

Demon, Helia, Radlac II, PBFA II, Epoch, Hermes III, Saturn, Rhepp I, Rhepp II, Z, RITS, ZR, Z Beamlet

PULSED POWER

at Sandia National Laboratories
the first forty years

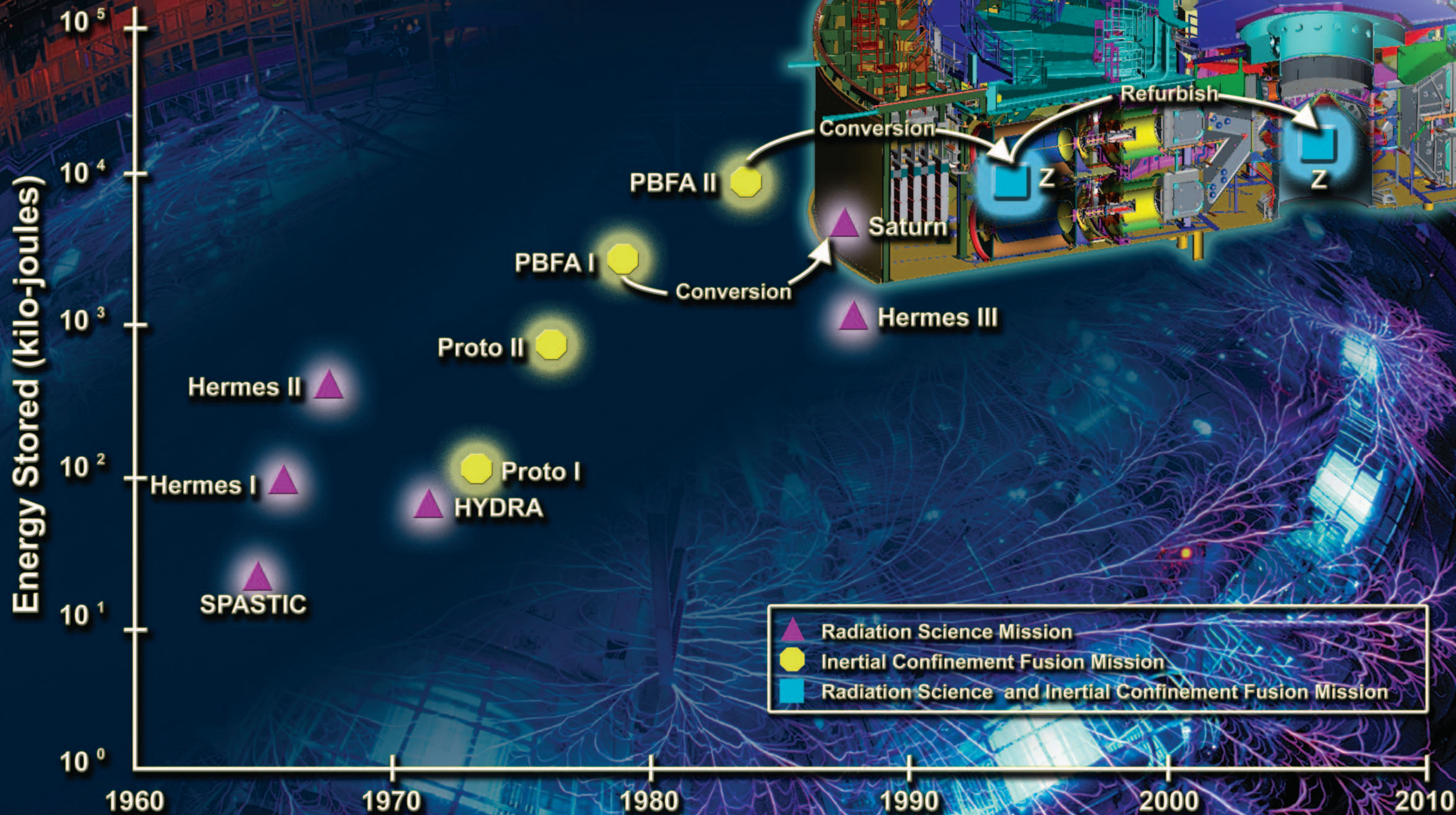


WHAT IS PULSED POWER . . .

In the early days, this technology was often called ‘pulse power’ instead of pulsed power. In a pulsed power machine, low-power electrical energy from a wall plug is stored in a bank of capacitors and leaves them as a compressed pulse of power. The duration of the pulse is increasingly shortened until it is only billionths of a second long. With each shortening of the pulse, the power increases. The final result is a very short pulse with enormous power, whose energy can be released in several ways. The original intent of this technology was to use the pulse to simulate the bursts of radiation from exploding nuclear weapons.

Pulsed Power Timeline (over)

Pulsed Power Machine History at SNL - Stored Energy



PULSED POWER

at Sandia National Laboratories

the first forty years

Anne Van Arsdall

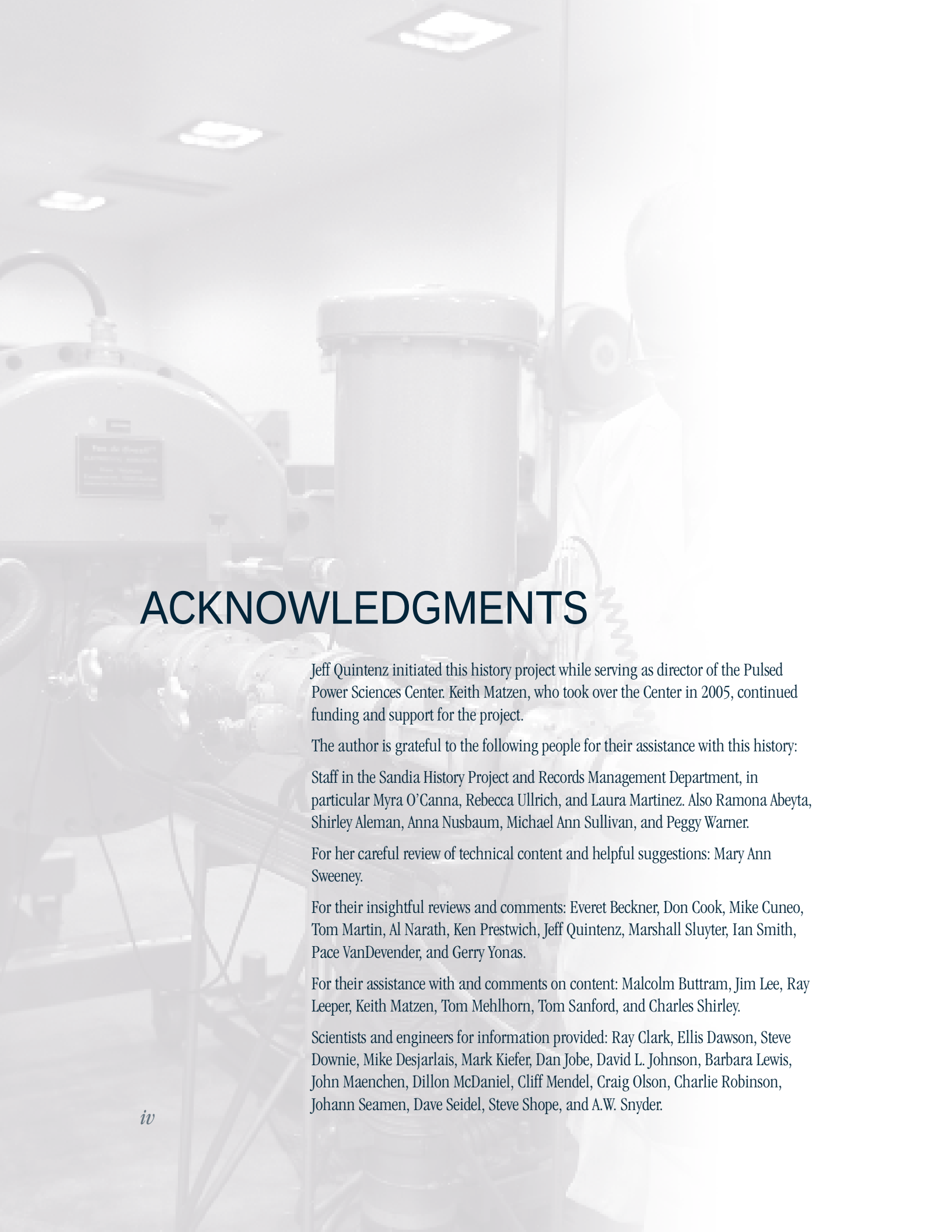
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1. **Introduction**
 2. **Methodology**
 3. **Results and Discussion**



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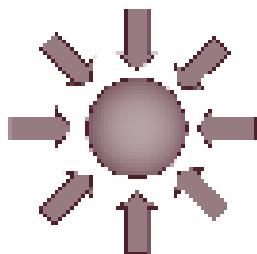
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INTRODUCTION

Pulsed power accelerators store electrical energy, compress it in time and space, and deliver it to a target as strong, short, fast-rising pulses of power. How the energy is delivered determines the type of radiation, or the beam, that will be produced. Sandia needed such capability beginning in the 1960s for one of its traditional responsibilities, weapons effects simulations. The military was building new kinds of electronics into warheads, and the United States needed to test their vulnerability to radiation from an enemy's nuclear weapons. The accelerators could simulate the effects of those weapons and harden US warheads against them.

Chapter one of this history outlines the early years of pulsed power at Sandia, the 1960s and early 1970s, when collaborations with the Atomic Weapons Research Establishment in the United Kingdom resulted in Sandia's building relatively small machines capable of simulating gamma rays and then x rays. At the same time, the Department of Defense was building competing accelerators for the same purpose, some of them attempting to create controlled fusion events in the laboratory in classified experiments. (Uncontrolled fusion reactions are used as the secondaries in nuclear weapons.) In parallel with accelerator development, the newly invented laser was being established as an important technology for many of the same applications as accelerators at Lawrence Livermore, Los Alamos, and Sandia laboratories, and at the Naval Research Laboratory.



*In inertial confinement
fusion, x-ray
illumination leads to ...*

During the 1960s, Sandia established a basic research program to support its traditional engineering design work. Al Narath and Everet Beckner, two new staff members who rose quickly into higher management, spearheaded this effort, and out of this program came the push to get Sandia into the inertial confinement nuclear fusion arena. Nuclear fusion was at the time dominated by Livermore and Los Alamos, using lasers as drivers. Realizing that pulsed power accelerators might be suited to fusion research, Narath and Beckner saw a fusion program as one way to attract new talent to Sandia. In addition, fusion research would help bolster Sandia's role in national defense and other areas and also had the potential for development as a source of energy, which greatly added to its appeal.*

Chapter two covers roughly the decade of the 1970s. In the early years of that decade, Narath and Beckner hired Gerry Yonas into Sandia because of his expertise at Physics International with large accelerators and fusion work. Very soon after coming to Sandia, Yonas began to champion Sandia's accelerators as potential drivers for inertial confinement fusion to the Department of Energy and Congress. Because lasers were seen as the frontrunner technology for fusion, the proposal to consider accelerators for the same purpose was viewed with some skepticism. Indeed, Livermore and Los Alamos did not welcome what they considered a dark-horse contender in the fusion arena. Pulsed power accelerators and their particle beams did not seem to them well suited to this work because the beams were difficult to focus to a small area. (Tight focusing, which lasers do easily, is crucial to compressing and heating the fusion pellet.) Moreover, Sandia would be competing for funding in an area the other laboratories had dominated.

Chapter two also relates how various test beds and increasingly powerful accelerators were developed in the pulsed power area for weapons effects simulations, as the inertial confinement fusion program grew. It was during this time that Sandia changed its approach from using electron beams to light ions for fusion. Reflecting the increasing complexity of fusion and weapons effects studies, the new field of computers and computer codes began to aid understanding and predictions.

Chapter three covers the 1980s and the beginning of Sandia's large complex accelerators designed specifically to ignite an inertial confinement fusion reaction. Teams of experts were brought together for this effort, which requires interdependent elements to make fusion work. The elements include designing the machines (such as PBFA I and PBFA II) and diodes to create particle beams or other mechanisms for delivering power onto a target, fabricating fusion pellets inside specially designed

* Inertial confinement fusion requires an enormous pulse of power focused for a few nanoseconds on a target the size of a BB. In less than the blink of an eye, the burst of power implodes a specially designed target, compresses the material in it, and heats it to temperatures near those at the center of the sun. In theory, this action will ignite a fusion reaction in the material. Pulsed power accelerators and lasers are used as 'drivers,' the machines that provide the power to drive the fusion reaction.

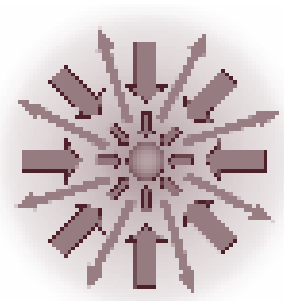
targets, implementing detailed diagnostics for experiments, and creating computer codes to understand and then predict what the diagnostics revealed.

In 1984, Pace VanDevender took leadership of what had grown into a Pulsed Power Program. Yonas left to become chief scientist in the national Strategic Defense Initiative (Star Wars), and, in fact, Sandia was assessing the use of pulsed power capabilities as beam weapons. As earlier, Sandia's particle beams were competing with the lasers at Livermore and Los Alamos in the areas of fusion and beam weapons. Chapter three outlines how simulation of weapons effects continued to be a mainstay of the Pulsed Power Program and subsequently began to vie with fusion in importance. At the national level, defense requirements necessitated a facility capable of high-yield fusion that could deliver levels of energy beyond simple ignition, and plans were formulated around even more powerful lasers and/or accelerators as drivers. Meanwhile, controlled fusion ignition continued to be assessed by computer calculations, but eluded laboratory experimenters everywhere. Sandia's main approach during this period was to use lithium ion beams as the driver for fusion.

