The Unitized Regenerative Fuel Cell

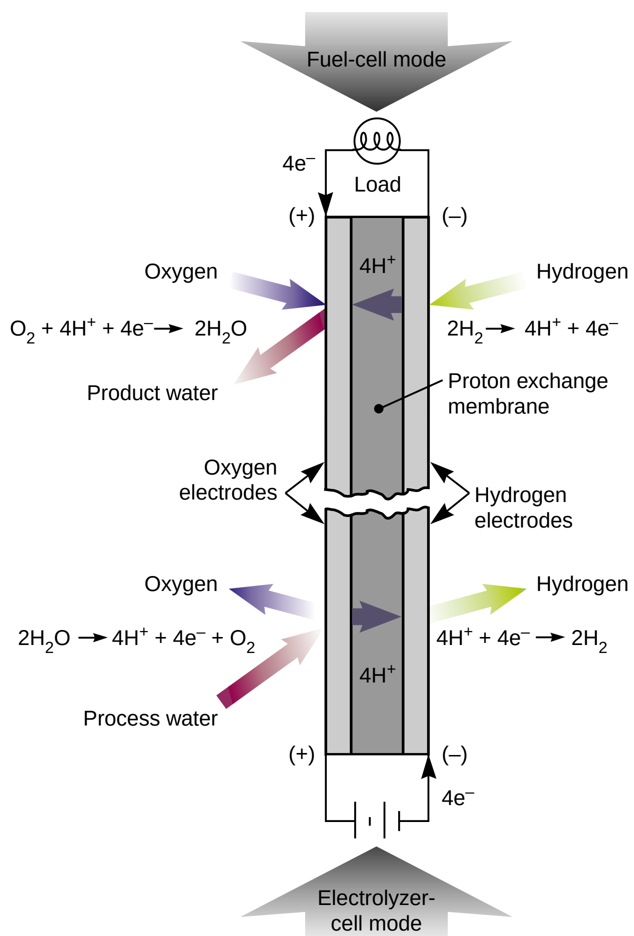

Figure 1. The electrochemistry of a unitized regenerative fuel cell. In the fuel-cell mode, a proton-exchange membrane combines oxygen and hydrogen to create electricity and water. When the cell reverses operation to act as an electrolyzer, electricity and water are combined to create oxygen and hydrogen.

SCIENTISTS are searching for cleaner ways to power vehicles and to make better use of domestic energy resources. The fuel cell, an electrochemical device that converts the chemical energy of a fuel directly to usable energy without combustion, is one of the most promising of these new technologies. Running on hydrogen fuel and oxygen from the air, a 50-kilowatt fuel cell can power a lightweight car without creating any undesirable tailpipe emissions.

If the fuel cell is designed to operate also in reverse as an electrolyzer, then electricity can be used to convert the water back into hydrogen and oxygen. (See Figure 1.) This dual-function system is known as a reversible or unitized regenerative fuel cell (URFC). Lighter than a separate electrolyzer and generator, a URFC is an excellent energy source in situations where weight is a concern.

Weight was a critical issue in 1991 when scientists at Lawrence Livermore National Laboratory and AeroVironment of Monrovia, California, began looking at energy storage options for an unmanned, solar-powered aircraft to be used for high-altitude surveillance, communications, and atmospheric sensing as part of the Strategic Defense Initiative. Called Pathfinder, the aircraft set an altitude record for solar-powered flight in 1995, flying to 15,400 meters (50,500 feet) and remaining aloft for about 11 hours. Pathfinder's successor, Helios, will remain aloft for many days and nights. For that aircraft, storage devices were studied that would provide the most energy at the lowest weight, i.e., the highest energy density. The team looked at flywheels, supercapacitors, various chemical batteries, and hydrogen–oxygen regenerative fuel cells. The regenerative fuel cell, coupled with lightweight hydrogen storage, had by far the highest energy density—about 450 watt-hours per kilogram—ten times that of lead–acid batteries and more than twice that forecast for any chemical batteries.

The Prototype

Fuel cells have been used since the 1960s when they supplied on-board power for the Gemini and Apollo spacecraft. Today, fuel cells are being used for Space Shuttle on-board power, power plants, and a variety of experimental vehicles. However, none of these applications uses the URFC because early experience did not uncover the usefulness of the reversible technology, and little research had been funded. Recent results of Livermore research indicate otherwise, based on more thorough systems engineering and improved membrane technology.

Challenged by a lack of information on the technology, Livermore physicist Fred Mitlitsky was determined to uncover just how to make the combination of technologies work. Mitlitsky continued in 1994 with a little funding from NASA for development of Helios and from the Department of Energy for leveling peak and intermittent power usage with sources such as solar cells or wind turbines. (See Figure 2.)

