would have been under anybody else's leadership. One of the most important of these was the confidence he had in people generally and especially in young people. He believed that if you give somebody responsibility, no matter how big, they grow to fill it. You don't need a long track record of experience or success. A lot of people talk about the importance of young people, but Lawrence was that very rare person who both talked about it and did something about it.

That accounts, in part, for the relative youth of the Laboratory's staff in the beginning. Most of us were about 30. Edward was 44, and there were a few other elders like Duane Sewell and Gerry Johnson, who were about 34. Harold Brown was 24.

Another special thing about Lawrence was his great credibility. It was that, plus Edward's credibility as well, that made our mode of operation acceptable in Washington. I can't imagine anybody else in the atomic energy system of the time entrusting a bunch of 30-year-olds with the establishment of a new weapons laboratory and getting away with it.

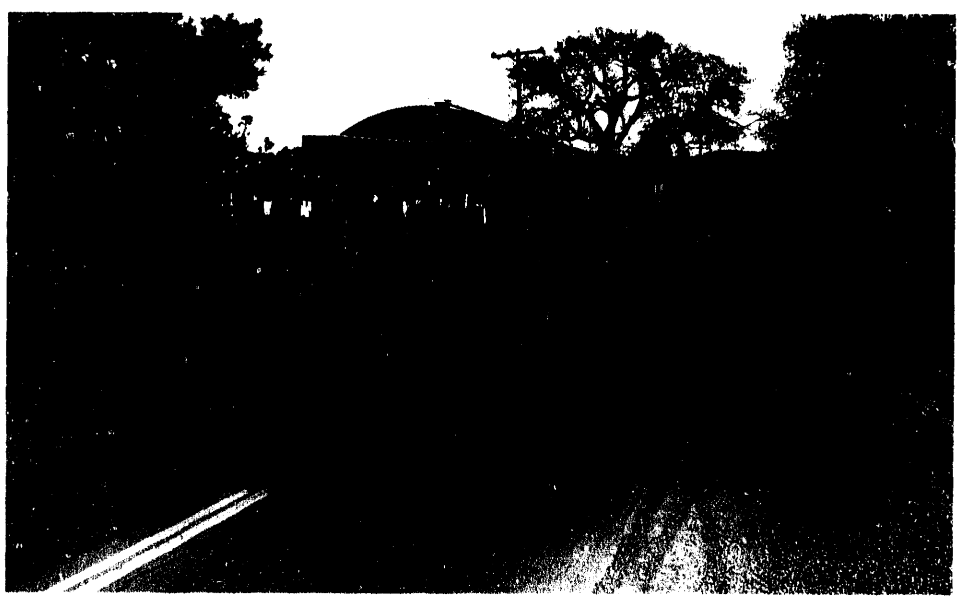
We were all aware of Lawrence's disdain for formal organization, especially in scientific organizations. I can recall a number of occasions when I or somebody else would suggest the need for some sort of a title to Lawrence. For example, I once remarked that I'd like to be an assistant professor in the physics department, and Lawrence got quite annoyed. (He was a man who became visibly annoyed—his eyes flashed, his jowls sometimes shook.) He replied by insisting that there was no better title in the world than "physicist at the Radiation Laboratory," and that he didn't want to hear any more talk about fancy titles.

On the other hand, Los Alamos had an organization with titles, as they had to, and we had to work with them. So, very quietly, I worked out an organization for Livermore. I appointed Harold Brown to head A Division, Johnny Foster to head B Division, Ken Street as C Division leader, and Gerry Johnson for L Division.

Finally we had division leaders, but I still didn't have a title. I don't think Duane Sewell did, either. I explained patiently to Ernest that we have to call people things like division leaders because Los Alamos used those titles, and we had to work with them. He finally agreed, but it took some persuasion because he never really thought you needed anything more than "physicist at the Radiation Laboratory."

The Mysterious Mr. Livermore

Still, I would go back to the AEC Washington headquarters about once a month to talk with people in what



East Avenue Bordering the Livermore Laboratory (1953). By the time the Livermore Laboratory opened in 1952, York had worked for Lawrence for nine years and was fully familiar with Lawrence's style of "management by walking around," frequently at night and on weekends and holidays.

was then the Division of Military Application, and occasionally with the AEC chairman. One of his deputies used to ask me, "And who is Mr. Livermore?" He didn't mean Robert Livermore—he meant, "Who's in charge out there?". It sometimes made things awkward. I was writing letters to Washington, classified letters, spelling out our work for the next year and a half. Then I'd sign my name with just an address underneath, no title of any kind indicating any kind of authority.

Finally, one day Ernest said, "Why don't you start calling yourself the Director?" So I told my secretary "the next time the phone rings, say it's the Director's Office." And that's how it started.

As I've suggested, formalities made Lawrence impatient. He would never have dreamed of using committees to decide who ought to be appointed or what they ought to be paid. So, essentially, I just sat by myself and figured out the salaries of the top half-dozen people. I would take them to Lawrence, he'd change one or two (always upwards), and that was it. I don't know who he had to persuade next, but that never seemed to be a problem for him.

During the periods when Lawrence was away, I had essentially no boss at all, and I was perfectly comfortable with it. Lawrence very seldom told me what to do. I was determined to do what I thought he would want, so I ran the Laboratory Lawrence's way. After nine years of working with him (I had started at Berkeley in 1943), I thought I knew what he would want.

You could never get away with an arrangement anything like that today, and for good reason. It was a special time, a new world, and you could get by on knowing the fundamentals without knowing all the details. Now it's the other way around. You have to know the details in order to handle the questions. You can't do things now the way we did then.

Visit to the Pacific Proving Grounds (1958). Lawrence and York led a tour of the Pacific Proving Grounds for the UC Regents in 1958. In the photo, York is seen disembarking from the Navy airplane that transported them to the South Pacific.

Kicking Tires

Another special thing about Lawrence was his very personal style of management. Almost every week, he would walk around the entire laboratory at Berkeley. It employed about a thousand people then. He used to come in while Jim Hadley, Chuck Leith, and I were using the big cyclotron at night and ask how we were doing. We would tell him, briefly, and he'd go on to see somebody else. Today we'd call that kicking tires, but it was just his extremely personal way.