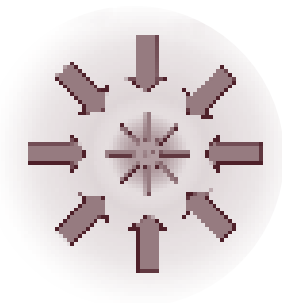
The final chapter in this history, chapter four, spans the 1990s and the early years of the twenty-first century. Using PBFA II, Sandia tried a variety of techniques to get its light-ion beams to deliver the power on target needed to prove this technology was capable of igniting a fusion reaction in a pellet. The caveat was that even if the technique were shown to be successful, a bigger machine would actually be required to deliver enough power to ignite fusion in a pellet. VanDevender led the program through this time, which involved a number of focused national reviews, and in 1993 turned the reins over to Don Cook, who had been the program manager under him.

As difficulties with the ion-beam approach were slowly being overcome, another long-time candidate for fusion, called the z pinch, scored unexpected successes on Saturn, one of Sandia's large accelerators (formerly PBFA I). Z-pinch technology—used in the target area to produce non-thermal x rays for testing nuclear weapons effects and for x-ray laser experiments—had been in the weapons programs for many years (harking back to the 1960s). It had been sidelined at Sandia in favor of ion beams because particle beams were considered at the time more suited for use in a fusion power plant. The upshot was that PBFA II was reconfigured for z pinches in 1996 and light-ion-beam work for fusion ceased. The new accelerator was renamed Z to emphasize the commitment to z-pinch research, and with Z, Sandia achieved an impressive series of scientific breakthroughs.

Cook left the Pulsed Power Program in 1999 to head up the new Microsystems and Engineering Science Applications (MESA) program. Succeeding him was Jeff Quintenz, a theorist who had been with pulsed power since coming to Sandia in 1975. A major event under Quintenz was obtaining approval and funding to refurbish and upgrade Z into the more powerful ZR. In 2004, soon after the funding for ZR was approved, Quintenz accepted a position outside pulsed power, and in



*blowoff and subsequent
compressing force ...*



in order to achieve fusion ignition.

January 2005 Keith Matzen took over the Pulsed Power Sciences Center. Matzen, a high-energy-density physicist, had been Quintenz's deputy and had long been a key player in the z-pinch program.

The spectacular Z, which prompted a story in *Esquire* in 1999, has continued to be a major tool in Sandia weapons effects, weapons physics, and fusion technologies (now more often called high-energy-density physics than fusion). Z and other capabilities in the pulsed power area are major contributors to Sandia's traditional mission of verifying the safety and reliability of the nation's stockpile of nuclear weapons. In addition, Z contributes to the development of the National Ignition Facility, just as the refurbished Z will when succeeding Z.¹

Although the research on Z has been the most visible and best-known part of pulsed power work at Sandia, other long-term capabilities continue to be strong. These capabilities include directed energy technologies and repetitive-rate high-energy pulsed power, and, harking to its beginning, weapons effects simulations and radiography. Because the emphasis in pulsed power at Sandia has been on building and operating accelerators, this history only briefly touches on theoretical and computational aspects, particularly before the late 1970s.

While reading this history, it must be kept in mind that the majority of activities at the Department of Energy/National Nuclear Security Administration weapons laboratories, such as Sandia, are government-funded. Proposals for new projects, requests for funds for ongoing projects, and project reviews to determine funding levels are part of life in the nuclear weapons complex. Without approval far in advance, very large projects, such as Sandia's accelerators PBFA I (Saturn), PBFA II (Z) and the Z-Machine Refurbishment (ZR), would not be possible. Even with projects planned and often funded months or years ahead, shifting national priorities and unforeseen budget constraints quite often enter into play and are reflected in reductions, less often increases, in the amount of funding certain projects receive. For this reason, an ongoing thread of discussion in the history is funding.

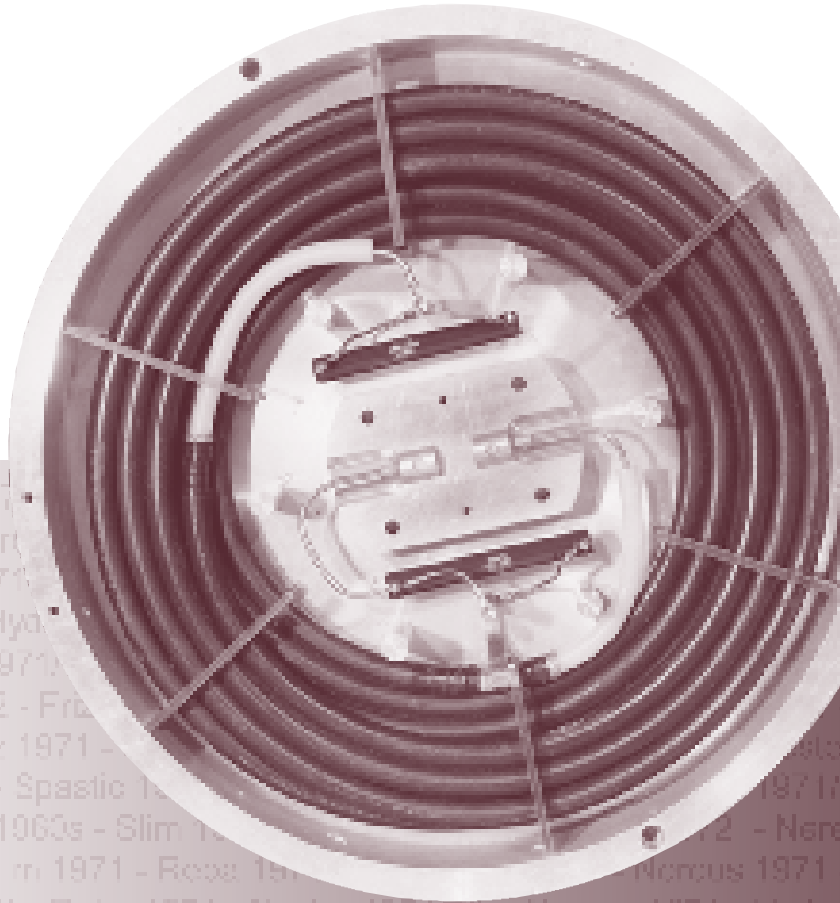
In this work, 'fusion' refers to inertial confinement fusion, meaning a controlled microfusion event in the laboratory involving a driver (such as a particle accelerator or a laser) and a fusion target. Where magnetic confinement fusion is meant, it is so named. The goal of both techniques is the same—to compress and heat a plasma to a temperature that will spark a fusion reaction within it. Magnetic confinement fusion is the technology being pursued in the international fusion energy effort named ITER. Inertial confinement fusion, on the other hand, has been sought primarily for weapons effects simulations, weapons physics, and other scientific reasons, and secondarily as a source of energy production.

This history is drawn from written archives and from the memories of many who contributed to pulsed power at Sandia.² The historic illustrations, schematics, and photos come directly from archival materials and were intentionally left unchanged.

endnotes

- 1 The National Ignition Facility, currently a \$3.6+ billion effort at Lawrence Livermore National Laboratory, will use multiple lasers to try to ignite fusion in a pellet. It received initial funding in 1992 and is scheduled to begin operation in 2009 (originally 2001). It is considered the centerpiece in the Department of Energy/National Nuclear Security Administration's inertial confinement fusion program, largely on the basis of the maturity of laser technology.
- 2 Sandia's History Program in the Recorded Management Division at the Laboratories maintains an extensive archive of materials on Sandia's Pulsed Power Program dating to the earliest days. Tom Martin, Ken Prestwich, Ray Clark, Don Cook, and Steve Shope provided much material for the archives, and the Pulsed Power Sciences Center contributed a great deal of archival material as well. Inventories of each collection are available at the archives. Sandia also has a complete set of the *Sandia Lab News*, the weekly company newspaper that began publication in November 1948 as the *Sandia Lab Bulletin* and continues today, appearing twice a month. The *Lab News* has a wealth of information on Sandia staff and technologies.

Cable Pulser



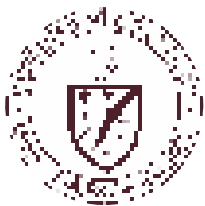
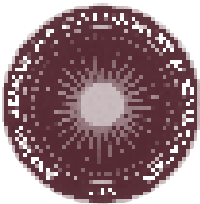
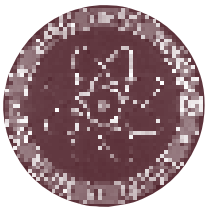
CHAPTER ONE

the '60s

By the end of 1953, the United States had a capability no other nation had: both fission and fusion devices in its stockpile of atomic weapons. Live field tests of nuclear weapons were being conducted, with each test heavily instrumented to capture minute details of the event. In the aftermath of each test, data were studied to improve the device, maximize yield, and more fully understand the underlying physics of the weapons.

Allies of the United States, notably Great Britain, were also making advances in nuclear weapons development at this time, but so was the Soviet Union.¹ The arms race with Russia escalated steadily during the 1950s, highlighted by the first Soviet fusion device being tested in 1955, closely followed by the launch of Sputnik I two years later. Although Sputnik was not a weapon but a satellite that orbited the Earth, its daily orbits and electronic signals were a constant reminder that US arms might not be supreme. With Sputnik II in the skies in November 1957 and the successful launch of a Soviet intercontinental ballistic missile that same year, the Cold War and the space race between the United States and Russia gained momentum.

From the Atomic Energy Commission to the Department of Energy/National Nuclear Security Administration



1946

August 1. The Atomic Energy Commission is created out of the war-time Manhattan Engineering District, and control of the nation's atomic energy program is transferred from military to civilian authority by an executive order signed on December 31.

Its counterpart in the Department of Defense for training in nuclear weapons operations is the Armed Forces Special Weapons Project from 1947-1959, followed by the Defense Atomic Support Agency from 1959-1971, and the Defense Nuclear Agency from 1971-1996.

1974

The Atomic Energy Commission is abolished and the Energy Research and Development Administration (ERDA) and the Nuclear Regulatory Commission take over its functions.

The Nuclear Regulatory Commission assumes responsibility for commercial reactor safety (and for Sandia's reactor safety assessments as well).

The ERDA maintains responsibility for nuclear weapons and energy research. In addition, ERDA is given oversight of fossil fuel research (it had been in the Department of the Interior), solar and geothermal research (formerly in the National Science Foundation), and automotive propulsion research (which had been in the Environmental Protection Agency).

The ERDA and the Department of Defense have shared and joint responsibilities for the US nuclear weapons programs, overseen by the Joint Committee on Atomic Energy.

1977

August. The Department of Energy is created as a cabinet-level entity, with responsibilities identical to those of the Atomic Energy Commission, but now headed by a Department Secretary reporting to the President.

The Department of Energy and Department of Defense continue shared and joint responsibilities for US nuclear weapons programs, overseen by the House and Senate Armed Services Committee.

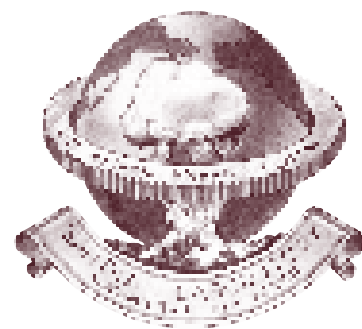
2000

The National Nuclear Security Administration is created as part of the Department of Energy, to be run by the Under Secretary for Nuclear Security and Administrator of the National Nuclear Security Administration. The administration oversees sites within the Department of Energy complex, including portions of the national laboratories. Its mission is to carry out the national security responsibilities of the Department of Energy, including maintenance of a safe, secure, and reliable stockpile of nuclear weapons and associated materials capabilities and technologies; promotion of international nuclear safety and nonproliferation; and administration and management of the naval nuclear propulsion program.

In the Department of Defense, the Defense Nuclear Agency becomes the Defense Special Weapons Agency from 1996 to 1998, when the On-Site Inspection Agency, the Defense Technology Security Administration, and selected other elements of the department are combined to form the Defense Threat Reduction Agency.

the '60s

This tense environment generated new responsibilities for the weapons laboratories in the United States during the 1950s. Realizing the Soviet Union had missile capability, possibly rivaling that of the United States, there were concerns about the effects of radiation from an enemy's exploding atomic weapons on US military equipment. New electronic systems were being deployed in US weapons control systems, and Sandia needed to test their vulnerability to radiation, especially to gamma rays. As vacuum tubes gave way to semiconductors, Sandia was responsible for hardening all the arming, fusing, and other systems it was developing against radiation from a nuclear explosion. (Please see following sidebar on Weapons Simulation and Radiation Effects Studies.)



Sandia artist's concept from the 1960s.

In 1957, basic research responsibilities were added to Sandia's Systems Research organization to probe the complex subatomic world behind radiation effects. This research laid the foundation for what would become the fledgling Pulsed Power Program within less than a decade. Established in 1952, Systems Research initially had the goal of promoting specialization in the areas of engineering associated with ordnance development. To begin the basic research effort, a high-voltage Van de Graaff accelerator was installed in Area I, and a *Sandia Lab News* story of March 22, 1957, said the accelerator would "establish the scientific basis for understanding and interpreting the effects of radiation environments." The Van de Graaff could accelerate single types of particles at selected intensities, allowing their effects on materials to be studied individually. The high-energy particles could also be used to produce x rays or neutrons.

Global concerns about radioactive fallout from international weapons testing prompted an agreement between the United States and Soviet Union suspending nuclear tests and prompting investigations into laboratory simulations to replace them. The moratorium on testing lasted from October 1958 to August 1961 and, for a time, put a brake on weapons design; however, weapons effects simulation studies in the laboratory continued unabated. In fact, such simulations had always been attractive since live tests were expensive and therefore limited in number. Great interest was sparked at this time in the United States in building a variety of machines to emulate a variety of weapons effects, and Sandia began building and/or acquiring new facilities to respond to this need.