The 50-watt prototype that Mitlitsky's team developed is a single proton-exchange membrane cell (a polymer that passes protons) modified to operate reversibly as a URFC. It uses bifunctional electrodes (oxidation and reduction electrodes that reverse roles when switching from charge to discharge, as with a rechargeable battery) and cathode-feed electrolysis (water is fed from the hydrogen side of the cell). By November 1996, the prototype

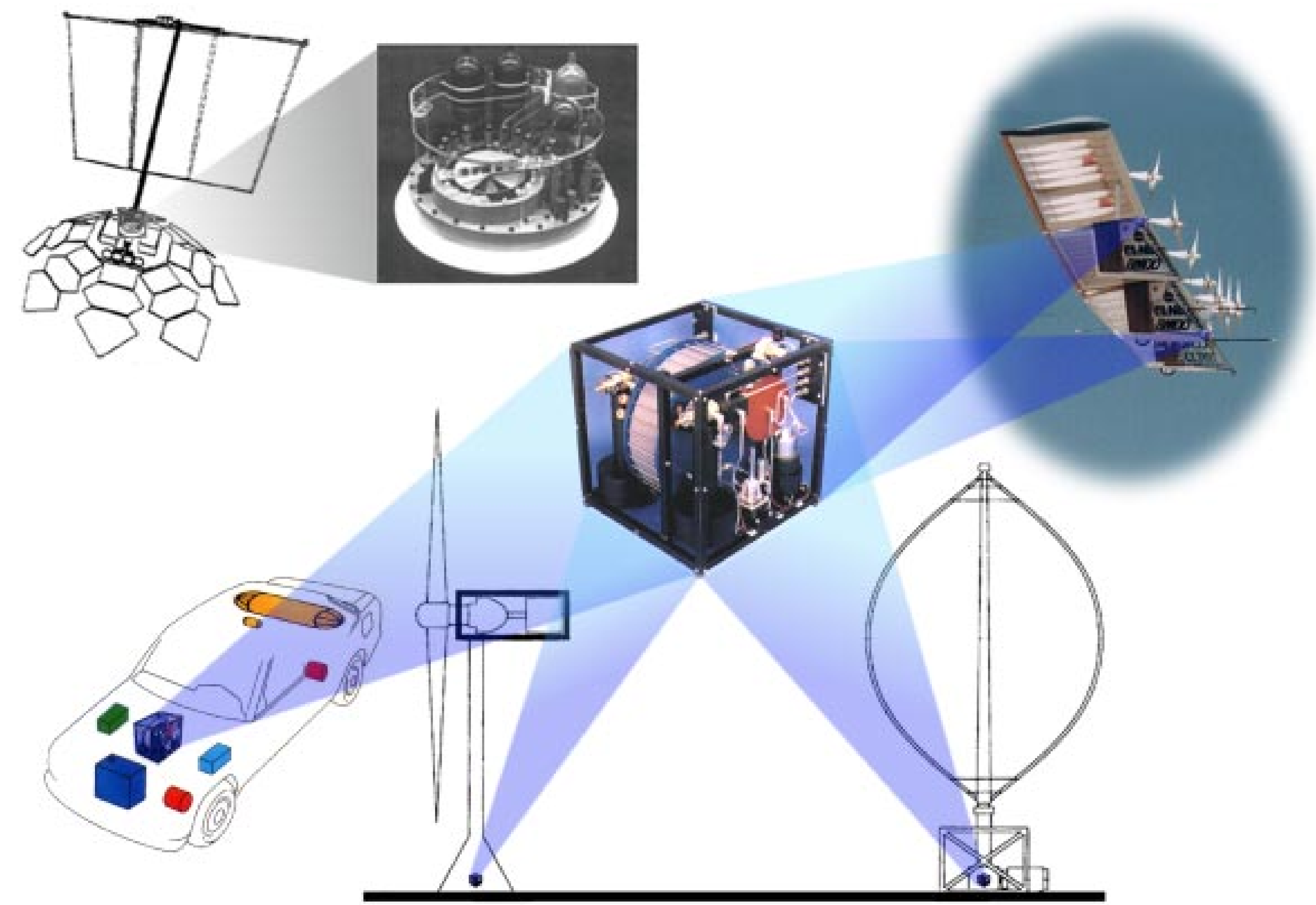

Figure 2. Unitized regenerative fuel cells will someday find a multitude of applications. URFCs are ideal for cars, solar-powered aircraft, energy storage, propulsion in satellites and micro-spacecraft, and load leveling at remote power sources such as wind turbines and solar cells.

had operated for 1,700 ten-minute charge–discharge cycles, and degradation was less than a few percent at the highest current densities.[1]

Testing will continue in a variety of forms. Larger, more powerful prototypes will be created by increasing the size of the membrane and by stacking multiple fuel cells. For use on Helios, a prototype will likely provide 2 to 5 kilowatts running on a 24-hour charge–discharge cycle. As funding becomes available, prototypes may also be tested for other uses. A lunar rover, for example, would require cycles of about 29 days.