One Christmas eve, when I was working with Bill Whitson on an improved version of the Calutron, Lawrence came by and chatted for a while. Then he went up to see the synchrotron, which they were in the process of turning on. He came back a few moments later with an amazed look on his face and said, "There's nobody there."

Behind his back, people used to call him "clockwise Lawrence." I was on Frank Oppenheimer's Calutron development team (Duane Sewell headed the other), and Lawrence would come and sit down at the console. We were trying to get as much juice out of the thing as we safely could, but Lawrence would proceed to turn all the control knobs to the right, as far as they would go. The thing would spark over and melt down, of course. Lawrence would then leave with a big smile on his face. And we'd have to fix it.

Lawrence followed the same style, years later, when he visited Livermore. He usually came out on a Friday afternoon, and we'd talk for a while in his office. But what he most liked to do was just to walk around the Laboratory. I would go with him, and we went everywhere. By the time a month had rolled by, we'd probably completed a full circuit. The next visit, we'd start another one. It was a practice I adopted from Ernest. As long as I was Director, I visited every corner of the Laboratory many times every year. I enjoyed it, and I hope it was a net benefit to everybody.

I left the Laboratory at the end of 1957 because of Sputnik, the first Russian artificial satellite. The United States hadn't launched one yet, and so it came as another unpleasant surprise. As a result, scientific and advisory functions were being strengthened in Washington. I went off to join that activity, first as a member of the President's Science Advisory Committee and then as Chief Scientist of ARPA [Advanced Research Projects Agency] and later as the first DDR&E [Director of Defense Research and Engineering]. Most of you know that the first three of DDR&E's were myself, Harold Brown, and John Foster, in the same sequence in which we were Directors at Livermore. That wasn't a coincidence.

Dealing with Duality

Some people, knowing my strong interest in arms control, have asked me when I changed my mind about nuclear weapons. I haven't always expressed my position accurately or sensibly, but my usual answer when I'm thinking right is that I didn't. What happened to me in Washington was that I expanded my point of view. I didn't change it.

Before going to Washington, I believed that nuclear weapons were a solution to an extremely difficult problem—the international situation I described earlier. After I'd been in Washington and had a chance to talk with President Eisenhower, James Killian [Eisenhower's science adviser], and others, I came to realize that while nuclear weapons were indeed a solution, they were also simultaneously a serious problem. That's what I meant by saying my perspective was expanded, and to this day I still look at it that way. Nuclear weapons are a solution to one set of difficult problems, but they are intrinsically a problem in themselves.

Fortunately, in my opinion, every President of the United States has seen it that way, too. Truman, Eisenhower, up through Reagan—all have shared that view. But that dual aspect of nuclear weapons inevitably gives rise to contradictions that cannot be fully resolved, so you have to learn how to live with them. These intrinsic contradictions occasionally produced policies that were in some way wrong but collectively were designed to cope with the total problem. From my perspective, every president eventually got it right, and that's why we're still here today.

In sum, the search for solutions to our most severe short-term problem—that is, how to deal with

Herbert F. York: The Mysterious Mr. Livermore

Ernest O. Lawrence had a genius for finding brilliant young scientists while they were still unknown. Such was the case in 1952 when he asked Herbert F. York to run the new Livermore Laboratory. At that time, York was 30, having earned his Ph.D. only three years earlier at UC Berkeley.

York guided Livermore through its early years. He faced two challenges simultaneously—planning the Laboratory's technical program and recruiting its staff. After consultations with scientists at Berkeley and around the country, he settled on a technical program with four elements: controlled thermonuclear fusion, diagnostic weapons experiments for both Livermore and Los Alamos, the design of thermonuclear weapons, and basic physics. Much of the staff was recruited from UC Berkeley. York vigorously promoted both peaceful and military uses of atomic energy; the development of the Polaris warheads began under him, as did the controlled fusion program. During York's years as Director, the Livermore Laboratory grew from a hundred or so employees to about 3000.

York left Livermore in 1958 to become Director of the Advanced Research Projects Division of the Institute of Defense Analysis. He later became the first Director of Defense Research and Engineering for the Department of Defense. He held that position until 1961, when he returned to teaching and the academic world at the University of California at San Diego. At UC San Diego, York served as Chancellor until 1964, and later as Dean of Graduate Studies. He also served as a member of the President's Science Advisory Committee and as a member of several arms-control and test-ban treaty delegations. In later years, York was the Director of the Institute for Global Conflict and Cooperation; he is now a Professor and Director Emeritus of the Institute.

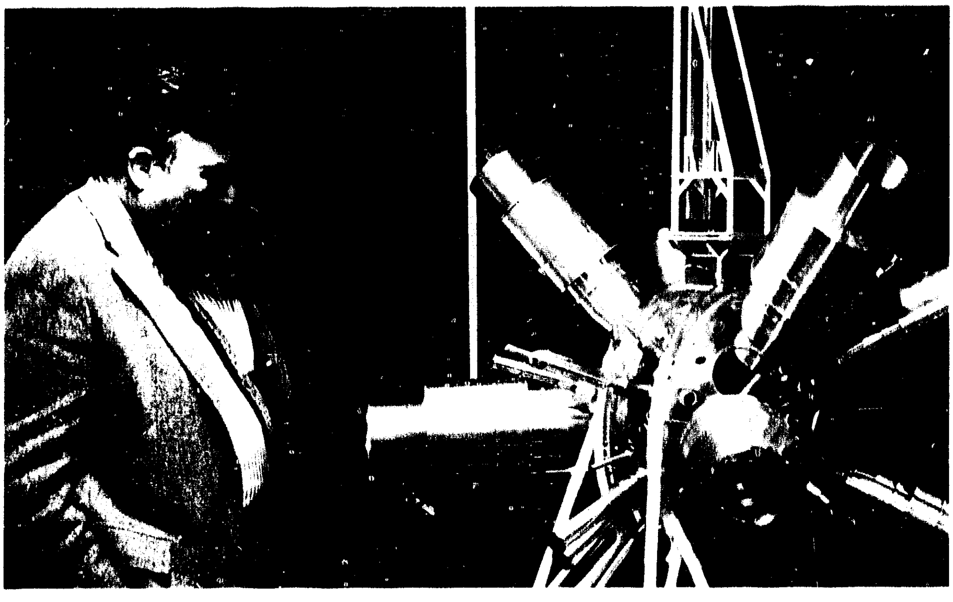
the latest Soviet action—pushed us in one direction, while the search for solutions to our most severe long-term problems—that is, how to avoid a nuclear holocaust—pushed us in quite a different direction. Nuclear weapons were part of the solution to one set of problems, but, as it turned out, they were in themselves a problem of a different kind.