In March 1961, as a companion piece to the Van de Graaff at Sandia, a newly acquired Cockcroft-Walton accelerator began creating positively charged ions and ion beams for various experiments and studies. A junior-size Cockcroft-Walton, the Microbevatron, joined the Systems Research organization in October 1961 to produce low-current electron and ion beams for this basic research. X rays and neutrons could be generated with these accelerators but at very low dose and dose rate levels and over very small volumes compared to the levels desired for the military's weapons effects studies. Planned since 1957, the Sandia Engineering

Early Weapons Effects Simulation and Radiation Effects Studies

To help explain the need for machines capable of weapons effects simulations in the 1960s and 70s, a simplified outline follows of aspects of a nuclear explosion that were of particular concern: gamma rays, x rays, and neutrons.

Gamma rays originate in the nuclei of atoms and are high-energy electromagnetic waves similar to x rays but with a shorter wave length and higher energy. They are sometimes called hard x rays. This radiation penetrates deeply and damages internal components such as cables, computer circuits and processor boards.

X rays are electromagnetic radiation lying between ultraviolet and gamma rays in the radiation spectrum. They are often called soft x rays, having lower energy and longer wavelengths than gamma rays, and depending on their energy can also be described as hot or cold. X rays do not penetrate as deeply as gamma rays, but deposit radiation close to the surface. X rays are produced when electrons of sufficiently high energy bombard matter.

Neutrons are large-mass particles released through fusion or fission reactions as nuclear weapons detonate. The number of neutrons depends on several factors, which are subjects of weapons effects studies. Neutrons can travel a long way through the air and penetrate thick materials.

Once released from the immediate environment of the exploding weapon, these kinds of radiation and neutrons can alter the performance of an opponent's weapons systems and related equipment. Because of the wide variety of materials in weapons and military equipment, studying the effects of x rays, gamma rays, and neutrons on multiple material configurations and with varying intensities and duration is a key part of weapons effects studies. At the beginning of weapons effects studies, nuclear devices were designed to be dropped from airplanes; later, and of concern to designers, nuclear warheads were mounted in ballistic missiles, whose systems would be adversely affected by the radiation and electromagnetic pulses from a nuclear explosion.

The initial radiation from a nuclear explosion consists primarily of gamma rays, x rays, and neutrons produced at the time of detonation. This initial radiation sets off several processes that produce electromagnetic pulses.

Weapons scientists and engineers began to realize in the 1950s that this effect was much more serious than they had realized, probably being responsible for multiple equipment malfunctions. They ascertained that intense electric and magnetic fields from nuclear explosions affected electrical and electronic equipment at great distances and over a wide area. In addition, they learned that gamma rays and x rays could penetrate the solid materials of electronic weapons systems and create a damaging electric field inside the weapon, creating electromagnetic pulses internal to the weapon.

Nuclear radiation, including electromagnetic pulses, increases rapidly, peaks, and then decays. The radiation ranges widely in frequency and strength, and the possible ways it could affect the electrical and electronic systems in US weapons were many and complex to analyze. The electric fields created by the nuclear electromagnetic pulses are very strong and delivered very fast, a situation electronic equipment never has to face under normal circumstances. The electromagnetic pulse is not a constant, but differs depending on the force of the weapon and where it is detonated, whether in outer space, near the earth, or underground.

The machines developed at Sandia and elsewhere simulated effects of the internal weapons electromagnetic pulse by creating short, intense pulses of electromagnetic radiation and using them to test weapons systems and components. The simulators' pulses were created when high-energy electrons bombarded metallic targets and the targets emitted x rays (the process is called *Bremsstrahlung*). The outcome depended on the circuitry inside the weapons as well as the intensity of the radiation.

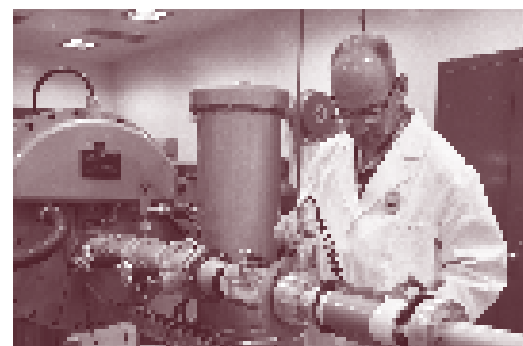
In the 1960s and early 1970s when weapons effects work began to escalate, the military, Department of Defense, and Atomic Energy Commission had numerous different requirements for electromagnetic pulse and radiation simulators because of the many types of weapons systems being designed and tested and the myriad effects they might face. The objective of all this work was to be able to build weapons and weapons systems that were hardened to (i.e., protected from) damage. Simulation work involved testing of existing systems to probe their vulnerabilities to radiation, to come up with approaches to harden future systems, and then to build and test experimental units and systems.

Pulsed Reactor Facility opened in 1961 in Area III, providing intense bursts of fast neutrons and gamma rays to use in radiation effects studies, in particular the effect of bursts and total doses of radiation on equipment.

In the early 1960s weapons scientists began to realize that gamma rays and a broad spectrum of radio frequencies (electromagnetic radiation caused by gamma rays) had the potential to harm the operation of weapons systems at long distance from the explosion.² As a consequence, the Department of Defense and the Atomic Energy Commission requested investigations of this phenomenon to ascertain where their electronic systems would fail. Thus, the weapons community and various Department of Defense agencies became very interested in the concept of high-current accelerators to generate x rays to simulate the effects of gamma rays. The unique aspect of weapons effects simulators was the requirement for very high dose rate over a relatively large volume compared to what could be produced with commercially available x-ray sources or government research accelerators.

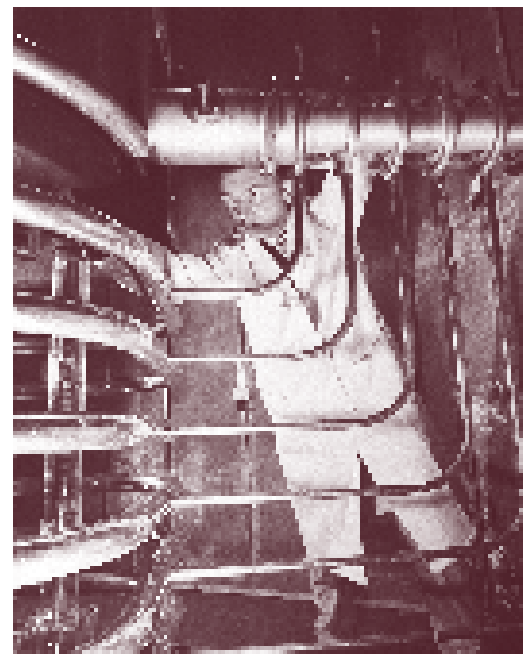
Because x rays are not as deeply penetrating as gamma rays, in the early days of weapons effects testing they were not considered to be of great importance for simulations. (In the literature, gamma rays and x rays are often not distinguished. Gamma rays are x rays at the high end of the radiation spectrum, but originate in the nucleus of the atom rather than in the surrounding electrons. Technically, gamma rays can be called x rays.) Some x-ray sources are high-voltage accelerators designed to produce an electron beam that bombards a metallic target. When the electrons are stopped in the target, a few percent of the kinetic energy of the beam is converted to x rays. The remainder of the energy heats the target. The x rays produced in this way are named Bremsstrahlung, a German term for braking radiation, because the x rays are formed by rapidly stopping the electron beam. If the electron beam is accelerated to energies in the 10 million electron volts to 15 million electron volts range, the Bremsstrahlung emission gives a good simulation of some weapons effects.

Field Emission Corporation was founded in 1958 to develop and market x-ray sources for commercial radiography and beam physics research studies. These devices, known as Febetrons, were high-impedance pulsed power sources that produced 30-nanosecond pulses up to 2.3 megavolts driving unique x-ray tubes that produced about two rads at one meter. Sandia purchased one of their first high-voltage machines. A.W. "Bill" Snyder, head of radiation effects then, said there was suddenly a huge market in the United States for these machines.³ Sandia started to develop pulsed power sources at the same time it acquired the Febetron, exploring in the laboratory how to build better radiation simulators. A machine called the cable pulser was the result, an effort that dates to the early 1960s. Researchers realized that the machine would not be able to produce adequate Bremsstrahlung x-ray intensities and dose rates over a large enough area to simulate gamma rays, and they began to look for a better way to produce the high voltage with the power needed.



Unidentified Sandia researcher and Van de Graaff accelerator (Sandia Lab News, March 1, 1961).

Ion beam passes from high-voltage stack of Cockcroft-Walton accelerator through horizontal accelerating tube (pictured is R.E. Ewing) to work area outside of screened room where any of seven portholes may be used at different experiment locations. (Story appeared in Sandia Lab News, March 17, 1961)



The Cable Pulser

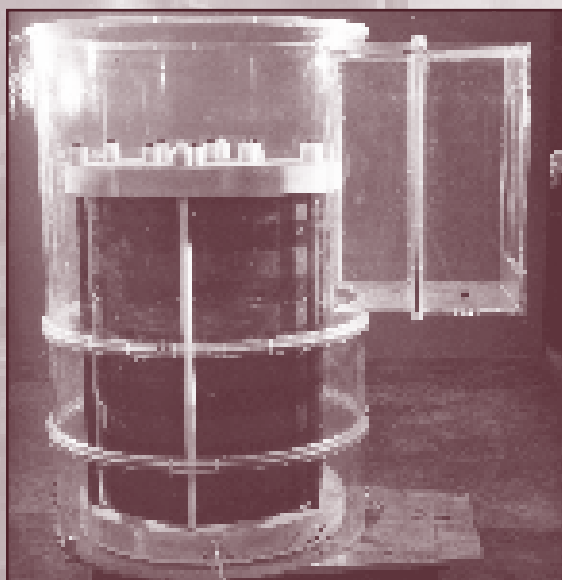
Ray Clark began his long career in pulsed power at Sandia working on a machine that never got a name and was simply known as “the cable pulser.” Clark said this machine began pulsed power work at Sandia, although many consider Spastic, which has a different design and is slightly later, to merit this honor.

The cable pulser was the responsibility of Chuck (C.F.) Martin, a staff member and project leader in S.C. “Clay” Rogers’ organization. Chuck Martin’s goal was to build a bigger, state-of-the-art machine like the Field Emission Corporation’s Febetron but producing 2 million volts and having a specialized tube to use in weapons hardening experiments. Clark was hired at Sandia to help Chuck Martin, and together they built the cable pulser. Clark recalled that “it never reached its full potential; it was a research project to build it.”

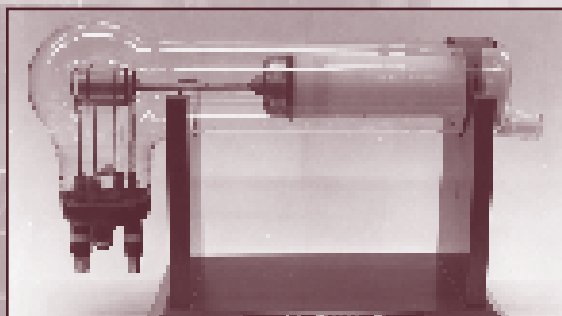
One problem with the cable pulser as Clark recalls it was trying to epoxy the cables so they would not break down under high voltage. In fact, recounting a memory of the early days of the Pulsed Power Program at Sandia for the *Sandia Lab News* of April 12, 1985, A.W. (Bill) Snyder remembered that as soon as the shot button was pushed, “vast quantities of molten copper spewed out on the floor.” The observers at the test had to scatter—and one of them was George Dacey, the vice-president for research at that time.

Clark and Chuck Martin also developed a new x-ray output tube, but never got to test it. Clark remembers the tubes then being hot cathode tubes made of glass that had to be heated.

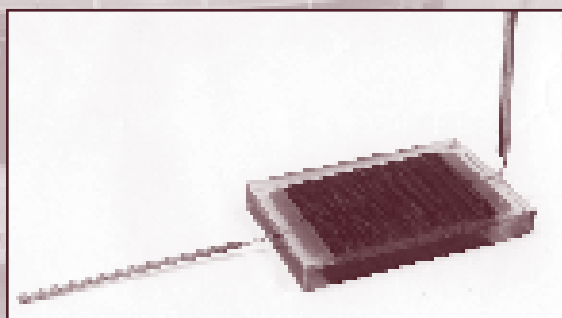
[Sources: Van Arsdaal interview with Ray Clark; interview with A.W. Snyder; box of materials donated by Clark to Sandia archives containing material on this subject.]



The cable pulser



X-ray tube



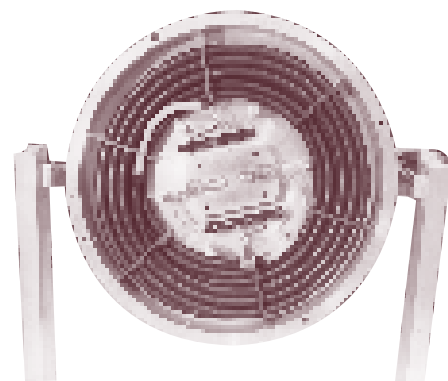
Early dummy load for the cable pulser

The requirement for high dose rate and the 15-megavolt limit meant high-current beams (100s-1000s kiloamps) and a pulse duration less than 100 billionths of a second were needed. Technology to satisfy these beam requirements was not available at this time, and as a result, Sandia and private companies interested in developing simulators for Department of Defense agencies began to seek new approaches. One interesting approach was being developed in Great Britain by a group headed by J.C. "Charlie" Martin⁴ at the Atomic Weapons Research Establishment (AWRE), Aldermaston. This group was exploring unique ways to create high-voltage, high-current pulses and new techniques to convert these pulses to high-current electron beams with short pulse duration. Such a technology was needed to make the high x-ray dose rates required to simulate gamma rays. The work at AWRE was the start of what was later termed pulse power or pulsed power technology and pulsed power accelerators. Rapid advances with this technology and success with innovative ideas in the United States and England resulted soon after in weapons effects simulators and the technology for pursuing research on microfusion and other applications.⁵

From 1961 to early 1963, information about the initial flash of radiation from a nuclear explosion and the effects of x-ray radiation had been obtained from aboveground and underground tests of nuclear weapons, supplemented by laboratory simulations using reactors and accelerators at weapons laboratories such as Sandia. However, radioactive fallout from aboveground testing and renewed popular concern about the global effects of radiation from weapons tests by an increasing number of countries led to a Limited Test Ban Treaty being signed in August 1963 by the United States, the United Kingdom, and the USSR. The treaty prohibited testing of nuclear devices in the atmosphere, in outer space, and underwater.