URFC-Powered Electrical Vehicles

In a 1994 study for automotive applications, Livermore and the Hamilton Standard Division of United Technologies studied URFCs. They found that compared with battery-powered systems, the URFC is lighter and provides a driving range comparable to gasoline-powered vehicles. Over the life of a vehicle, they found the URFC would be more cost effective because it does not require replacement.[2]

In the electrolysis (charging) mode, electrical power from a residential or commercial charging station supplies energy to produce hydrogen by electrolyzing water. The URFC-powered car can also recoup hydrogen and oxygen when the driver brakes or descends a hill. This regenerative braking feature increases the vehicle's range by about 10% and could replenish a low-pressure (1.4-megapascal or 200-psi) oxygen tank about the size of a football.

In the fuel-cell (discharge) mode, stored hydrogen is combined with air to generate electrical power. The URFC can also be supercharged by operating from an oxygen tank instead of atmospheric oxygen to accommodate peak power demands such as entering a freeway. Supercharging allows the driver to accelerate the vehicle at a rate comparable to that of a vehicle powered by an internal-combustion engine.

The URFC in an automobile must produce ten times the power of the Helios prototype, or about 50 kilowatts. A car idling requires just a few kilowatts, highway cruising about 10 kilowatts, and hill climbing about 40 kilowatts. But acceleration onto a highway or passing another vehicle demands short bursts of 60 to 100 kilowatts. For this, the URFC's supercharging feature supplies the additional power.

A URFC-powered car must be able to store hydrogen fuel on board, but existing tank systems are relatively heavy, reducing the car's efficiency or range. Under the Partnership for a New Generation of Vehicles, a government–industry consortium dedicated to developing high-mileage cars, the Ford Corporation provided funding to LLNL, EDO Corporation, and Aero Tec Laboratories for development of a lightweight hydrogen storage tank (a pressure vessel). The team combined a carbon fiber tank with a laminated, metalized, polymeric bladder (much like the ones that hold beverages sold in boxes) to produce a hydrogen pressure vessel that is lighter and less expensive than conventional hydrogen tanks. Equally important, its performance factor—a function of burst pressure, internal volume, and tank weight—is about 30% higher than that of comparable carbon-fiber hydrogen storage tanks. In tests where cars with pressurized carbon-fiber storage tanks were dropped from heights or crashed at high speeds, the cars generally were demolished while the tanks still held all of their pressure—an effective indicator of tank safety.

Unlike other hydrogen-fueled vehicles whose refueling needs depend entirely on commercial suppliers, the URFC-powered vehicle carries most of its hydrogen infrastructure on board.[3] But even a highly efficient URFC-powered vehicle needs periodic refueling. Until a network of commercial hydrogen suppliers is developed, an overnight recharge of a small car at home would generate enough energy for about a 240-kilometer (150-mile) driving range, exceeding the range of recently released electrical vehicles. With the infrastructure in place, a 5-minute fill up of a 35-megapascal (5,000-psi) hydrogen tank would give a 580-kilometer (360-mile) range.

Commercial development of unitized regenerative fuel cells for use in automobiles is perhaps 5 to 10 years away. With their long life, low maintenance requirements, and good performance, URFCs hold the promise of someday supplying clean, quiet, efficient energy for many uses.

—Katie Walter

Key Words: electric cars, fuel cell, Helios, hydrogen, Partnership for a New Generation of Vehicles, zero-emission vehicles.