Individuals never deal very well with problems in which long-term considerations and short-term considerations lead in opposite directions. Collectively, we don't do much better. But in dealing with these particular contradictions, the American leadership did it right—all of them, and in depth.

Notwithstanding the very dramatic events of recent years, I think the Cold War actually ended ten years ago. It essentially ended when Lech Walesa led a strike at the Lenin shipyard in Poland, and they didn't immediately arrest and shoot him. That ought to have told us that the whole Communist system was eventually going to collapse. And that's what happened.

People often say, with good reason, that we won the Cold War. I prefer to look at it differently. It was the enormous internal contradictions in the Soviet system that finally brought it down. Beginning with Walesa, thousands of other heroes, many of them unknown, did what they could to promote peaceful change.

What the United States did, I think, was to win the peace. Since the end of World War II, we've enjoyed almost 50 years of peace, the longest period of peace in the West since nation-states have existed. During that time, there were many crises and plenty of opportunities for nuclear war. But it never happened, because our leaders were able to cope with the dual nature of nuclear weapons and played it right. The Laboratory played a major part in that process, because high technology of all kinds, including nuclear weapons technology in the service of national security, created the circumstances necessary for our leaders to carry out their responsibilities well, wisely, and correctly.



York visits the Livermore Laboratory (1987). York left Livermore in 1958 to become the Director of the Advanced Research Projects Division of the Institute of Defense Analysis. In 1961, he returned to the academic world at the University of California at San Diego. He is now a Professor and Director Emeritus of the Institute for Global Conflict and Cooperation, San Diego, California. In this photo, York is viewing a model of the target chamber for the Nova laser.

Paradoxes of Proliferation

But all that is behind us now, and the question is: What next? In my view, there's no international problem in sight that the big countries (China, the United States, and the former Soviet Union) can't solve better by using conventional weapons, especially the newer and smarter kinds that are coming along.

Judging from their actions, this is not true for all countries. India, Israel, and Pakistan are all widely believed to possess nuclear weapons. Ukraine seems somewhat reluctant to dispense with its inherited nuclear weapons. It's arguable that in these states nuclear weapons are seen, and will continue to be seen, as a solution to problems for which there is no strictly conventional solution.

This leads to another paradox. I suspect that ten years from now, countries in the Middle East, South Asia, and other parts of the globe will play a much greater role in determining basic nuclear weapons policy. In these places, there are people who, with one justification or another, see nuclear weapons as a solution to otherwise intractable problems.

It's clear that in Washington, the leadership—in depth—has always seen nuclear weapons as both problem and solution. But for 40 years, the weight has been on the solution side. That position, I think, is now shifting widely and across the board. When nuclear weapons are talked about at all now, the concern is always the problems they will create if somebody else gets them rather than the edge we'll be able to gain from having them ourselves.

Carving Up the Weapons Program

What impact will these changes have on the weapons laboratories? I think a core program related to nuclear weapons will continue at both laboratories—Los Alamos and Livermore. It will be about the same size at both laboratories but smaller than it is today. I think the Los Alamos program will be a downsized version of what they have now: an across-the-board program in nuclear weapons and nuclear weapons technology, with responsibility for the current and future stockpile.

The future Livermore program, in my opinion, might well be different from the Los Alamos program. One component will be the inertial-confinement fusion program, hopefully in the form of a microfusion laboratory. Another possible element will conjoin intelligence, nonproliferation activities, and dismantlement efforts, focused mainly but not exclusively on nuclear weapons. Another component will address environmental health and safety problems related to past abuses elsewhere in the nuclear weapons program. Those efforts will be supported by a theoretical and computational group that will maintain a full understanding of all the physics of nuclear weapons.

How to Avoid Painting Furniture

With respect to the other technologies developed at Livermore, the Laboratory will be competing with both industry and the universities. There's plenty of demand out there. Despite projected long-term declines in the defense budget, many people expect funding for defense research and development to remain essentially constant. Thus, the demand for high technology in the interest of America's national security is going to continue, but the competition will be much more severe.

I'd like to see people here at the Laboratory get much more directly engaged in that competition. I'll give a trivial example of what I mean from my own experience. In 1943, I arrived in Berkeley with a fresh master's degree in physics. While I was working on the Calutron project I've mentioned, custodians seemed to be in short supply, so I did a lot sweeping up. One day, I was told to paint an equipment rack that needed painting. I started to think: "What is this? I've got a master's degree in physics, worked hard, learned all this stuff, and here I am painting some furniture."

So I went to Frank Oppenheimer, who was fortunately a generous and kindly person, and described my frustration. "Isn't there something I should be doing that makes greater use of my talents?" I asked him. He looked at me and asked, "What do you want to do?" I realized I hadn't the foggiest idea. By the next morning, I was resolved I would never again get myself into a situation where I didn't know what I wanted to be doing the next day.

Now, a lot of you are probably aren't sure about what you're going to be doing tomorrow. I have some suggestions. First, don't rely on the leadership, either here or in Washington, to figure it all out for you. Everybody needs to get involved in this process. Second, start on the demand side. What are the problems, and what might the solutions be? People who are otherwise friendly to us have said that the laboratories simply don't understand the difference between push and pull with respect to commercial demand and technology supply. And you've got to in order to survive in this new world.

Someone else has observed that the laboratories think of marketing technology as a sort of big chuck-wagon breakfast. You go out there and lay it all out, then you ring a bell and shout, "Come and get it!" That won't work either, because no matter how delicious the goodies look, you aren't going get enough customers just by ringing a big bell.

So get busy.

For further information contact Herbert F. York, Institute for Global Conflict and Cooperation, San Diego, California (619) 534-3357.

COG: A New, High-Resolution Code for Modeling Radiation Transport

The new COG code is simple enough to be run on a desktop workstation and yet is more accurate and versatile than older radiation-transport codes that were written for the big mainframe computers. COG has a variety of industrial applications and will soon be released into the public domain.