With full-scale aboveground tests no longer possible, weapons effects work would henceforth be laboratory simulations, supplemented by underground testing. Nuclear detonations produce a spectrum of radiation and radiation effects, so the machines used to emulate them had to be capable of producing similar spectra. Sandia and other weapons laboratories as well as private industry began a stepped-up effort to develop machines capable of producing the effects needed to understand how to harden US weapons absent any aboveground testing.

In 1963, Sandia began to investigate the work Charlie Martin and his group were doing at AWRE. The highest energy, highest dose machine they had developed was called SMOG, said to stand for "Six Megavolts or Good-Bye." (However, SMOG produced 4 megavolts and they did not give up.) AWRE needed flash x-ray radiography, but could not afford the enormous sums Los Alamos had spent for this purpose on PHERMEX, a linear electron accelerator built for flash radiographic studies of explosively driven metal systems such as imploding nuclear weapons. Built in 1957, the Pulsed High Energy Radiation Machine Emitting X Rays



Cable Pulser

(PHERMEX) at Los Alamos represented a unique—and expensive—diagnostics capability in flash radiography at the time.⁶ The AWRE pulsed power radiography approach was less expensive than PHERMEX technology, and used lower energy, higher current electron beams. The lower voltage, higher current aspect promised to better satisfy simulation requirements. These positive aspects factored into Sandia's decision to try to adopt the new pulsed power technology.

Collaboration with AWRE was enabled by the Mutual Defense Agreement of 1958, which provided the basis for extensive nuclear collaboration between the United States and Britain. The agreement permitted the two countries to exchange classified information to improve their atomic weapons capability. As a result, a number of Joint Operations Working Groups (JOWOGs) were formed with the Atomic Energy Commission labs, primarily involving AWRE and Sandia, Los Alamos, and Livermore in topical areas. AWRE had a different structure than the weapons labs here. Whereas Sandia designed and developed the non-nuclear parts of nuclear weapons, and Los Alamos and Livermore the nuclear side, AWRE, on the contrary, had responsibility for complete weapons systems.

Ken Haynes, a reactor specialist in Snyder's group, went with several other engineers to AWRE in 1963 and 1964 to learn their technology. The contact with Martin's work convinced Sandia's staff that, with the help of Charlie Martin and his UK engineers, they could build a machine similar to SMOG to do the experiments needed for radiation hardening. Sandia had been weighing the merits of purchasing a pulsed power machine from Ion Physics or Physics International, firms that were having mixed results with their initial attempts at fabricating high-energy machines to generate x rays. Instead, Sandia opted to sign an agreement with AWRE to build a machine to create a large x-ray output.⁷

Tommy Storr and Ian Smith came over from the UK to work with Haynes in Area V in the basement of the reactor building where they built Spastic, Sandia's version of SMOG. Because of Sandia's interest in studying radiation effects using extremely high doses of Bremsstrahlung, the primary reason for building Spastic was to simulate gamma radiation. Using high doses of x rays from the machine, transient radiation effects on electrical components, electronic circuits, and systems could be analyzed. Snyder thought Spastic stood for "Sandia Pulsed Aqueous Solution Transit Irradiation Source something or other—a contrived name of some kind," but others say the name described the way it worked. (Please see following sidebar on Spastic.)

The *Sandia Lab News* of January 15, 1965, reported "Sandia Laboratory Team Develops New Flash-X Ray Machine—World's Largest," though in the story the machine remains nameless. Haynes is listed as project leader with Ray Clark and Paul Beeson as his team, and the success is attributed to international cooperation that began the previous April in England. The cooperation culminated in the first test of the device in November 1964. When it was first fired, Haynes told the *Sandia*

Pulsed Power

In the early days, this technology was often called 'pulse power' instead of pulsed power. Both names reflect the essential technical concept, which is taking a pulse of electrical energy and shortening its duration to increase its power, summed up in the equation $\text{Power} = \text{Energy}/\text{Time}$. In a pulsed power machine, low power electrical energy from a wall plug is stored in a bank of capacitors and leaves them as a compressed pulse of power. The duration of the pulse is increasingly shortened until it is only billionths of a second long. With each shortening of the pulse, the power increases. The final result is a very short pulse with enormous power, whose energy can be released in several ways.

The original intent of this technology was to use the pulse to simulate the bursts of radiation from exploding nuclear weapons. Because of their intended use, these pulses are far beyond everyday requirements. In fact, they involve great amounts of electricity, at first megawatts, currently tens of terawatts. In the decades since their creation in the 1950s, the available power from these machines has increased dramatically and their uses have expanded beyond weapons effects simulation. Below is a schematic of the initial concept for pulsed power accelerators, which has been the basis for many Sandia machines and test beds.

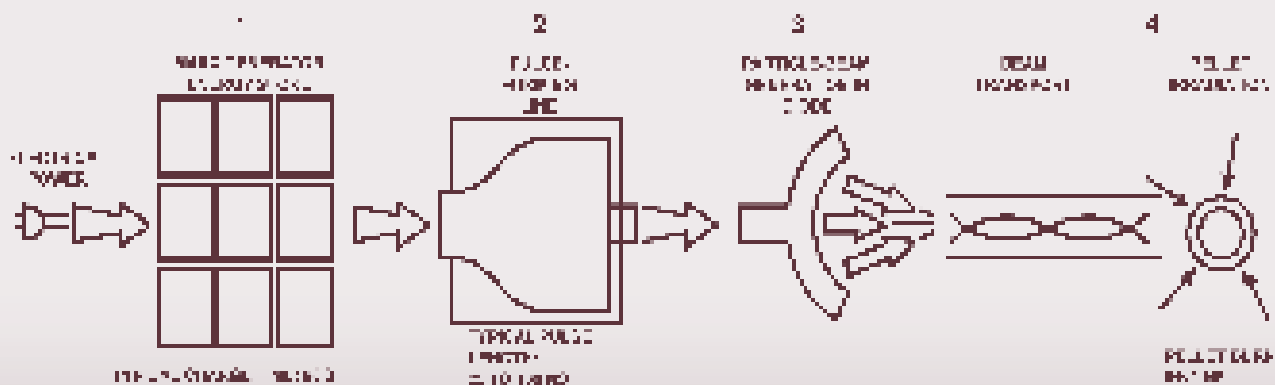
The process of energy compression begins with electrical power being stored in **Marx generators**, which are banks of capacitors similar in purpose to batteries. (Professor Erwin Marx, d. 1980, invented this kind of generator in Germany in 1928.) The capacitors are charged in parallel and are then discharged in series. To give an idea of the scale, the Marx compresses the charge in 100 seconds and discharges in a microsecond, representing a 10^8 pulse compression. The energy flows through sparks

across switches, charging **pulse-forming lines** (Blumleins or coax lines). Blumleins are essentially voltage multipliers designed to accommodate pulses of power. (The configuration was invented by British engineer Alan D. Blumlein for radar systems in 1940-41. Blumlein was killed in an air crash in 1942.)

The compressed energy is then switched into **transmission lines**, insulated using oil or water. In the early days, the transmission lines brought the energy to a vacuum x-ray tube containing a cathode and an anode, where a beam of electrons was produced. This beam was aimed at a tantalum target and when the beam hit the target, a sub-microsecond burst of Bremsstrahlung ensued, which then could be used to simulate gamma rays.

In later machines, the transmission lines were connected to a **diode** consisting of two parts with opposite charges, the positive anode and negative cathode. The diode emits particles; at Sandia they were originally electrons, later protons, and other ions. One goal was to have a **stable beam** leaving the cathode or the anode and continuing toward the target. The entire process happened in a hundred nanoseconds, or the time it takes light to travel about 30 m. Over the years, the diode configuration was a matter of continued experimentation because of its importance. Sandia demonstrated that the goal of focusing a beam on a target using tens of megamps was complex but possible.

[Sources: T.H. Martin, A.H. Guenther, M. Kristiansen, and J.C. Martin, *On Pulsed Power*, *Advances in Pulsed Power Technology*, Vol. 3, New York: Plenum Press, 1996; K.H. Prestwich, "Electron and Ion Beam Accelerators," *AIP Conference Proceedings* 249, Vol. 2; *The Physics of Particle Accelerators*, New York: American Institute of Physics, 1992; Dan Jobe, Ktech Corporation, Albuquerque, "Introduction to Pulsed Power," notebook of materials on Pulsed Power for an internal Sandia class, October 2003; interviews with Tom Martin and Ken Prestwich.]



Spastic

Built by Sandia in 1965 and based on the UK's SMOG, Spastic was designed for gamma-ray output to simulate the effects of the electromagnetic pulse created by a nuclear explosion. Under guidance from UK engineers Tommy Storr and Ian Smith, Spastic was assembled and tested in three weeks at Sandia.^a Ken Haynes, the project leader, told the *Sandia Lab News* at the time that Spastic would be used to study transient radiation effects on electrical components. He said, because of its huge output dose, it would be useful for testing large electronic circuits and systems. Haynes said they had hoped for an output of 12 rads (units of absorbed radiation) from Spastic, but got 20. By adding more strip lines and power, the team was hoping eventually for 50 rads output.^b Initially, Haynes was supported by one technician, Ray Clark, and then a second technician, P.M. Beeson, was added.

In Spastic, a 20-kilojoule capacitor bank provided the energy for the flash x-ray pulse, charging the generator in 2.5 microseconds. The generator was then fired to produce a high-voltage pulse at an x-ray tube. The generator section was composed of 23 strip transmission lines made of thin strips of copper separated by polyethylene and submerged in a tank of demineralized water. The strip lines were 3 m long and 66 cm wide. The tank that held the generator was 107 cm wide, 112 cm deep, and 4.2 m long. Its walls were made of hollow fiberglass filled with freon gas, to add dielectric strength.

Ray Clark, who worked on Spastic, said that the important innovations made by AWRE included demountable Lucite-insulated vacuum envelopes, and diodes with cold cathodes so the vacuum tube did not have to include heating elements. No oscilloscopes were made then that could easily withstand

the electromagnetic noise generated by Spastic and measure its output, so Sandia built its own based on Charlie Martin's advice on how to do so. Clark designed a cathode ray tube and had a vacuum tube manufacturer named Dumont make it for Sandia. Because of the high electromagnetic radiation from the machine, Sandia built its oscilloscopes in a copper box and put the copper boxes in a copper-screen room. This double screen isolated the tube from Spastic's electromagnetic radiation "noise"—at the time, there had never before been such high energy transferred in so short a time.

Ordinary resistors would not work in this kind of machine because of the large amount of energy involved, and Sandia used and improved liquid resistors in Spastic. The machine worked by building up a 200-kilovolt charge voltage on the 23 Blumleins, incorporating a solid dielectric switch on every Blumlein, and when the voltage got to a certain point triggering all the switches and optimally releasing the energy in a 30-nanosecond pulse at the 4.5 megavolts generated by connecting all the Blumleins in series. All the switches had to be changed after each shot, and everything was immersed in a copper sulfate solution. So even though the machine provided the desired high voltages and currents, it was cumbersome to operate. Based on the experience with Spastic, Sandia adopted oil-filled Blumleins for its next gamma ray simulators.

[Sources: Box 13, Martin-Prestwich Collection, Sandia Archives. For details on Spastic and its immediate successors, see the undated memo from S.C. Rogers to T.B. Cook and A.W. Snyder, Re: Tentative Plans for Constructing a Large X-Ray Generator, ca. February 1965, copy in Van Arsdall collection 1950s-60s. For technical detail, see Charlie Martin's notes on SMOG in Box 19 of Martin-Prestwich collection. See Van Arsdall interviews with Ray Clark and Tom Martin and comments from Ian Smith in 2006.]

- a In 2006, Ian Smith recalled that AWRE pre-tested materials Sandia sent to England, even glue, to make sure the Sandia materials were in no way different from those used in SMOG. Smith set up a 1-megavolt pulse transformer in the Spastic lab so Sandia could do similar testing. The author is grateful to Smith for his help with this sidebar.
- b Sandia Lab News, January 15, 1965, "Sandia Laboratory Team Develops New Flash X-Ray Machine—World's Largest."

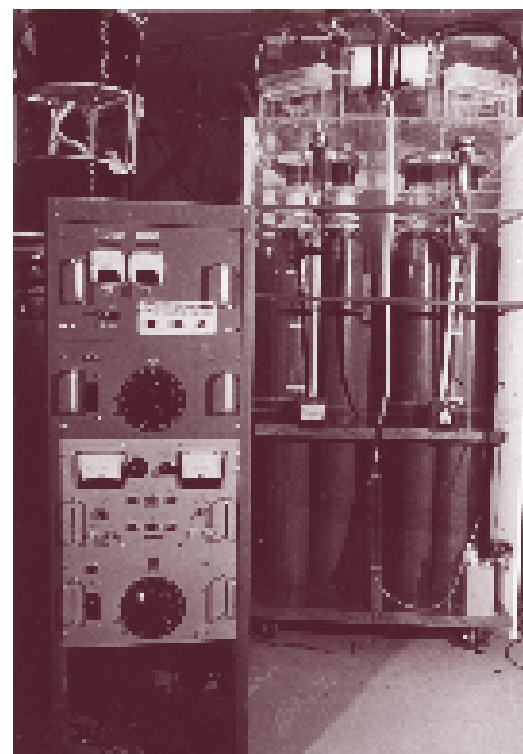
Oscilloscope built for pulsed power at Sandia using Charlie Martin design.