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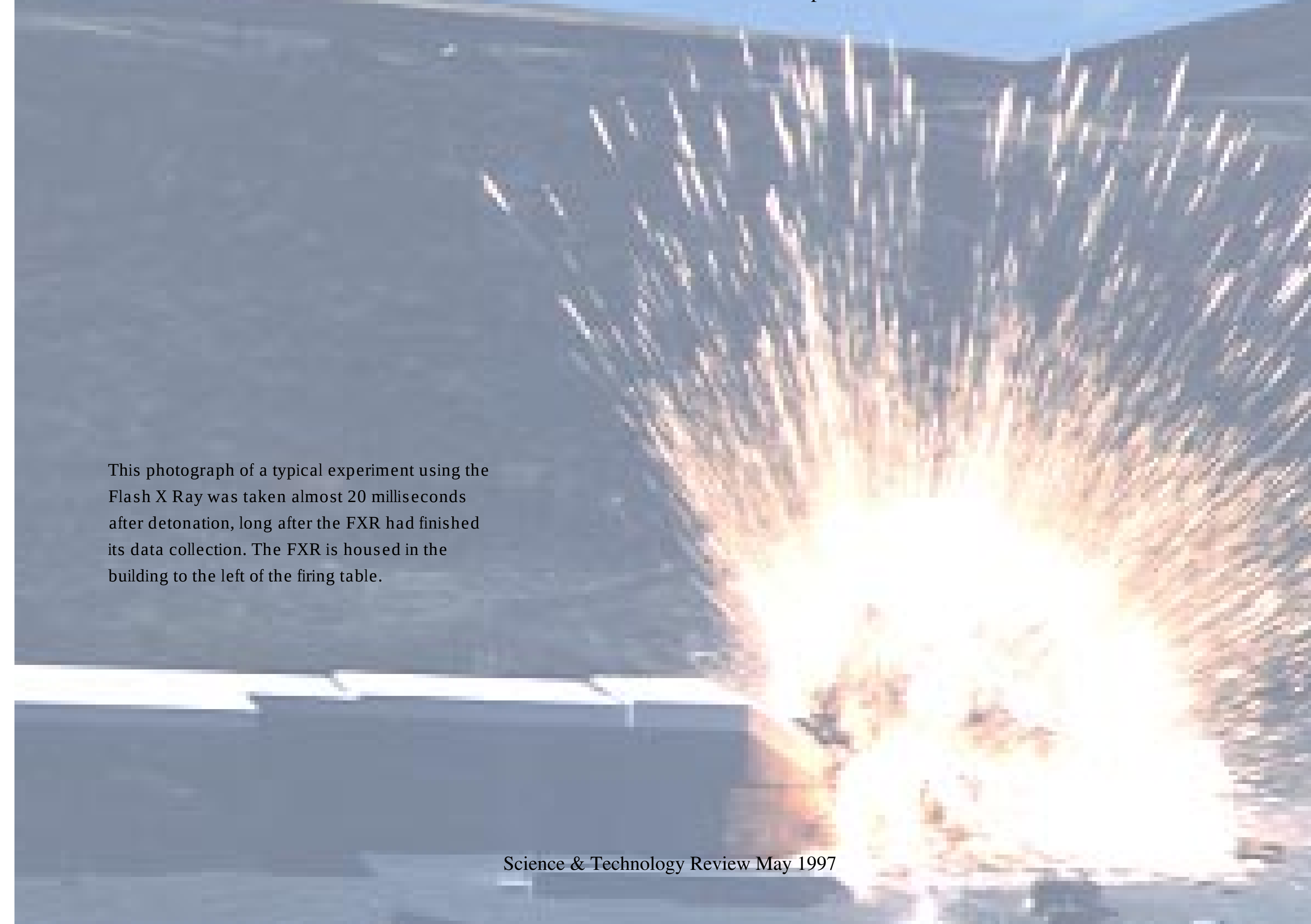
Better Flash Radiography Using the FXR

IMAGINE a very powerful x-ray machine, several billion times more powerful than the one your dentist aims at your jaw. X rays can penetrate more than a foot of steel and record the motion of materials moving at ultrahigh speeds, making it an excellent tool for peering into the interior of a nuclear weapon's imploding primary stage.

Non-nuclear hydrodynamic experiments reveal the behavior of a nuclear weapon from ignition to the beginning of the nuclear chain reaction. These experiments consist of wrapping inert (nonfissile) material in a high explosive that is then detonated. The resulting explosive compression deforms the material, makes it denser, and even melts it. This process replicates the effects in the core of a nuclear device. High-speed radiographic images of the implosion process are taken with the powerful x-ray machine known as the Flash X Ray, or FXR, which was developed by scientists at Lawrence Livermore National Laboratory in the early 1980s'

Data from the FXR's x-ray images are used to verify and normalize Livermore's computer models of device implosions. In the absence of nuclear testing, scientists must rely on these computer calculations to develop the judgment necessary to certify the safety and reliability of nuclear weapons, a critical part of the Laboratory's role in the stewardship of our nation's nuclear stockpile.



This photograph of a typical experiment using the Flash X Ray was taken almost 20 milliseconds after detonation, long after the FXR had finished its data collection. The FXR is housed in the building to the left of the firing table.

To improve capabilities for science-based stockpile stewardship, Lawrence Livermore has been upgrading many diagnostic facilities at Site 300, the Laboratory's experimental test site. The FXR was already the most sophisticated hydrodynamic flash radiography system in the world. In response to the need for data supporting ever more exact computer modeling codes, it has been made more powerful and capable of producing sharper, more useful radiographs.