THERE are many situations in which scientists or engineers need to know how penetrating radiation, such as neutrons and gamma rays, interacts with matter. Designing the shielding for a nuclear reactor, ensuring that shipping and storage containers for radioactive wastes are safe, computing the criticality of an assembly of fissile material, evaluating the design of a charged-particle accelerator—all require accurate and reliable knowledge of how radiation is transported through the various materials. In many cases—in a reactor, for example—the geometry (that is, the arrangement of materials inside the reactor) is quite complex. Although experiments can be set up to measure shielding effectiveness, for example, a faster and much less costly approach is to compute the transmission of radiation through the shielding with a radiation-transport code. Of course, the value of such simulations depends on their accuracy.

The basic equations of radiation transport were first written down more than a hundred years ago by the German physicist Ludwig Boltzmann, after whom they are named. The Boltzmann equation for the transport of particles such as neutrons is a conservation equation in a six-dimensional phase space. Except in the simplest of cases, this is a very difficult equation to solve exactly. For realistic problems, therefore, scientists must resort either to numerical solutions of the equation (the discrete ordinates method) or to particle-by-particle simulation of the entire transport process (the Monte Carlo method).

The discrete ordinates method offers rapid solutions to problems of limited complexity and dimensionality, but it cannot accurately handle complex three-dimensional geometries. The Monte Carlo method, when properly applied, as in COG, is capable of solving any radiation-transport problem to any desired degree of accuracy, being limited only by the amount of computer time available for solution.

Since realistic problems are typically simulated by tens of thousands to millions of particles, the use of a high-speed computer is essential in arriving at a reliable answer in a reasonable time (a few hours to a few days). Over the years, a number of Monte Carlo radiation-transport codes have been written by researchers at LLNL and elsewhere. However, because they were developed for older, slower computers with relatively small memories, these codes had to compromise between good physics and the practical need to solve a problem in a reasonable length of time. As a result, most of the earlier radiation-transport codes suffer from serious inaccuracies or other flaws that limit their usefulness.

The Genesis of COG

The primary impetus to develop a more accurate radiation-transport code came from the Laboratory's underground nuclear testing program. As the number of nuclear tests conducted each year began to decline in the 1970s, scientists worked to increase the quantity and quality of diagnostic data obtained per test. In a typical test, radiation from an exploding nuclear device is viewed through many lines of sight (evacuated steel pipes) by detectors mounted in a diagnostic canister that is suspended above the device (Figure 1). To avoid leakage of radiation that could invalidate the test results, the line-of-sight pipes must be shielded from one another, typically with iron or lead sheathing. Multiplied by a large number of lines of sight, the cumulative weight of this shielding could quickly make the large diagnostic canister too heavy for the crane that must lower it into the test hole.

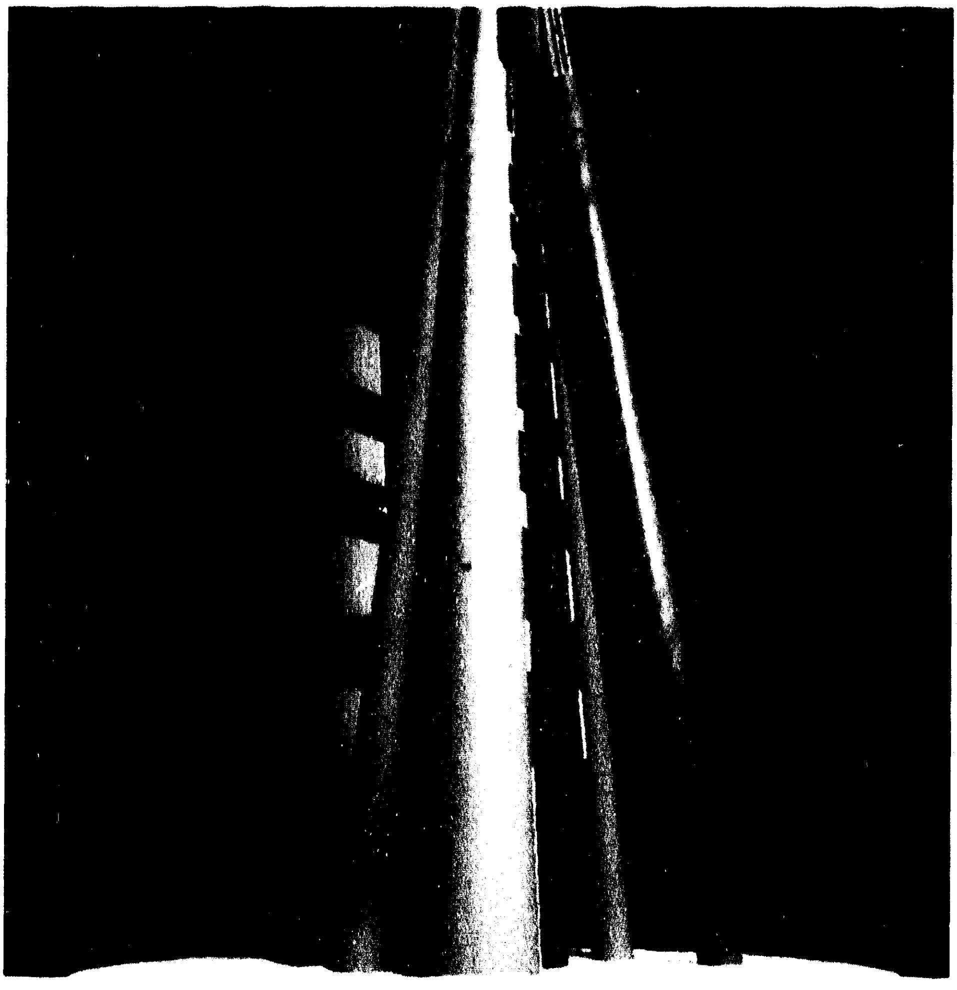


Figure 1. COG model of a typical diagnostics canister for an underground nuclear test. (Many structural parts of the canister have been removed to show the experimental setup.) Detectors located in the orange and yellow boxes are aligned to view directly, through line-of-sight steel pipes, radiation sources lying below the white bulkhead. A major issue in designing the experiments is to keep the detectors free of radiation that scatters into them from neighboring collimators and pipes, creating unwanted backgrounds. To ensure the return of high-quality data, we developed COG to calculate the shielding for these complex experiments.