Lab News, “There was this loud bang as the capacitors discharged, the water on the surface of the generator tank rippled, and we set the world’s record for output x-ray dose. Naturally we felt good.” Clark, too, a long-term member of the Pulsed Power Program, remembered the effects Spastic had on its surroundings. He said that it put out so much electromagnetic noise, when it went off phones rang and the lights went out, “but only when we made x rays—it did not happen if we were unsuccessful in making x rays.”⁸ Initially, the team hoped for an output of 12 rads from Spastic at a meter from the target, but even in its first few months, it was producing more than 20 rads.⁹

Haynes was a key man and had the advantage of being trained by Charlie Martin and his group, but for reasons that appear to be personal, Haynes left Sandia and the new pulsed power effort rather abruptly to work at White Sands on reactors. The untimely death of Ken Haynes, not long after, in a sports-car accident is a memory everyone from the early days carries with them. Also a universal memory is that Charlie Martin at AWRE was not particularly pleased with Sandia because Haynes left the Labs. Charlie had mentored and tutored Haynes specifically on the technology of the pulsed power machine at Sandia, and the two of them had worked on an initial concept for Hermes II. He expected the collaboration to endure.

The new Sandia group was able to re-establish a productive working relationship with the UK’s father of pulsed power, a relationship that was to flourish for decades afterward. Tom Martin was promoted to supervise a new Flash X Ray Research Division in the summer of 1965, responsible for the development of pulsed power sources.¹⁰ Tom Martin reported to Snyder, who had already obtained approval to start development of the next-generation gamma-ray simulator, later named Hermes II. Martin would remain with Sandia’s Pulsed Power Program during his long and successful career at the Labs. His name is associated with several of the ground-breaking accelerators created at Sandia, and for his achievements, he received the prestigious biennial IEEE Erwin Marx award in 1985. (Charlie Martin received this award in 1981, and Ian Smith was the 1983 recipient; Tom Martin was the first American-born researcher to receive it.)

The collaboration with AWRE to build Spastic was part of Sandia’s long-range decision to construct large, high-energy machines capable of generating x-ray dose levels closer to full weapons effects simulation than was then possible. Since Spastic was built, Physics International had developed more powerful machines using a new technology in which the megavolts needed were obtained in a single Marx, and self-healing oil provided the insulation, the dielectric, and the switch medium. Sandia recognized this as a much more practical approach to generating high-voltage pulses in repeated, routine operation. A competing technology at that time was based on a Van de Graff generator, which Ion Physics, a subsidiary of High Voltage Engineering, was pursuing. (High Voltage Engineering was the principal supplier of Van de Graff generators in the United States.) Sandia realized



Spastic charging supply, UK capacitors.

the technology used in Spastic was not suited to producing multiple shots, and a second-generation machine using oil-filled Blumleins was already envisioned when Tom Martin was put in charge of the new department. Sandia was not alone in this pursuit. Through the Air Force Weapons Laboratory, the Department of Defense/Defense Atomic Support Agency (DASA) was placing contracts with Physics International and Ion Physics for x-ray generators and studies of x-ray tubes, and the Ballistic Systems Division of the Air Force had placed a contract with Physics International for a 6-megavolt machine with an eye toward its being eventually capable of much more.¹¹ In addition, Sandia learned that the Air Force was very interested in developing neutron generators for simulation applications.

With the decision to build large flash x-ray machines, Sandia entered a competitive arena, one in which the Labs believed it could excel.¹² Sandia's second-generation pulsed x-ray machine was envisioned as delivering 1500 to 2000 units of absorbed radiation for the Atomic Energy Commission/Department of Military Applications. Because of technical considerations, attempting to build a machine that would produce more than 2000 units was considered risky. Tom Martin weighed the risks and decided not to build the new machine, by then called Hermes, for the designed output. A working model was built for scaling parameters, named Hermes I. It was one-tenth the desired energy and began operation in 1966. To accommodate the planned new machines, a large warehouse was built in Area V: a high-bay, metal-sided Butler Building, with no insulation.¹³ Sandia tried unsuccessfully to get Congressional line-item funding for the initial Hermes effort and finally had to improvise to build the machine. Obtaining used capacitors from a cancelled program in the UK was one way to shave some costs. Somewhat ironically in view of the future course of pulsed power at Sandia, the capacitors came from a fusion program that had been abandoned because it was believed doomed to failure. Because of their low cost, Sandia was able to use as many capacitors in Hermes II as the machine could hold, and the extra capacitors enabled advances at Sandia that later played into its fusion work.¹⁴

When it was obvious that the performance of Hermes I was acceptable, work began in August 1967 on building the full-size Hermes II in Area V with a budget of \$900,000. It was test-fired in the summer of 1968, and the *Sandia Lab News* of July 26 reported the initial shot, saying it paved the way for producing "unprecedented radiation sources." The initial test was designed to discharge 500,000 joules of electrical energy into a target in a 10-million-volt, 100-nanosecond pulse. The maximum capacity of Hermes II when fully operational was one million joules. Hermes II was at one time the largest flash x-ray machine in operation anywhere, a record accomplished by increasing the voltage usually obtainable in Marx generators from 4 megavolts to nominally 12 megavolts. Based on information from Hermes II, Sandia estimated that even higher voltage Marx generators could be built. (Please see following sidebar on Hermes I and II.)

At the same time Sandia was designing the higher voltage Hermes machines for the Atomic Energy Commission, the Department of Defense was funding Physics International and Ion Physics Corporation to build similar machines at the Air Force Weapons Laboratory at Kirtland Air Force Base, Albuquerque, next door to Sandia. All these machines were scheduled to be completed at about the same time, and Sandians who worked on Hermes remember competition to see who would test-fire the first successful gamma-ray simulator. Hermes II and the Physics International 1590 machine, using a design similar to Hermes III, were neck and neck.¹⁵ Based on a Van de Graaff accelerator rather than the Marx generator principle, the Ion Physics machine was successful in producing high-power pulses, but well below specifications. (Other Van De Graaff machines performed well for decades, for example at the Air Force Weapons Lab, at Harry Diamond Labs, and at Boeing.)

Competition between the nuclear sides of the Department of Defense and Atomic Energy Commission began to heat up at this time, because both agencies were interested in using laboratories like Sandia or private contractors to build machines for similar weapons effects studies. For example, about this time the Defense Department requested proposals for a 50,000 rads at a meter machine that would provide rather uniform dose over a one-meter cube volume. After several iterations on possible designs, including proposals by Physics International and Ion Physics and concepts by Charlie Martin and Tom Martin, the Department of Defense awarded Physics International a one-year research and development program to assess the technology and finalize the conceptual design. The successful Physics International proposal was headed by Ian Smith, and a contract was awarded to build an extremely large accelerator named Aurora in a facility to be located at Harry Diamond Laboratories in Silver Spring, Maryland.¹⁶ Tom Martin likened its capabilities to four Hermes II machines in one.¹⁷ The advantage Aurora had was its ability to test large-sized flight packages. Aurora represented the continuing rapid advance of this technology after the successful development of Hermes II and the Physics International 1590 at the Air Force Weapons Laboratory. With facilities for this work becoming larger and more expensive, Congress was beginning to put the weapons programs of both agencies under increasing scrutiny. The key was to be able to demonstrate—or argue persuasively—that one approach made more sense than another and merited funding.

With Hermes II up and running, the Marx generator from Hermes I was then used as the heart of a new machine, the Relativistic Electron Beam Accelerator (REBA). (Please see following sidebar on REBA.) REBA was built in Area V inside a new test facility specifically to study the properties of materials used in weapons systems and the propagation of electron beams. This machine was also used to explore the possibility of using de-ionized water instead of oil as insulation in the transmission lines. REBA began testing in November 1969 and was fully operational soon afterward, with David L. Johnson as project lead, assisted by Don Butel, Ken Prestwich,



Sandia's pulsed power research began with simulations of effects on weapons. In this 1979 photograph, Sandians prepare to test the effects of gamma rays on an experimental army armored vehicle by using the Hermes II accelerator (barrel-like structure in the right-hand corner).

Hermes I and II

Hermes I and II were x-ray machines designed to simulate the flash of gamma radiation from a nuclear explosion. At the time it was built, Hermes II produced more radiation than any similar machine in the United States. Hermes I was a prototype for Hermes II and was one-tenth its size (3 megavolts, 50 kiloamps, 50 nanoseconds), beginning operation in 1966. It was converted to generating x rays instead of gamma rays in 1968 when Hermes II was completed. The Marx generator from Hermes I was then used in the Relativistic Electron Beam Accelerator (REBA), which went on line in 1969.

Hermes I and II were built using low-inductance Marx generators, Blumlein transmission lines, and a vacuum tube where the electron beam was formed and accelerated. In Hermes II, its high-voltage portions were submerged in 150,000 gal. of transformer oil for insulation, enough to fill 12 railroad tank cars. It was housed in a bottle-shaped steel tank 26 m long and 6.7 m wide, which Eidson Metal Products on Edith Boulevard in Albuquerque welded together for Sandia. (Eidson usually made large water tanks.) Heavy concrete blocks provided shielding for the machine.

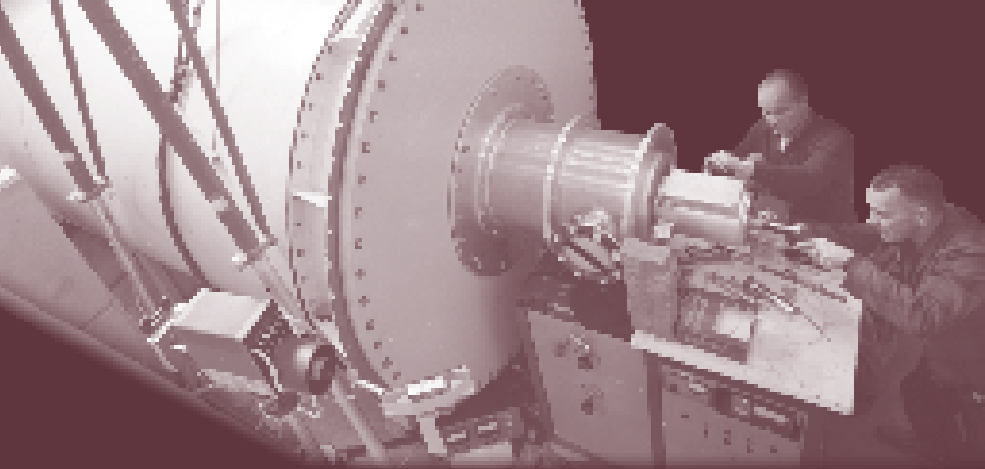
Operation of Hermes machines. First the capacitors are charged in parallel with electrical energy (in Hermes II, there were 186 100-kilovolt capacitors). Next, the capacitors are switched and discharged in series into the Blumlein transmission line, a voltage multiplier made of three steel cylinders. Finally, a switch (spark gap) is triggered and the energy from the Blumlein transmission line is discharged in an x-ray tube made of Lucite, where a high-current beam of electrons is produced. The high-energy beam is directed at a metallic target. X rays are produced by Bremsstrahlung when the electrons interact with the atoms in the target. The resulting burst of radiation lasts 70 billionths of a second.

Hermes II was used for many years. The *Sandia Lab News* of September 13, 1974, reported its 10,000th shot and called Hermes II “the largest and longest-lived facility of its kind in the world.” Hermes II had an original design life of 1,000 shots. More than 10 years later, the ‘workhorse’ was still going. In a May 10, 1985, story, the *Lab News* reported that Hermes II had fired its 25,000th shot and was booked solid for use out through 1991. The only major renovations over the years were rebuilding the 10-megavolt Marx generator in 1981, redoing the tank that stores the 150,000 gal. of mineral oil used as the dielectric in 1985, and overhauling the data acquisition system in 1988.

Even as its successor, Hermes III was being completed, Hermes II was fired for the 30,000th time, at 6:30 p.m.

July 5, 1988, as upper management watched and cheered. International phone calls reported “the shot heard round the world,” as the *Sandia Lab News*, July 15, 1988, called it. By this time, Hermes II was being operated in Area V by the Simulation Technology Department, a sister organization to Pulsed Power, because its primary mission was still producing gamma rays for weapons simulation. It was also being used in the directed-energy-weapon program to





HERMES I, a one-tenth scale model of HERMES II, was built to help solve the complex problems involved in creating the world's largest flash x-ray generator. The model is now a useful device in Sandia's radiation effects program. Jim Maxim, left, and Ralph Schellenbaum operate the machine. (Image appeared in Sandia Lab News Vol. 20, No. 15, Pg. 2, 26 July 1968)

test whether high-energy, high-current electron beams can initiate explosives (they can). Estimates at the time of the milestone shot were that Hermes II had averaged six shots a day every working day for two decades. The final shot on Hermes II was December 22, 1989, and Tom Martin and Ken Prestwich were there as the shot fired. The two men designed and helped build Hermes II. The *Sandia Lab News* marked the event with a photo in the January 12, 1990, issue.