The FXR in Action

The FXR is an induction linear accelerator specifically designed for diagnosing hydrodynamic tests and radiographing the interior of an imploding high-explosive device. Its x rays penetrate and are scattered or absorbed by the materials in the device, depending upon the density and absorption cross section of the various interior parts. The x rays that are neither absorbed or scattered by the device form the image on photographic emulsions or on the recording surface in a gamma-ray camera.

An injector introduces an electron beam into the FXR accelerator. After passing through the accelerator, the beam enters a drift section that directs it toward a 1-millimeter-thick strip of tantalum, called a target. As the high-energy electrons pass through the target, the electric field created by the stationary charged particles of the heavy tantalum nuclei causes the electrons to decelerate and radiate some of their energy in the form of x rays. The product of this slowing process is called bremsstrahlung (braking) radiation.

The x-ray photons travel toward the exploding device, where most are absorbed. The photons that make it to the camera are the image data.

A Better Radiographic Process

The upgrades to the FXR centered on improving the quality of the beam and adding a new gamma-ray camera system that is 70 times more sensitive than radiographic film. In this camera, designed by Livermore scientists, the beam hits an array of bismuth–germanate crystals with which the x rays interact to generate visible light. This light is recorded on photographic film.

The first task in increasing FXR beam quality was to improve the magnetic field that transports the electron beam through the accelerator. New focus solenoids and printed-circuit magnetic steering coils were installed in each of the accelerator and injector cells. Transverse magnetic forces that had been pulling the beam out of alignment were reduced by a factor of 10 to 20.

The next task was to double the injector beam voltage from 1.2 megavolts to 2.5 megavolts. At the same time, the injector electron beam current was increased from 2.2 kiloamperes to 3 kiloamperes. The number of cells in the injector was increased from six to ten, and the electron diode and the injector magnetic transport solenoids were redesigned.

With the completion of these upgrades, the FXR is producing a higher overall x-ray dose and a smaller spot size. Today, the central portion on the x-ray spot is twice as intense compared with pre-upgrade levels. Because tuning the FXR is an ongoing process, improvements in performance are expected to continue.

Prior to the addition of the gamma-ray camera, the size of the beam where it hits the tantalum target was a major concern; a smaller "spot size" increases the sharpness and clarity of the radiographs. Achieving a smaller effective spot size was accomplished by passing the x rays through a small hole in a thick plate near the target, a process known as collimation. But because x rays emitted outside the collimation diameter are lost to the radiographic process, collimating the beam meant that thicker materials could not be studied.

Today, however, the increased sensitivity of the gamma-ray camera and the increased current density of the central portion of the electron beam combine to more than compensate for the losses due to collimation. The gamma-ray camera can produce much sharper, clearer images than before even with a lower available dose. The camera's sensitivity combined with the newly increased x-ray dose at the target means that collimation can be used for experiments involving even higher density materials. Preliminary results indicate that the FXR upgrade—in conjunction with the gamma-ray camera—have significantly improved the radiographic capability at Livermore.

In the near future, the Laboratory will be adding a double-pulse feature to the FXR to provide two radiographs of a single explosion–implosion separated by 1 to 5 microseconds. Researchers can use this information to follow the time evolution of an implosion and learn more about how an implosion progresses. Restoring single-shot, full-energy operation will require simply setting the pulse interval to zero. Livermore scientists are also developing a two-frame gamma-ray camera to capture the fast successive images of double-pulsed FXR radiography and record them on a charged-coupled device camera. Work on the double-pulse feature and the two-frame camera is expected to be complete in 1998.

Key Words: flash x radiography (FXR), gamma-ray camera, hydrodynamic testing, induction linear accelerator, pulsed electron beam, pulsed x-ray source, stockpile stewardship.