To estimate accurately the minimum shielding required, we needed a radiation-transport code that was both more accurate than its predecessors and able to handle the complex geometries created by the multiple lines of sight. To deal effectively with such problems, the code would have to exploit the power of modern, high-speed computers while rectifying the physics compromises of earlier codes. In a whimsical moment, the new code was baptized COG. (The unabridged Oxford English Dictionary tells us that in Shakespeare's time, the verb "to cog" was London street slang for the practice of manipulating the roll of a pair of dice. Since COG relies heavily on the Monte Carlo method, a computational technique involving probabilities, the name was considered apt.)

After five years of development, COG began running on the Laboratory's powerful Cray computers in the mid-1980s.[1] The code is written in Fortran, the standard scientific programming language since the early days of computing. Taking advantage of the high speeds and large memories of modern computers, COG is free of the physics approximations traditionally used in radiation-transport calculations. In designing COG, we selected the best features of earlier codes and incorporated the most advanced algorithms available today.

Tracking Particles with COG

COG was developed to answer questions about how neutrons and photons (gamma rays and x rays) interact with matter as they pass through complex geometries. To do this, COG simulates multiple neutron-photon interactions on both the atomic and nuclear levels. As such processes are governed by statistical probabilities, COG uses the Monte Carlo method, a long-established computational technique that uses random numbers to simulate alternative outcomes of physical events (see the box on p. 12).

In simulating the passage of a neutron through a lead shield, for example, COG first assigns the particle's initial energy and direction and then calculates the particle's trajectory through the material. A sampling procedure tells COG the average distance the neutron travels through the shielding material (e.g., lead) before interacting with one of its constituent nuclei. For each interaction event, COG then consults a database that contains the probabilities of alternative outcomes and applies the Monte Carlo method to assign a particular outcome—that is, whether the neutron is scattered, reflected, absorbed, and so on. This process is repeated until the particle escapes, is absorbed, or otherwise disappears from the computation. The result is a complete history of the neutron's trajectory that is accurate within the limits of the database used. COG makes this kind of simulation for every one of the particles in the problem—which can number many millions of neutrons and/or photons—and then pools the individual histories to arrive at a collective result. For the lead-shielding problem, the result is the expected flux of neutrons and photons that penetrates the shield.

COG offers a number of improvements over its predecessors:

- It uses pointwise physics data to eliminate the errors of earlier codes, which use group-averaged data. All the numerical information that describes a particle's interaction with matter (the cross-section data) is provided to COG at the highest accuracy and resolution available. These data files are consequently very large (15 megabytes for neutrons) but enable us to model the interaction process as accurately and completely as possible. We thereby eliminate the inaccuracies of earlier codes, which used averaged data to save storage space and computation time.
- Its radiation-transport physics package uses no approximations. For instance, it uses exact angular scattering distributions instead of the approximating fits used in other codes. In this way, COG realizes the accuracy and resolution benefits of the pointwise cross-section data by preserving accuracy at every step in the transport process.
- COG is rich in techniques for reducing the uncertainties in computed solutions. A distinguishing feature of deep-penetration problems (i.e., those involving thick layers of shielding), which COG was expressly designed to solve, is that particles emitted from the source must travel through many mean-free-paths of shielding material before they reach regions where the particle flux is to be estimated. In a straightforward analog simulation of particle trajectories, perhaps only one particle in ten thousand reaches a region of interest. The code must therefore simulate the trajectories of many millions of particles to obtain a statistically significant answer. In some real cases, the amount of computer time required to generate a significant answer extends to weeks, making such calculations infeasible. COG employs several uncertainty-reducing techniques, both simple and sophisticated, that enable us to solve these problems with many times fewer source particles and thus to obtain more precise answers in shorter computer runs.
- COG includes user-friendly code inputs and problem-debugging aids. For example, to aid the user in verifying the correctness of his problem setup, COG can generate views of the geometry, offering both

The Monte Carlo Method

A Monte Carlo simulation can be applied to any stepwise process for which the probability distributions for continuing, terminating, or otherwise modifying the process are known at every step. The COG database contains experimentally obtained quantities, known as cross sections, that determine the probability of a particle interacting with the medium through which it is transported. Every cross section is peculiar to the type and energy of the incident particle and to the kind of interaction it undergoes. Hence, there are many different types of cross sections. These partial cross sections are summed to form the total cross section; the ratio of the partial cross section to the total cross section gives the probability of this particular interaction occurring. The database also contains experimentally obtained quantities that may be sampled to determine the properties (energy, direction, and so on) of the scattered or secondary particles.

To solve the Boltzmann radiation-transport equation, COG uses the Monte Carlo method as described in the following procedure.

1. Particles are "born" at a source (see figure) with a set of parameters that are determined by randomly sampling the user-provided source descriptions. These parameters include energy, position, direction, age, statistical weight, and particle type (neutron or photon).

2. COG uses the total cross section to determine the average distance a particle will travel before interacting with the medium. From the source, the particle is tracked in a straight line through the medium until it either escapes the geometry or collides.

3. When a collision occurs, COG samples the cross sections to determine in which isotope or element the reaction occurred and the type of interaction (elastic scattering, fission, gamma-ray production, Compton scattering, electron-positron pair production, and so on).

4. COG then samples the reaction properties to determine the parameters of the scattered particle and of any secondary particles. Parameters of secondary particles are banked for later use.

5. The program repeats steps 2 through 4 until the particle escapes, is absorbed, or is terminated by some random-walk condition (reaches an energy cutoff, for example).

6. Steps 2 through 5 are repeated for each secondary particle until the secondary-particle bank is exhausted.

If at any time, along its often tortuous and convoluted path, a particle interacts with a user-defined detector, the detector is credited with an appropriate score. After COG has run perhaps millions of source particles, the answer to the problem is just the averaged score for each type of particle at each detector.

COG uses either of two cross-section databases. One is LLNL's Evaluated Nuclear Data Library (ENDL-90), and the other is the Evaluated Nuclear Data File (ENDF/B-V). The accuracy of a calculation in COG is limited only by the accuracy of the data it uses. As cross-section accuracies improve, they can be easily incorporated into COG's database.