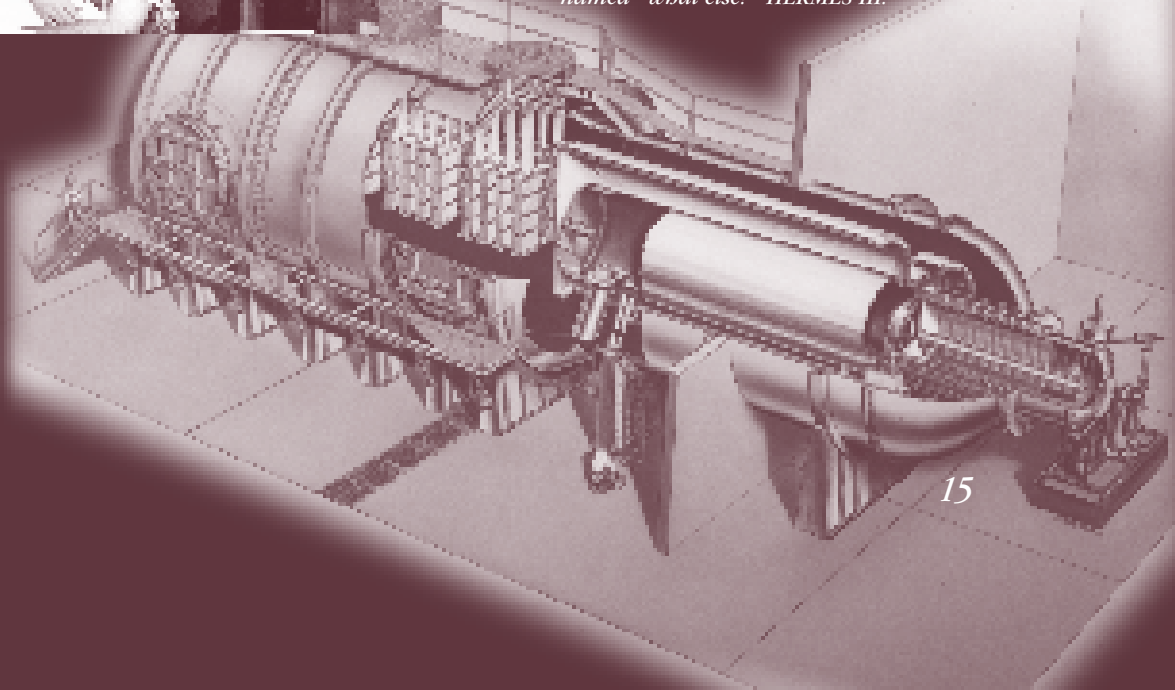
The Hermes project included Tom Martin, Ken Prestwich, Ray Clark, Paul Beeson, David L. Johnson, Don Butel and J.E. Boers.

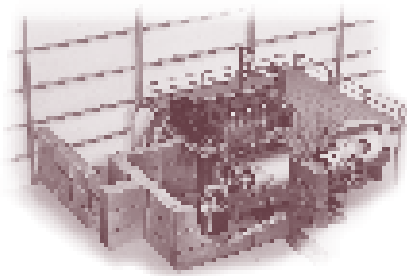
[Papers of interest include T.H. Martin, "Design and Performance of the Sandia Laboratories Hermes II Flash X Ray Generator," *IEEE Transactions of Nuclear Science* 16(3), June 1969:59-63; K.R. Prestwich and D.L. Johnson, "Development of an 18-Megavolt Marx Generator," *Ibid.*:64-69; T.H. Martin, K.R. Prestwich, D.L. Johnson, Summary of the Hermes Flash X Ray Program," Sandia National Laboratories report SC-RR-69-421, October 1969; "Giant Flash X Ray Machine Test Fired," *Sandia Lab News*, July 26, 1968.]



"Final Pop" - After more than 30,000 "shots," Sandia's HERMES II gamma-ray simulator was fired for the final time on December 22, 1989. The facility was used to test hundreds of weapon and space-system components during its 20-year life. Preparing for the final loud pop are (standing, from left) Ken Prestwich, manager of Pulsed Power Applications Dept. 1240; Tom Martin, research scientist of Pulsed Power Dept. 1290; and Jerry Zawadzka, supervisor of STL Operations Division 9343. Seated at the control console is Gary Devlin (contractor). Ken and Tom designed and helped build HERMES II in the late '60's. Sandia's gamma-ray simulation work is now done on a newer machine named - what else? - HERMES III.

HERMES II





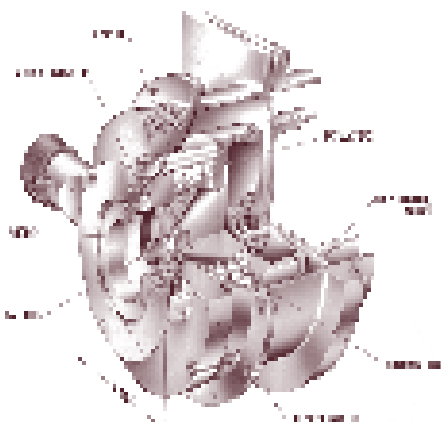
REBA

and Ray Clark, all of them in Tom Martin's department. Johnson had joined Snyder's group a few years earlier as a student and he would remain a key person in developing accelerators in the Pulsed Power Program for decades. Ken Prestwich became part of Tom Martin's group in 1965 as the first staff member in the new department. Within a few years, Martin and Prestwich were synonymous with pulsed power at Sandia. Prestwich would win the Erwin Marx award in 1989, and both men are recognized not only as pillars of the Sandia program but also of international pulsed power technology. (See sidebar on REBA.)

Toward the end of the 1960s, in the wake of the Test Ban Treaty, the military began to ask for machines capable of simulating the spectrum of x rays at frequencies below gamma rays. The technology was different from Hermes II, requiring low voltage and high current. As a result, Prestwich and a team were asked to design an electron-beam accelerator to provide low-energy x-ray simulations to deposit the energy on the outside of weapons components (instead of using high energies that would penetrate them). The result was a desk-sized device called Nereus, with an adjustable pulse length. Nereus was Sandia's first machine designed specifically for water transmission lines, hence its being named for a sea god. The machine proved to be extremely popular because of its relatively small size and versatility. Besides satisfying early Sandia requirements and being useful for about 30 years, Nereus-type machines went to such diverse locations as the Massachusetts Institute of Technology, the Weizmann Institute in Israel, Los Alamos Laboratory, and the University of Illinois.

Water insulation in the Nereus transmission lines provided the characteristics required in these lower voltage devices. For this reason, water lines would be an advancement used in future Sandia machines. Based on the success with Nereus, Tom Martin began working on the design of a bigger water-insulated machine that would produce two electron beams simultaneously and combine them to increase the available energy at the target. The Hydra accelerator was the result, a Martin design featuring two lines and simultaneous gas switching. Martin worked with Johnson, Ray Kline, and Johann Seamen to build the 1-megavolt, 1-megamp Hydra. (Seamen remains a contributor to Sandia's Pulsed Power Program.) At one time, Hydra was envisioned as having as many as nine beams for large-volume irradiations and more energy density at the target, a concept the Department of Defense was funding on large machines elsewhere, such as Casino at the Naval Surface Weapons Center.¹⁸ Named for a sea monster with several heads, Hydra came on line in 1972.

Following the cautious approach it had taken with Hermes, Sandia built one module of Hydra with two beams to see how the beam-combining idea would work. At the same time, Prestwich was tasked with creating a machine to investigate beam drifting and recombining. The outcome was SLIM (Sandia Low-Impedance Mylar-insulated accelerator). Both SLIM and Hydra were operated as test beds to



NEREUS DIODE

REBA: Stand-Off and Self-Pinch Effect

The Relativistic Electron Beam Accelerator (REBA) could be operated in two modes: as a flash x-ray machine to create gamma rays or to produce a high-current electron beam. It began operation in 1969, and was built using the Marx generator from Hermes I. Its high-current electron beams were the primary interest for experimenters. The beams were used to directly bombard a target, simulating the x-ray deposition from a nuclear explosion. Two issues complicated the proposed technology. One was that the current had to be increased dramatically to obtain the desired simulations, and the other, which was related to it, was how to get the high-current beam from the diode and into the target without blowing the machine up in the process. The problem was to get the beam to propagate through the gas in the diode and keep its energy as it traveled to a target positioned away from the machine that had created it. Such a phenomenon is called stand-off. (Tom Martin likened the lack of stand-off to setting a fire-cracker off on the end of one's nose.)

Sandia was one of several laboratories investigating these issues in the late 1960s and early 1970s on a variety of accelerators. In the course of investigating stand-off on its Gamble I and II accelerators, the Naval Research Lab discovered an effect that allowed the electron beam to exit the diode and propagate a fair distance. The effect is self-pinching, in which the beam is affected in the diode by its own magnetic field and self-pinches in the gap between the anode and cathode. This pinch self-focuses the beam and gives it high enough intensity to exit the diode and propagate beyond it.^a Discovering the self-pinching phenomenon enabled a new generation of much more powerful accelerators to be envisioned, with relatively low voltages (ca. 1 megavolt) and currents about 10 times higher than before, or more than a million amperes. There was now theoretically no limit to the size of the 'bang' emerging from the diode because it was not close to the machine that created it.

Sandia began to study beam propagation and self-pinching on REBA, and very soon, this self-pinch effect would enable Sandia to begin its fusion program. Work on REBA confirmed that a self-pinch effect would enable much higher energy to be deposited on the target and also that electron beams could be made to propagate a distance from the machine.

Configured to maximize the number of experiments that could be set up, REBA used the old Hermes I Marx generator to charge two Blumlein transmission lines aimed at two separate target areas. Both were shielded by heavy concrete. The generator had 38 100-kilovolt capacitors, and this bank of capacitors was stored in a 23,000-gal. tank of mineral oil. REBA had both an oil and a water transmission line, permitting dual use. Sandia had been considering water lines instead of the traditional oil-filled Blumleins, and REBA provided some of the experience that led to water lines being adopted. REBA was 8.5 m long and 7.3 m wide. The *Sandia Lab News* of November 7, 1969, reported that REBA produced a beam of electrons about 10 cm in diameter traveling at near the speed of light. The machine had an energy output of 3.25 megavolts at 50,000 amperes released in a pulse only 70 nanoseconds long.^b REBA's design permitted it to be used as a flash x-ray machine as well, though its primary mode of operation was to be electron beams.

In 1973, Pulsed Power's John Kelly used REBA to develop a generator that used a unique geometry to achieve a pinch in the beam, allowing the area of the beam to be concentrated by a factor of 10. Although certain problems limited its usefulness, it pointed the way toward approaches for future work in beam concentration. The Atomic Energy Commission patented the invention.^c

In conjunction with laser work that year, the *Sandia Lab News* reported that REBA used its intense beams of electrons to pulse a hydrogen fluoride laser to record energy levels. The power output from the laser was a 228-joule beam in a 55-nanosecond pulse, a power output of 4 billion watts, and 45 times more than that confirmed on any gas laser. While experimenting with electron beams for weapons effects simulations and for fusion, using these beams as a way to excite (or heat) large volumes of laser gases was for a time an important area of work in the Physical Research area at Sandia. The beams could excite the gas without forming arcs, a drawback of other means of excitation. High-energy electron beams were believed to be a promising means of exciting future high-energy gas lasers, and at that time, Sandia and Los Alamos were working together on certain ideas related to laser excitation using electron beams.^d

a A.E. Blaugrund and G. Cooperstein, NRL, Shyke A. Goldstein, University of Maryland, "Relativistic Electron Beam Pinch Formation Processes in Low Impedance Diodes," *Physics of Fluids*, October 1976. Copy in Box 11 of Martin-Prestwich collection; also see *Sandia Lab News* of April 12, 1985.

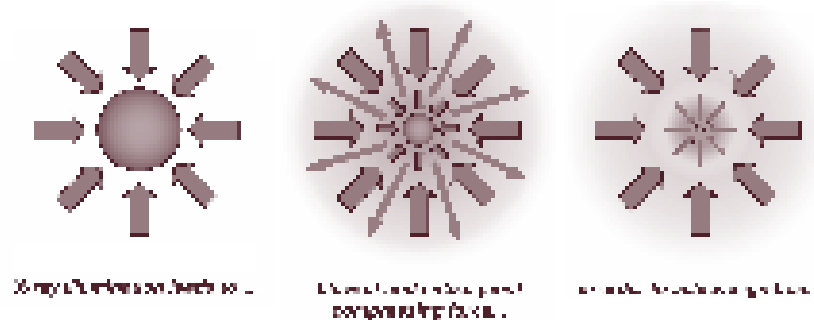
b *Sandia Lab News*, November 7, 1969, "REBA Gives Flash Performance: New Electron Accelerator."

c *Sandia Lab News*, November 16, 1973, "Kelly's Electron Beam Generator."

d *Sandia Lab News*, October 19, 1973, "HF Laser Pulsed to New Peak Power Level."

gain information before deciding on a next step. For accelerator developers like Sandia, the challenge was to achieve a combination of higher power levels and lower voltages than anything currently in existence to produce the radiation needed for weapons effects tests. Given the atmosphere of competition among Atomic Energy Commission and Department of Defense entities, the pressure was on. The outcome of work on SLIM and Hydra convinced Sandia not to build machines for beam combination, but to find a way to increase the power of an individual electron beam.¹⁹ (Please see following sidebar on Hydra and SLIM.)

In Hermes II, Sandia had the gamma-ray capability it needed. In the weapons community, the thrust now was to find a technology that could create x rays at a spectral frequency below gamma rays. The actual dose requirements for the x-ray and gamma-ray parts of the spectrum are not the same, and it is extremely difficult to satisfy the x-ray portion with an x-ray tube.²⁰ One approach, that taken initially at Sandia, was direct irradiation by electron beams, which requires high-current machines with low impedance. The second approach to achieving the broad spectrum of x rays needed for weapons effects simulations was nuclear fusion. This effect would emulate the environment created when a fusion device was detonated, but on a much smaller scale using a machine in the laboratory to make a fusion pellet implode.



Scientists at Lawrence Livermore Laboratory in California were making a strong case at this time to the Atomic Energy Commission to pursue inertial confinement fusion using the newly invented laser. Sandia had a modest laser program as well, some of it for fusion, and its electron-beam accelerators were used to drive the lasers for weapons applications. Two recent additions to Sandia's newly created research organization, Al Narath and Everet Beckner, realized Sandia's electron-beam accelerators might be used for fusion if the beams could be focused on a target and the high power density required to implode a fusion pellet could be achieved. Electron-beam technology, they knew, was much less expensive than lasers. In the 1960s, Narath and Beckner envisioned fusion as a new program at Sandia, one that would attract new staff and broaden Sandia's capabilities. The results of their vision emerged beginning in the 1970s, as outlined in chapter two.