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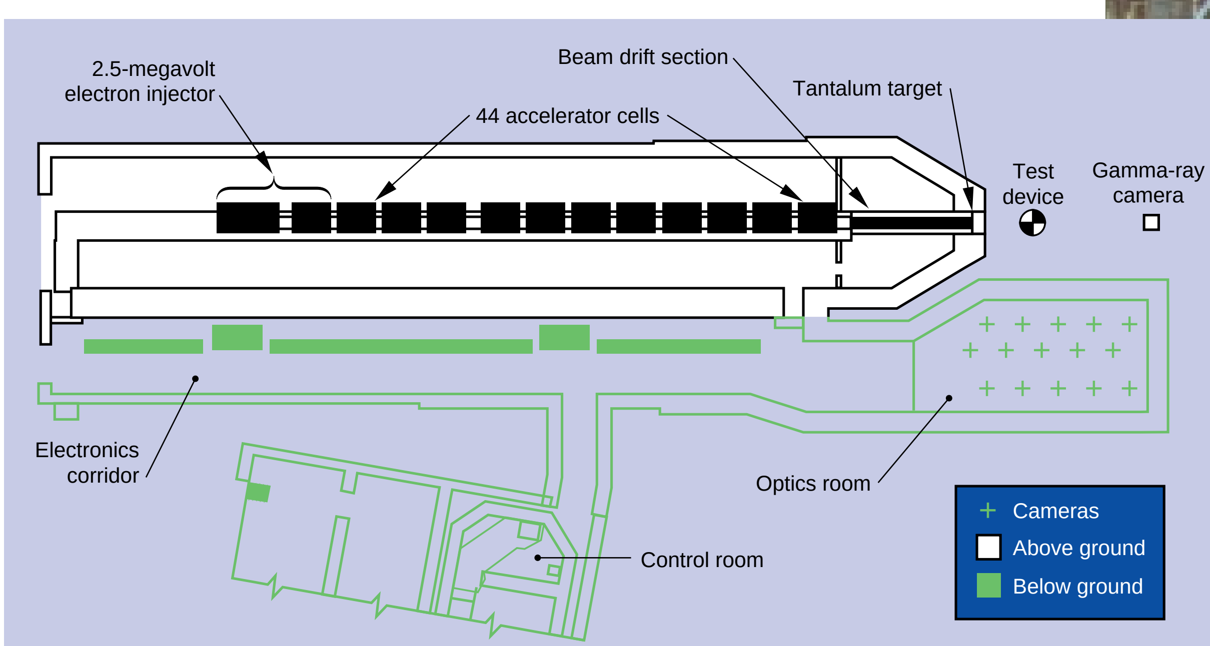
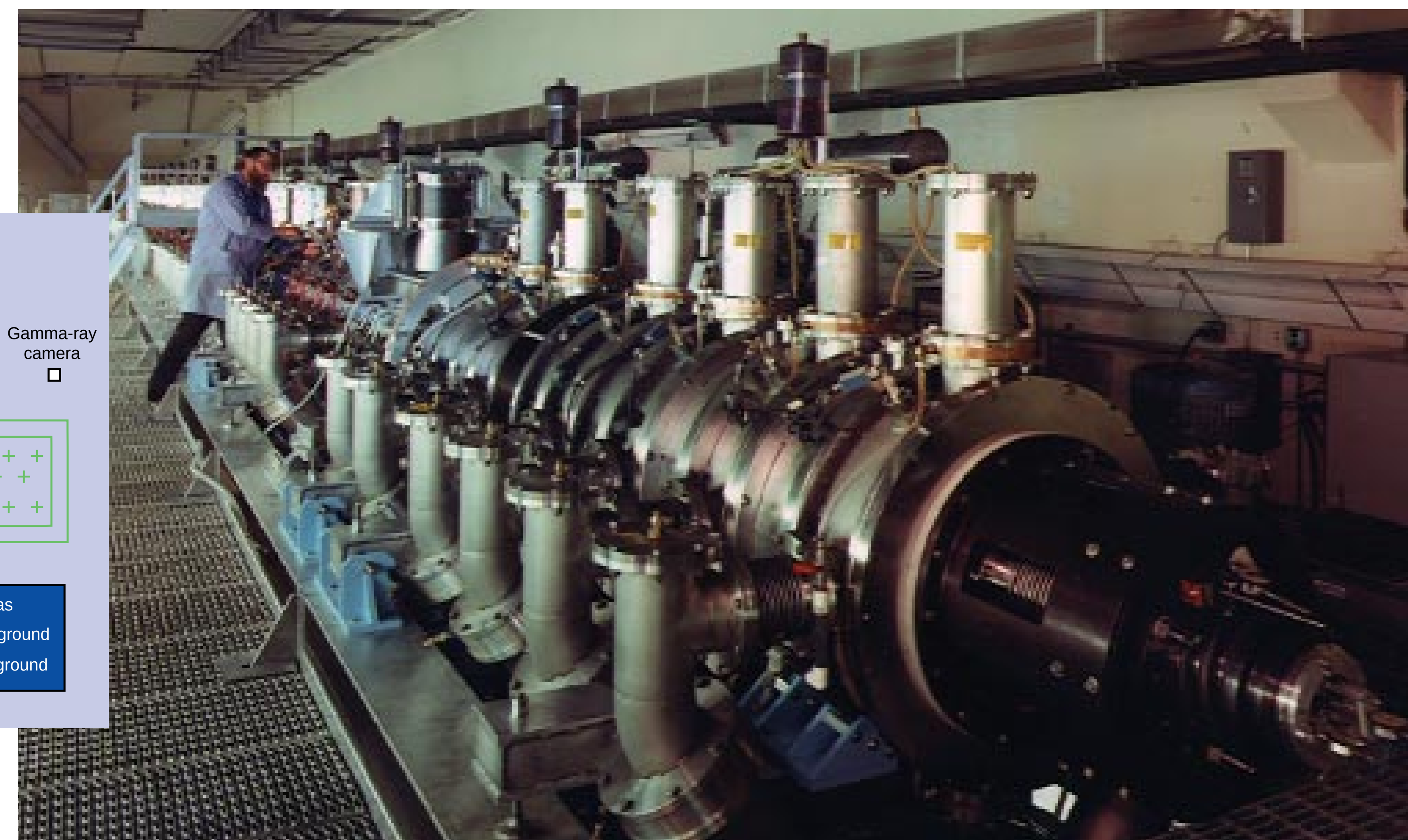
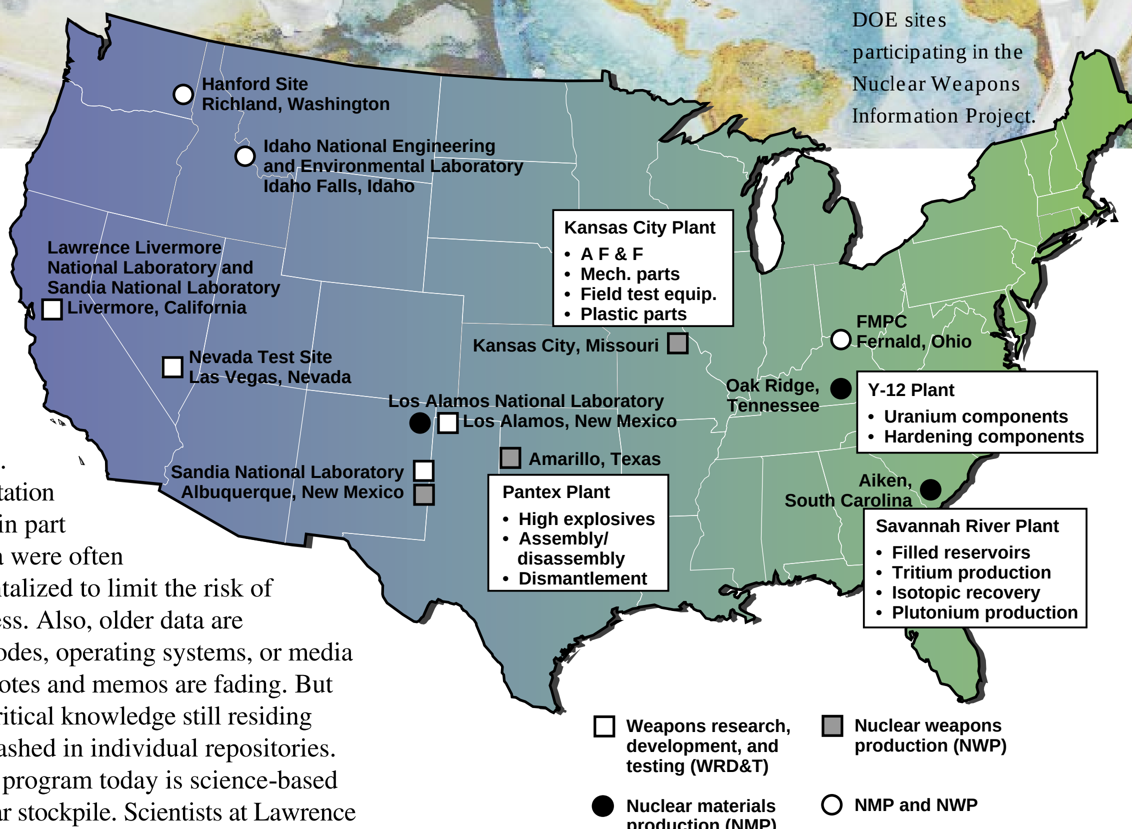
The Flash X-Ray beam area is on the same level as the firing table outside the building. The electronics corridor, optics room, and control room are underground, one level below the beam area and offset from the accelerator as shown in this schematic. Several of the accelerator cells can be seen in the photograph to the right.