A particle is born at the source and is tracked by COG until it collides with another particle (in medium 1), creating a secondary particle (dashed line). The original particle is scattered and is again tracked until it collides again (in medium 2), creating another secondary particle. The scattered particle is tracked until it escapes, and each secondary is tracked in turn. In this example, the first secondary particle collides (in medium 1) and then escapes, while the second simply escapes.

two-dimensional pictures of planar slices and simulated three-dimensional perspective pictures.

- It allows the user to customize the processing of results. COG supplies several kinds of simulated radiation detectors that compute the code's answers—for example, the particle flux crossing a boundary, or the dose deposited in a volume, or the number of counts in a simulated sodium iodide detector. But for users who wish to do more complex scoring (such as counting only particles that have passed through a set of specified geometry regions) or who must model complicated detector responses, COG allows them to write their own Fortran subroutines for custom processing. COG loads the user-provided routines at runtime and passes them arrays that contain the history of each source particle. The user's code then computes the appropriate score.

COG's accuracy and reliability have been proven through extensive benchmarking on shielding and criticality problems and through extensive use in the nuclear test and criticality safety programs.

COG was originally developed for large mainframe Cray computers. We have just finished converting the code to run under the Unix operating system on workstation platforms. In the past two or three years, RISC (reduced instruction set computer) workstations have become almost as powerful as a single-CPU Cray for scalar floating-point operations and much less expensive. For example, COG runs on a $25,000 Hewlett-Packard workstation half as fast as it does on a multimillion-dollar Cray. The affordability of RISC platforms means that COG can now be made available to a wide range of governmental, industrial, and academic users. Versions of COG for Hewlett Packard and Sun workstations are now available, and versions for IBM and SGI workstations are planned.

Applications of COG

In addition to its Laboratory uses, COG is finding a variety of industrial applications as the examples below highlight.

Reactor Criticality

COG's neutron transport capabilities allow it to calculate the degree of criticality of an assembly of fissile materials—for example, the fuel rods of a nuclear reactor (Figure 2). COG can accurately handle many computationally difficult situations, such as when the reactor fuel rods are partly immersed in water and partly exposed to steam.

Shipping Casks

One typical application of COG is to determine the gamma-ray dose outside of a shipping cask carrying plutonium oxide (PuO_2) pellets; the pellets will be incorporated into a radioisotope thermoelectric generator and used to power space satellites. Figure 3 shows the cask, designed by Mound Laboratory for the Department of Energy. The iridium-clad PuO_2 pellets are surrounded by graphite, and the cask in which they

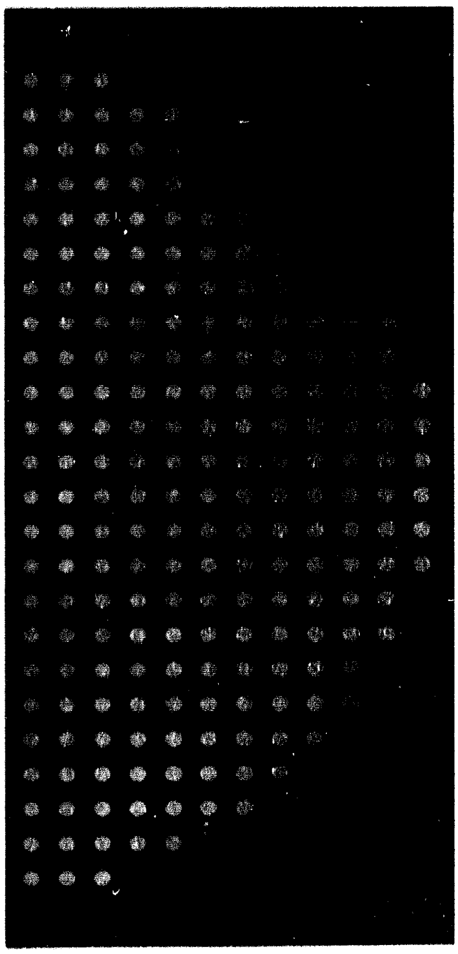


Figure 2. Partial COG model of a reactor core for a nuclear criticality calculation, showing array of uranium fuel rods (yellow) in a water moderator (blue) (supporting structures and shielding are not shown). COG is capable of accurately modeling large and complex three-dimensional structures such as a nuclear reactor. It will produce correct estimates of criticality even for computationally difficult cases, such as fuel rods, whose lower surfaces are in contact with water and upper surfaces with steam.

are encased is stainless steel. In order to model this complex assembly, we had to specify 45 surfaces to COG. Without COG's UNIT feature, which allows us to specify identical subassemblies such as the fuel pellet modules just once, we would have had to specify more than 130 surfaces.

Detector Modeling

COG was also used to simulate the response of a large sodium iodide (NaI) detector designed to measure total gamma-ray energy and gamma-ray angular distributions produced by the reaction of 14-MeV neutrons with copper-63 and plutonium-239 targets. The Laboratory-developed detector, called the High-Energy Gamma-Ray Spectrometer, consisted of a large 28-cm by 30-cm NaI crystal encased in a plastic anticoincidence shield of boron-carbon 408. Additional shielding was provided by lead, B_4C resin, and borated (5%) resin. The detector is unique inasmuch as the crystal and its shielding form a single unit that may be rotated around the beam line.

COG used the model shown in Figure 4 to compute neutron transport and photon production in the targets. We used the Electron-Gamma Shower code (EGS4) to compute transport of the photon shower. The detector's response function depends on its size, shape and composition as well as on the detailed geometry of the irradiation conditions. COG enabled us to model the shielding as well as the detector itself.

Rocket Motor Probe

In another application, we used COG to simulate a gamma-ray source designed to probe the interior of a solid-fuel rocket motor, before and during burn, to detect mechanical flaws or anomalous burn behavior.