As the 1960s ended and the subsequent decade began, the military and Congress became increasingly interested in using lasers for controlled thermonuclear fusion because of its interest to weapons physics and basic research. (Please see following sidebar on Lasers.) From a national standpoint, inertial confinement fusion might be developed as an inexhaustible source of energy that could be used in power plants. The nuclear weapons design laboratories, Lawrence Livermore and Los Alamos, were interested in fusion primarily from a weapons physics standpoint. If a high-yield fusion event on a microscale could be produced in the laboratory, it might yield a spectrum of radiation available only in underground tests; hence it was highly desirable. The development of lasers at Lawrence Livermore and Los Alamos was thus destined to intersect with Sandia's accelerator history in the decade to come.

Laser beams can be focused easily, but they do not have the energy of electron (and other particle) beams. Because of this, many laser beams have to be used to provide the energy that is in one particle beam. However, it is difficult to focus particle beams, a necessary step to getting the power on target needed to ignite fusion. For this reason, Sandia would later try different kinds of particle beams in its fusion work. Because of the many unknown and difficult aspects of the new accelerator technology Sandia was proposing, from the outset Livermore, Los Alamos, and sponsors at the Atomic Energy Commission considered it risky, even improbable for fusion. As a result, Sandia faced an uphill battle to get into the fusion game, and in the coming years, competition for successes and the related arguments for funds would become an integral part of the pulsed power story.

A report to the Congressional Joint Committee on Atomic Energy in the fall of 1971 outlined progress since 1967 in applying intense beams of relativistic electrons to controlled thermonuclear research (i.e., fusion research) and compared that approach to lasers. The report concluded that relativistic electron-beam accelerators “produce considerably greater energy than high-power lasers, operate at comparable power levels for longer duration, but cannot be focused with the same ease.”²¹ The joint committee report noted that little had been done in this country on relativistic electron-beam focusing, a remark that was to prove prophetic of a major challenge in years to come. The report contained this additional statement, also prophetic: “The possibility of compressing these intense energy sources in both space and time sufficiently to meet the criteria of igniting fusion in solid-state density plasmas presents a considerable challenge and will require significant innovative improvements in the state of the art.” ♦

Hydra

The Hydra electron beam accelerator was designed to simultaneously produce two 1-megavolt, 0.5-megampere, 80-nanosecond electron beams that could be combined to form a single beam. It consisted of a low-inductance Marx generator, two water-dielectric pulse-forming and impedance-transforming transmission lines, and two low-inductance, high-current diodes.

The generator was submerged in transformer oil and separated from the transmission line water by a Lucite interface. It charged each coaxial pulse-forming transmission line, which was deionized water insulated to 3 megavolts, in 0.9 microseconds. At peak voltage, a 3-megavolt SF_6 spark gap electrically connected the 4-ohm pulse-forming line to the impedance transformer transmission line. The pulse was transmitted through that line to the single radial insulator diode. A 30-kilojoule, 100-nanosecond duration electron beam was formed by a cold cathode in each diode.

The Marx tank was approximately 4.2 m wide, 6 m long, and 3.3 m deep. Attached to the Marx tank were two water-insulated coax

transmission lines 1.4 m in diameter and 1.4 m long. These lines were mounted to form a convergence angle between the two lines of 15 degrees. The transmission lines then tapered down for a distance of 2.4 m to the flat surface insulator diodes at the front of the machine. The angle of the lines allowed the two electron beams to be formed with a spacing and direction appropriate for combination and interaction experiments.

The 200-kilojoule Marx generator was composed of 62 stages of 0.7 microfarad, 100-kilovolt capacitors.

The outer diameter of the 137-cm-long pulse-forming line was 137 cm, and the diameter of the inner cylinder was 76 cm. With the water dielectric, these dimensions formed a pulse-forming line with 4-ohm output impedance and a nominal electrical length of 80 nanoseconds.

The SF_6 gas trigatron switch was housed in a plastic cylinder measuring 38 cm in length; 38 cm outer diameter, 30 cm inner diameter. The switch could be externally triggered, with

the trigger pulse transmitted through a copper sulfate resistor between the inner and outer cylinders of the transmission lines.

Between the SF_6 switch and the transmission line was a Lucite barrier that decoupled the back of the main SF_6 switch from the transmission line. Inside the barrier were six smaller self-breakdown SF_6 switches that fired shortly after the incident wave from the pulse-forming line arrived. These switches performed a dual function. First, the capacitive coupling from the pulse-forming line and the main SF_6 switch to the transmission line was greatly decreased. Thus, during charge of the coax line by the Marx generator, the voltage generated across the transmission line and the anode-cathode gap was greatly reduced. Second, the switches acted as open circuits immediately after the main SF_6 switch fired and reflected the low voltage portion of the rising wave front. This action effectively decreased the voltage and current rise times.

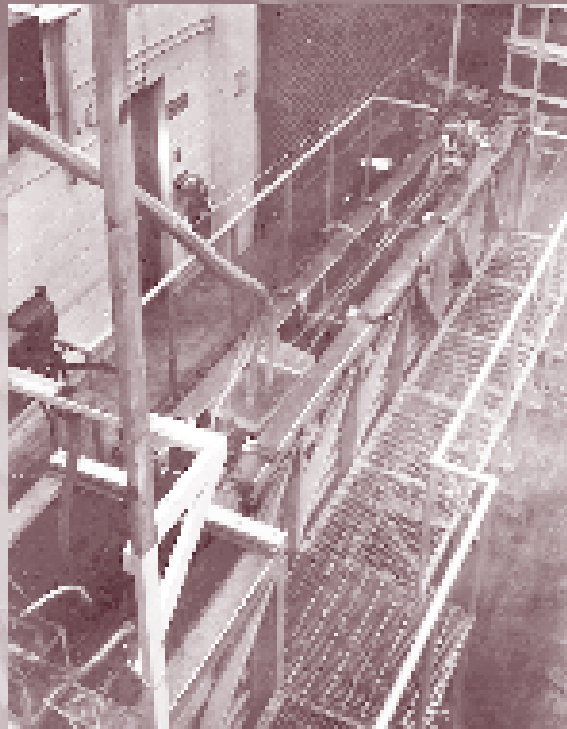
Because the transformer line was tapered, it acted as a short transformer line. In practice, the pulse amplitude could be calculated by assuming no transformer action. The transformer was tapered from an outer diameter of 111 cm to one of 81 cm at the end of the tube.

The diode had a flat disk Plexiglas insulator with a 91-cm outer diameter and a 25.4-cm inner diameter. The geometry was chosen for ease of cleaning and maintenance, and low inductance. This diode was similar to one developed at the Naval Research Laboratory. The cathode, located at the center of the tube insulator surface, could be readily changed.

The electron beam was formed in the anode-cathode gap and was extracted through a 0.5-mil mylar window. The beam could then be drifted externally to the machine.

The Hydra team included Tom Martin, Ray Kline, Dave Johnson, and Johann Seamen.

[From an undated conference paper (ca. 1971-72) by Tom Martin, "The Hydra Electron Beam Generator." Box 14 of the Martin-Prestwich collection at Sandia.]



SLIM

SLIM (Sandia Low-Impedance Mylar) was a related research and development program aimed at creating an electron-beam accelerator capable of producing several megamps of 300-400 kilovolt electrons in a 50-nanosecond pulse. Techniques for concentrating the beam in a small area were investigated as well, such as beam combination to obtain more density on target. The major components were a Marx generator, two mylar-insulated Blumleins, diode, and beam-handling apparatus.

The four-stage Marx generator was rated at 400 kilovolts, 60 kilojoules and was Freon-insulated. The charge leads between the Marx and Blumleins were 7 m long. The Blumlein tank was 2 m tall, 0.3 m wide, and 6 m long and made of wood. It was filled with copper sulfate during operation. The diode had 20 cathodes and the beam chamber indicated schematically the object of the beam experiments. The team working on SLIM included Ken Prestwich, Gerry Yonas, John Corley, Ray Clark, and David L. Johnson.

Lasers and the early inertial confinement fusion program

This history concentrates on the history of Sandia's pulsed power accelerators and their contribution to the field of its inertial confinement fusion, because in the end, such accelerators proved to be Sandia's strong point. A parallel story exists on laser fusion, but outside Sandia. The early growth of the laser fusion program is outlined here to give a national perspective to the Pulsed Power Program at Sandia. The trend begun in the 1960s continues to the present, with laser fusion dominating the national inertial confinement fusion program over the years.

In the early 1960s, Lawrence Livermore Laboratory indicated it had made calculations suggesting that thermonuclear reactions could be set off by intense light from a laser.* A small group was created at Livermore to carry out theoretical and experimental work on laser fusion, seen at that time as part of the weapons program. By 1967, Livermore was operating a 12-beam, spherically symmetric laser irradiation facility providing 20 joules of energy in 10 nanoseconds used in plasma-heating experiments. At the same time, the laboratory was developing what would be the forerunner of large disk lasers.

The goal for laser fusion systems (the same as for particle beam fusion) was to produce more energy from the fusion pellet than is delivered to the pellet.

In 1966, a laser program was established at Sandia as part of its weapons effects simulation work. Sandia built a neodymium-glass laser system that produced intense, very short laser pulses, which were applied to laser-target interaction experiments. In 1969, the system produced neutrons from a lithium deuteride target. These were the first laser-produced neutrons in the United States. (The results confirmed research reported by N.G. Basov at the Soviet's Lebedev Institute.)

Los Alamos began its laser program in 1969, and developed electron-beam-stabilized, large-aperture CO₂ lasers. Research centered on the physics of laser-plasma interactions and laser-induced implosions of fusion pellets.

Laser fusion research funded through the Atomic Energy Commission increased from about 30 people at Livermore in the early 1960s to 570 at the three nuclear weapons laboratories by mid-1974.

In addition to the Atomic Energy Commission laboratories, other organizations in the United States began doing laser fusion research in these early years.

KMS Fusion began as KMS Industries (KMSI), developing laser fusion technologies for peaceful purposes. KMSI later established KMS Fusion for laser fusion research generally, some of it classified for weapons. KMS Fusion built a two-beam target irradiation facility using a neodymium-glass laser. The Atomic Energy Commission permitted KMS to do the work under a no-cost contract.

The Laboratory for Laser Energetics (LLE), part of the University of Rochester, developed a four-beam neodymium-glass laser system designed to demonstrate laser fusion energy gain. Funding was from an industrial-university-state consortium.

Naval Research Laboratory/Plasma Physics Division was funded by the Atomic Energy Commission and the Department of Defense. The Naval Research Laboratory used a neodymium-glass laser system primarily for the detailed physics of certain aspects of laser-matter interactions.

Research at the Battelle Memorial Institute/Electromagnetic and Plasma Physics Section was funded by the Department of Defense and Battelle. The program aimed at a break even in energy. Its laser system had six beams of neodymium-glass laser amplifiers. Most experiments used metallic targets to enhance the conversion of laser light to x rays.^a

Between 1973 and 1982, a significant laser program was funded at Sandia. (The origins of the laser program go back to 1966.) In a quest for more efficient lasers that would be needed in a laser-driven inertial confinement fusion reactor, the Atomic Energy Commission/Department of Military Applications funded an advanced laser research program, with some of it at Sandia. In the early 1980s, laser activities were transitioned into laser-triggered switching and ion source research and the laser program diminished in size as the particle beam fusion effort grew in importance.

* Laser means "light amplification by stimulated emission of radiation." A laser converts input power into a narrow, intense beam of light. The input power excites the atoms of an optical resonator to a higher energy level, and the resonator forces the excited atoms to radiate in phase. (McGraw-Hill Dictionary of Scientific and Technical Terms, fourth edition)

a AEC. "AEC Laser and Electron Beam Programs: FY 1976-FY 1980." July 15, 1974. WASH 1363.UC-21. AEC:USGPO.

endnotes

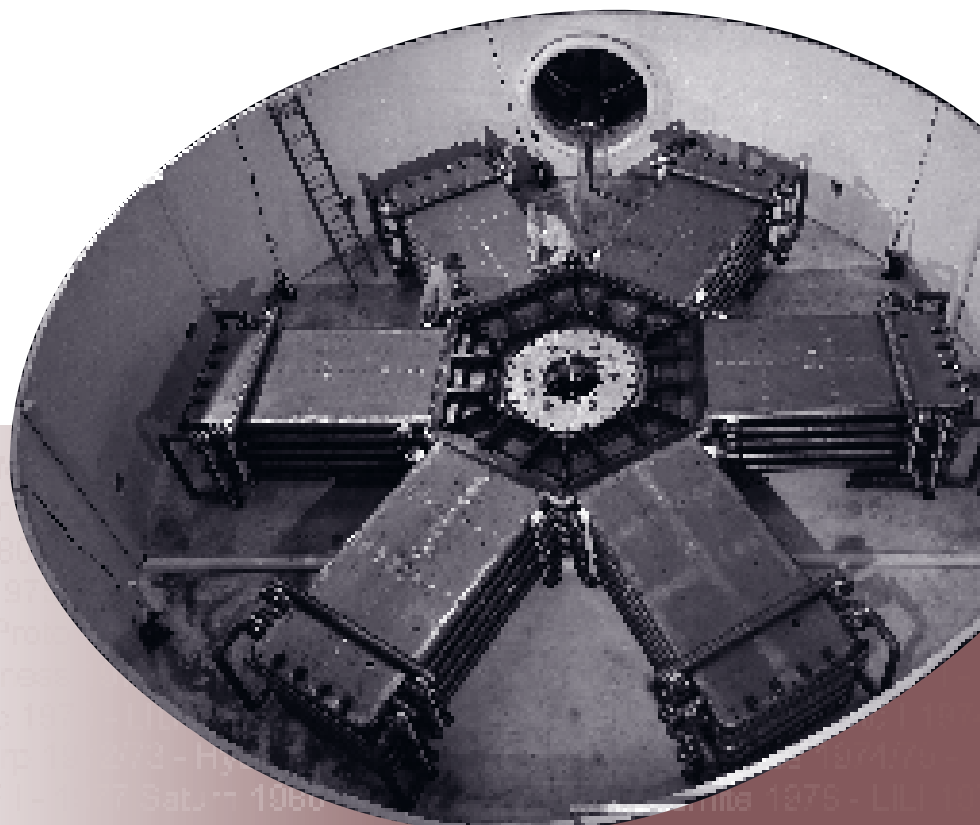
- 1 The Soviet Union tested a 0.5-megaton device in August 1953, described as a thermonuclear device, and another in 1955, which entered their stockpile; so the arms race was close.
- 2 Samuel Glasstone and Philip Dolan, eds., *The Effects of Nuclear Weapons*, third edition, Washington, DC: Department of Defense and Energy Research and Development Administration, 1977. Ken Prestwich (2005) explained Sandia's needs this way (paraphrased from an interview): Gamma rays and x rays are produced by the bomb. Intense gamma rays can ionize air and the movement of the electrons and ions created in this ionization process creates radio frequency waves. These radio frequency waves created the need for electromagnetic pulse simulators. Sandia had a requirement to test against this threat and either purchased or built test sources. The pulsed power group did not develop these sources. Some of us acted as advisors on both Sandia and military laboratory sources. Gamma rays can harm weapons at long range although probably at less distance than the radio frequency waves.
- 3 Van Arsdall interview with A.W. Snyder, June 2, 2004.
- 4 In a strange coincidence, several men associated with the early days of pulsed power had the last name of Martin: Chuck Martin at Sandia, J.C. "Charlie" Martin at AWRE, and, only a few years later, Tom Martin at Sandia. Don Martin led pulsed power work at Physics International, including the development of Marx-oil Blumlein technology.