Preserving Nuclear Weapons Information



DOE sites participating in the Nuclear Weapons Information Project.

HISTORICALLY, the primary mission of DOE's nuclear weapons laboratories has been weapon development and testing. The goal was to get the job done better and faster than anyone else in the world.

Access to the full documentation today is sometimes difficult, in part because weapons-related data were often classified and/or compartmentalized to limit the risk of inadvertent disclosure or access. Also, older data are dependent on old computer codes, operating systems, or media that cannot be read, and old notes and memos are fading. But even more vulnerable is the critical knowledge still residing only in scientists' heads or stashed in individual repositories.

The thrust of the weapons program today is science-based stewardship of the U.S. nuclear stockpile. Scientists at Lawrence Livermore National Laboratory are responsible for four of the nine weapon systems in the enduring U.S. stockpile, including the only ones that incorporate all modern safety features. Maintaining and managing those systems will be Livermore's responsibility for years to come.

With rare exceptions, the people who will manage the stockpile in the next century will do so without the direct knowledge that comes from having designed and tested a nuclear weapon. Because the generation of designers responsible for the current stockpile is reaching retirement age, "downloading" essential information from their heads is critical for future scientists.

Scientists and engineers at Livermore, proud of their work, enthusiastically embraced the Nuclear Weapons Information Project (NWIP), an archiving effort established in early 1993 to rescue at-risk data and knowledge. Bill Bookless, Principal Deputy Associate Director in the Defense and Nuclear Technologies Directorate, is the project leader. Late in 1993, the Defense Nuclear Facilities Safety Board issued Recommendation 93-6, which emphasized retaining safety-related capabilities and capturing weapons knowledge. That directive enhanced the visibility and priority of NWIP work.

The Nuclear Weapons Information Project will preserve Livermore's portion of the Department of Energy's Stockpile Stewardship and Management Program. It will also preserve data for training future scientists, engineers, and technicians and will provide immediate critical information for emergency response to nuclear weapon incidents.

The information archived in NWIP will support proliferation analyses to deter the spread of nuclear weapons to other countries and to terrorist organizations. And the database will provide the fundamental information necessary to resume weapons design, development, testing, and production if required by changes in a volatile world situation.

Because scientists at Livermore depend on access to information at all DOE nuclear weapon facilities, in 1994 Livermore also took a leading role in implementing an information preservation collaboration across the DOE weapons complex. The Nuclear Weapons Information Group (NWIG) today includes participants from the DOE sites shown in the figure, the Department of Defense's Defense Special Weapons Agency, and the United Kingdom's Atomic Weapons Establishment.

The Task at Hand

When work began on the DOE project, the most critical needs were learning what information existed and how to get appropriate access to it. Some DOE sites have as many as 300 different databases or catalogs of relevant data. And some data shelved in unmarked boxes have never been catalogued. Consequently, the initial focus of the group was on "metadata," which are data about data—typically bibliographic data—and on standardization efforts.

Terminology has changed over time, and various organizations across the DOE complex use different terms for the same thing. Local glossaries have been developed and are being shared and integrated, and a categorization system is being developed to define common subject areas. Livermore leads the working group that is developing metadata standards and has led the pilot implementation of searches in and across multiple catalogs.

Capturing documents and data is actually the easy part of the project. Capturing the knowledge that is in people's heads and that cuts across program boundaries is more difficult. Videotapes are being made of panel discussions, tours, lectures, and operations to save undocumented anecdotal technical information and historical perspectives.

Livermore has already adopted the NWIG standards and methods for access by implementing commercial "browser" software to provide access to its electronic archives. A pyramidal need-to-know model is also being implemented, such that individuals authorized at the top of the pyramid may have access to nearly everything while those authorized at other levels have access only to information in a particular domain or perhaps about specific weapon systems. By enhancing its classified network infrastructure, Livermore can balance the increased access to information against the increased threat of compromise.

Translating archived files into such standard formats as HyperText Markup Language (HTML) and Portable Document Format (PDF) minimizes the number of platform-sensitive formats that must be translated indefinitely as the technology changes. Settling on a few standard formats also allows the search engine to index every word of every document for retrieval. Links can then be made to the actual archived online documents, or for catalog searches, the search engine can indicate where the documents can be found.

Cutting-Edge Technologies

Several advanced technologies are being applied to the Nuclear Weapons Information Project at Livermore. An example is the online video search and retrieval system, which will provide authorized users of the archives access to videotaped information through a search of the automatically generated transcripts. A search will yield both words in the transcript and matching video images.

The access control mechanisms work together with state-of-the-art identification and encryption technology to ensure authorization, authentication, and secure delivery of information on distributed classified networks. Administrators in weapons-related divisions at Livermore are also making use of this new commercial technology to better protect sensitive unclassified information. Livermore is leading the effort across the DOE complex to establish and implement access control policies and procedures.

Information Is a National Asset

Downloading the knowledge from scientists' heads and archiving those stashed personal files—plus organizing and categorizing more accessible data—are essential tasks. The project team is establishing the archives so that this accumulated information, an important national asset, is preserved for the long term and readily accessible whenever needed. The success of much of DOE's Stockpile Stewardship and Management Program depends on these new archives.

Key Words: archives, Nuclear Weapons Information Project, Stockpile Stewardship and Management Program.

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