Clandestine Delivery Defense

COG has become an important tool within the Clandestine Delivery Defense Program, which seeks ways to detect and interdict smuggling of

(a) (b)

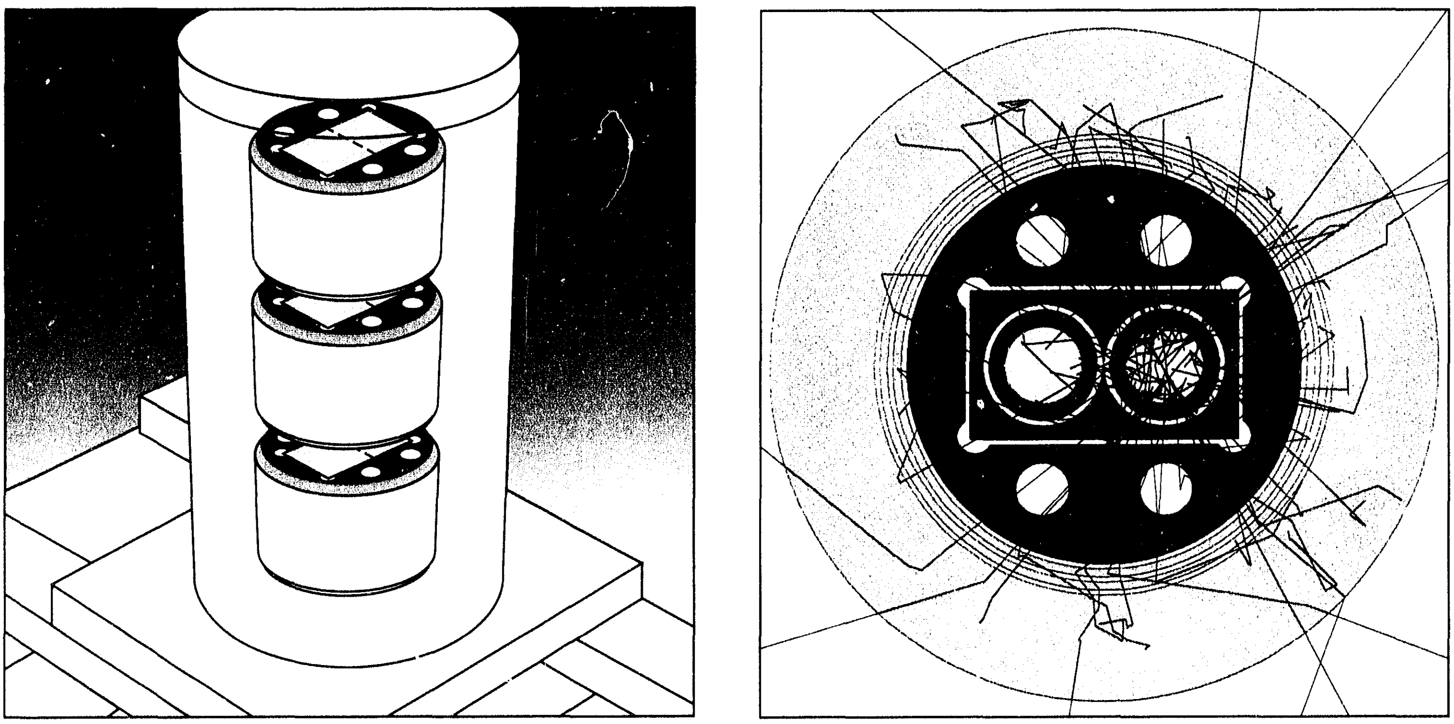


Figure 3. (a) Cylindrical shipping container designed to transport radioactive fuel. (b) COG calculation of gamma-ray shielding effectiveness shows energetic gamma rays (black) produced by the decay of the plutonium fuel pellet (yellow). They are tracked by COG until they are absorbed or escape through the stainless-steel shielding (blue). For clarity, the figure shows the high-energy gamma rays from only one pellet. In a complete COG calculation, millions of such trajectories are simulated to produce a precise estimate of the escaping flux.

nuclear weapons materials into the United States. By simulating the characteristic radiation signals emitted by nuclear materials, COG can be used to evaluate proposed detection schemes.

Contraband Detection

Various agencies have shown interest in COG's potential for modeling proposed methods of using radiation to detect concealed high explosives, drugs, and other contraband. Analysis of the radiation scattered by inspected materials can reveal distinctive atomic "signatures." However, some recent scanning devices have been designed without the benefit of a complete transport calculation. A recent COG study of a high-energy neutron system proposed for scanning airline luggage showed that the performance estimates for the system were overly optimistic. Detailed COG calculations like this one can accurately assess the performance of systems before expensive hardware is built and can minimize the risk of installing systems that prove inadequate for the job.

Making COG Easy to Use

A crucial element in radiation-transport problems is the fidelity with which the input data represent the often complex configurations of materials in the problem. The position and orientation of surfaces in the problem are specified by fields of numbers in the COG input file, which the user must supply for each surface. Specifying surfaces in this mathematical manner is always a difficult, nonintuitive, and error-prone procedure. For moderately complex geometries, the time spent by the user setting up the geometric model accurately in COG (or in any other radiation-transport code) can amount to 90% of the total solution time. To speed up this process, we wrote a Macintosh program called MacCOG to check the user's problem input before it is submitted for a full COG run. MacCOG reads in the user's COG input file, searches for syntax and geometrical errors, and produces diagnostic pictures of the problem's geometry.

We have taken another major step to greatly reduce the labor and errors involved in setting up a geometric model for input to COG. We can now link COG to Pro/Engineer, a powerful computer-assisted design (CAD) software package. This commercial CAD program allows the user to create the individual parts of the problem geometry and assemble them in a graphically intuitive manner. The CAD program prevents the accidental overlap of parts, a problem commonly encountered when geometry is set up the customary way. When the user is satisfied with the CAD assembly, the CAD database is automatically converted into a COG geometry input file. COG's ability to use a commercial CAD program for preparing three-dimensional geometry input is unique among transport codes.

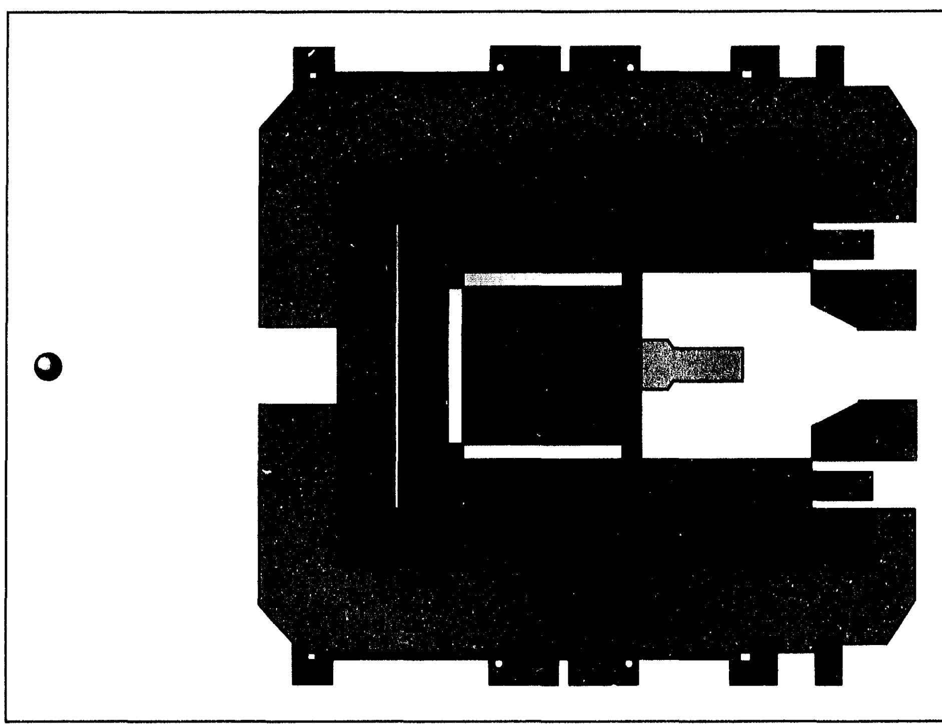


Figure 4. COG-generated model of the Laboratory-developed High-Energy Gamma-Ray Spectrometer. The active element (red) is a sodium iodide (NaI) crystal surrounded by an anti-coincidence scintillator (pink) that rejects neutron counts. The blue and tan materials are shields. COG computed the gamma rays produced when a neutron beam irradiated a copper target (the black sphere at the left of the detector). We used the COG geometry package and the EGS4 electron-gamma shower code to compute the resulting photon-electron cascades and the detector's response. Together, these codes provide a very efficient method for computing such responses.

Future Developments

A major planned enhancement to COG is the addition of electron transport. Currently COG can calculate the production of secondary electrons in a detector or target but cannot follow the subsequent electron trajectories. Knowledge of these trajectories would significantly enhance COG's ability to model accurately the response of radiation detectors and to localize precisely the deposited energy or dose to a target. However, the addition of electron transport is not a simple issue. Electrons scatter much more frequently in matter than do gamma rays or neutrons, and a collision-to-collision transport step for electrons would cause the code to bog down inordinately. Instead, we will use a condensed-history method, whereby each COG transport step encompasses many electron scatterings. This type of transport is central to the well-known EGS electron transport code,[3] and we plan to adopt this model.

Because of its greater efficiency for many kinds of calculations, parallel processing is likely to dominate high-end computing by the end of the century. The iterative nature of COG's operations makes COG well-suited to parallelization. Using the same problem geometry, the same radiation sources, and the same radiation detectors, COG could, for example, simultaneously run ten different particle trajectories on ten processors, speeding up the overall calculation by—in this case—a factor of ten.

COG will soon be released as public-domain software, making it available to any user with the requisite computational resources. As with most technological advances, COG is likely to be applied to problems that its developers never dreamed of. We are pleased to be able to transfer this LLNL-developed advanced transport technology to the nation's criticality and shielding communities.

Key Words: Boltzmann equations; computer code—COG, Monte Carlo, radiation transport.

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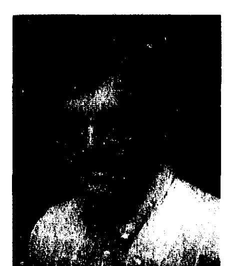

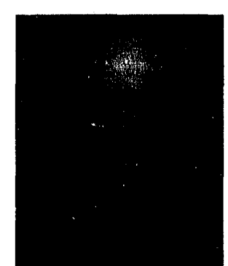

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Abstracts

Herbert F. York: The Legacy of E. O. Lawrence and the Role of the Laboratory in the Future

Herbert York was the first Director of the Laboratory, serving from 1952 through 1957. He guided the Laboratory through its early years and was instrumental in recruiting much of its staff and planning the its technical program. The development of the Polaris warheads began during York's directorship, as did the controlled fusion program. During his years as Director, the Livermore Laboratory grew from a hundred or so employees to about 3000. York left Livermore at the end of 1957 to become the Director of the Advanced Research Projects Division of the Institute of Defense Analysis.

As part of the Laboratory's 40th anniversary observances held in the fall of 1992, York was invited to lecture on his years at Livermore and his views of the changing world and the role of the Laboratory in the future. He recalled the world situation when the Livermore Laboratory was founded and reminisced about the legacy of E. O. Lawrence. He also expounded on the dual aspect of nuclear weapons—that although they are a solution to one set of problems, they are also intrinsically a problem in themselves. York also commented on the problems of nuclear proliferation, especially now that the U.S.-Soviet Cold War has ended. In his view, there is no international problem that the large nuclear powers (China, the United States, and the former Soviet Union) cannot solve better by using smart conventional weapons. But that isn't true for some other states, specifically Israel and Pakistan. York cautioned that ten years from now, basic nuclear weapons policy may not be made in Washington, Moscow, or Beijing but rather in places like Jerusalem or Baghdad. York ended his talk with some suggestions for the Laboratory and its role in the years to come. He urged the Laboratory to identify the problems facing the country and to find possible solutions, to develop an understanding of the difference between push and pull with respect to technology demand and technology supply, and to "get busy."

Contact: Herbert F. York, Institute for Global Conflict and Cooperation, San Diego, California (619) 534-3357.

COG: A New, High-Resolution Code for Modeling Radiation Transport

COG is a new Monte Carlo neutron/photon transport code that solves complex radiation shielding and nuclear criticality problems. Unlike earlier codes, COG makes no physics compromises and is as accurate as the underlying empirical database allows. It is simple enough to be run on a desktop workstation yet is more accurate and versatile than older radiation-transport codes written for big mainframe computers. COG has a variety of industrial applications and will soon be released into the public domain.

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12/28/93