Chapter One

- 5 For details on the weapons effects simulation needs, the technology improvements needed, and other information in this section of chapter one, I am indebted to Ken Prestwich for a careful review and helpful additions, and to Tom Martin for a careful review and patient explanations of technical subjects. For more information on the early history of pulsed power, see Ian Smith, “The Early History of Western Pulsed Power,” *IEEE Transactions of Plasma Science* 34, No. 5, October 2006.
- 6 Van Arsdall interview with Ken Prestwich, May 13, 2004. Note: Livermore was also working on this (like John Maenchen’s work at Sandia and the DAHRT at Los Alamos); they wanted to take pictures of bomb implosions.
- 7 Undated memo from S.C. Rogers, Org. 5221, to T.B. Cook, Org. 5200, and A.W. Snyder, Org. 5220, on “Tentative Plans for Constructing a Large X Ray Generator.” From internal evidence, it must date to ca. February 1965. In Box 18 of the Martin-Prestwich Collection, SNL Archives.
- 8 Van Arsdall interview with Ray Clark, January 19, 2005.
- 9 Van Arsdall interview with Prestwich, May 13, 2004. “Ian Smith and Tommy Storr built Spastic based on their SMOG machine, and in many ways it was the most sophisticated machine we ever had. You get 23 switches to go at the same time, and have fast rise time; it’s amazing! Especially at that time. But that technology has not continued because it is difficult to work with.”
- 10 Van Arsdall interview with A.W. Snyder, June 2, 2004.
- 11 Tom Martin, phone interview with Van Arsdall of October 25, 2005.
- 12 Tom Martin said he felt “there is always a problem contracting out for machines. You always wonder if they built what you wanted—that’s why Charlie built his own and so did we—using the principle of the cheapest thing to do the job.” Van Arsdall interview with Tom Martin, April 29, 2004.
- 13 Van Arsdall interviews with A.W. Snyder and Tom Martin. Snyder called this building a real dump. Tom Martin said the reason there was no insulation was that the sheets of material used for the purpose were held in place by rivets. The metal rivets were put in place by rivet guns; when the machine went off, the rivets came out of the wall and the insulation would not stay in place.
- 14 Tom Martin, phone interview with Van Arsdall of October 25, 2005.
- 15 Ian Smith provided the following information about this competition in January 2006: “The 1590 was first test-fired in late 1966 (I saw it when I arrived at Physics International the first week of January 1967); it met specifications there in May 1967, and factory-acceptance tests by the United States Air Force were complete on 2 June 1967. Since Hermes II construction began in August 1967 and the first test firing was in the summer of 1968, the priority of the 1590 as pulsed power seems clear. Shipment of the 1590 to Albuquerque was delayed by a contractual problem; still it was test-fired in Albuquerque in late April 1968; it reached full power in late June, and on-site acceptance tests for the Air Force followed days later. Hermes II could have reached full power before the end of June 1968, or been the first to do simulations for users—I just don’t know. During shipment, the Air Force has Physics International change the change the 1590 tank from an L to a straight tank, allowing a few more Marx stages and about 10% more power in Albuquerque than in San Leandro.”

- 16 Sandia supported the development of Aurora by participating in the Defense Atomic Support Agency review panels.
- 17 Ian Smith, an engineer in Charlie Martin's group, was by then at Physics International working on Aurora. Smith became and remains one of the leading pulsed power experts in the world. For an in-depth overview of the early days of pulsed power, see Ian Smith, "The Early History of Western Pulsed Power," cited in note 5.
- 18 Casino, true to its gambling name, was not completely successful and the outcome vindicated Sandia's decision not to build machines for beam combination but to increase the power of an individual electron beam.
- 19 Information from Van Arsdall interview with Tom Martin, April 29, 2004; notebooks belonging to Gerold Yonas dating from the early 1970s in the Sandia archives; N.S. Furman, Interview with Gerry Yonas of June 22, 1984; Sandia archives, Furman Sandia Pulsed Power and Electron Beam Fusion collection.
- 20 Van Arsdall interview with Prestwich, May 13, 2004; Van Arsdall interview with Martin, April 29, 2004.
- 21 Controlled Thermonuclear Research: Hearings before the Subcommittee on Research, Development and Radiation of the Joint Committee on Atomic Energy (JCAE), November 10 and 11, 1971. Printed for the JCAE by the Government Printing Office, 1971. Copy in Furman Collection.

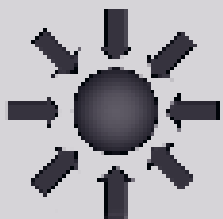
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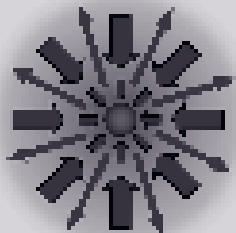
CHAPTER TWO

the '70s

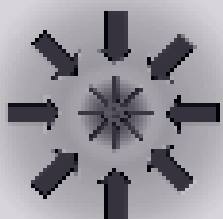
The 1970s and 1980s are the Cold War era, marked by competition between the United States and the Soviet Union over supremacy in strategic nuclear weapons. With their responsibilities for national defense, the Department of Defense and the Atomic Energy Commission had overlapping requirements for weapons-related programs, and they both funded work at a number of laboratories throughout the country to try to find the best solutions.¹ Of the Atomic Energy Commission's nuclear weapons laboratories, Sandia had developed a special skill in designing pulsed power accelerators for the many types of radiation simulations needed by the weapons community. Lawrence Livermore and Los Alamos, on the other hand, had pioneered laser development to study the physics of inertial confinement fusion in addition to weapons physics. If lasers could ignite fusion in the laboratory, fundamental questions in weapons physics could be studied, and the spectrum of radiation for simulations could be enlarged when high gain was achieved (high gain means much more energy is produced than went into producing the reaction).



*X-ray illumination
leads to ...*



*blowoff and subsequent
compressing force...*



*in order to achieve
ignition.*

Fusion

Fusion, the source of the sun's energy, is generally believed to be the ultimate source of energy for the earth as well—if it can be produced on a scale useful for a power plant. The fuel—deuterium, a hydrogen isotope—is found in water and is therefore plentiful; it is readily available, essentially hazard free, environmentally acceptable—and cheap.

But there's a hooker: power-producing fusion requires physical conditions beyond present scientific capabilities. Those conditions are rigorous: a) heat the fusion fuel above ignition point—about one hundred million degrees kinetic temperature; at that point the fuel becomes a plasma, a totally ionized gas; b) while maintaining its temperature, isolate the plasma from its container long enough so that the release of fusion energy is greater than the energy required to heat the fuel (for inertial confinement fusion, the container was the outer metal shell of the capsule); and c) convert the released energy to a useful form, such as electricity.

Fuel densities must be high and confinement times long in order to reach an efficient reaction. The most widely accepted approach to achieving the required conditions is confinement of the plasma in magnetic traps—toroidal pinch devices, for example. Another approach is pulsed fusion through inertial confinement, the basis for both particle beam and laser work.

Whereas nuclear fission is a process of breaking apart heavy atomic nuclei, thereby releasing energy, nuclear fusion refers to joining together—fusing—the nuclei of light atoms. To make nuclei fuse, scientists put energy into fusion fuel, raising its temperature and setting the atoms into rapid motion. At high temperatures, all the electrons are stripped from the atoms, leaving bare nuclei and free electrons—creating what is known as plasma. In these very high temperatures, the nuclei move energetically enough to collide, and then the nuclear force comes into play. Short in range but extremely powerful, the nuclear force binds the colliding particles together. This binding is fusion.

Although the process sounds straightforward, there is an almost overwhelming problem: finding a way to introduce large amounts of energy into the fuel while maintaining confinement long enough for fusion to occur.^a

Inertial confinement fusion requires rapidly compressing a capsule of fuel only millimeters in size to densities and temperatures higher than those at the center of the sun. It requires high fuel density confined and heated for a billionth of a second. Either a particle or laser beam heats the spherical shell of the fuel pellet, vaporizing the shell and causing it to ablate (be blown rapidly outward). The resulting shock wave of the outward ablation drives the fuel pellet inward. Shock compression raises the density and temperature of the fuel to the point necessary for fusion (1000 times solid density and 100 million degrees Celsius). This process has been called pellet crushing compression.

At that temperature and density, deuterium and tritium will be able to collide. Pairs of deuterium and tritium nuclei will fuse, each pair becoming a single helium nucleus. Another nuclear particle, a neutron, will be released, along with energy.

The combined energy of trillions of individual fusion reactions will blow the pellet apart. But the inertia of the inward-moving material will counteract, keeping the pellet together until the reaction has spread through most of the fuel—hence the term “inertial confinement.” The result will be a fusion reaction in the form of a small thermonuclear explosion. The laboratory-scale explosion will allow better understanding of the physics of nuclear weapons and is a potential source of energy for power plants.^b

Magnetic confinement fusion uses lower fuel density than in the inertial confinement approach, but requires the fuel to be confined for a longer period of time. The aim in this technique is to confine and heat the plasma, using extremely strong magnetic fields, long enough for fusion reactions to occur. The magnetic fields are designed to create a kind of bottle that will contain the immensely hot and unpredictable plasma and keep it away from the walls of the bottle so that fusion can take place.

^a Paragraphs on fusion are adapted from Sandia Lab News, September 21, 1973, “Fusion and Electron Beams.”

^b Inertial confinement fusion description based on Particle Beam Fusion Accelerator II, SAND86-0861.

Though perhaps far in the future, the concept was always there that fusion could be at the heart of a facility providing an inexhaustible source of energy.

In the opening years of the 1970s, Al Narath was director of Solid State Sciences in Sandia's research organization and Everet Beckner was manager of Plasma and Laser Physics Research. Beckner's group was studying the production and output of dense plasmas. Both men recognized the importance of Sandia's high-power electron accelerators for weapons effects because of their ability to provide intense x-ray sources. In time, they became convinced that fusion research also suited Sandia's accelerator capabilities and, in addition, that an inertial confinement fusion program would greatly benefit the Labs. As a companion to Livermore and Los Alamos programs, where laser fusion studies were already under way, Sandia pointed to its lasers in addition to its electron-beam accelerators as potential fusion drivers. However, neither of the other laboratories thought electron-beam technology was suited to fusion, and they resisted Sandia's attempts to enter the field (see chapter one). In spite of the opposition, Narath and Beckner relentlessly insisted upon Sandia's capabilities to do fusion and their intent to establish a program at the Labs.

In looking back on the early days of pulsed power at Sandia, Narath said he believed Sandia needed a great new initiative to attract technical talent and help keep the Labs alive, because weapons programs began to decline after 1972.² He said that fusion for energy was the major reason for taking on the research, although because of the classified nature of the targets required, inertial confinement fusion activities were funded by defense programs.³ At the same time, the stable of pulsed power machines being developed for weapons effects simulations, including Hermes II, was becoming a Sandia hallmark. In fact, the military had additional demands for new and more powerful machines capable of delivering different spectra of radiation for weapons effects simulations.⁴ That pulsed power accelerators might be developed to meet these needs, in addition to doing fusion experiments, opened new possibilities at Sandia.⁵

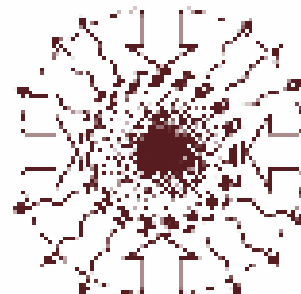
Fusion involves ignition and burning of a form of matter known as plasma, requiring enormously high temperatures like those in the center of the sun. Beams produced either by lasers or particle-beam accelerators theoretically have the capability to implode a fusion capsule; ideally the implosion will compress and heat a target within it to fusion conditions. Lasers concentrate power in short pulses and can be focused easily, but they are inefficient and expensive. Electron-beam accelerators, on the other hand, create beams with high energies and are efficient and relatively less expensive than lasers. However, precisely focusing electron beams is difficult, because the like charges of the particles in the beam repel one another and spread the beam. In addition to the challenges of beam focusing, to use accelerators as a trigger for fusion also requires scaling the beams to the power required. For these and other reasons, much of the technical community looked

Magnetic Confinement Fusion



Magnetic field holds heat.

Inertial Confinement Fusion



Collapsing shell confines and heats fuels.

upon electron-beam fusion research with skepticism. However, Sandia believed the potential advantages far outweighed the drawbacks, and moreover considered electron-beam fusion technically feasible.

In 1971, the nation's fusion programs went under a Controlled Thermonuclear Research Division within the Atomic Energy Commission. These programs were growing rapidly both in expense and importance; as a result, that year several Congressional hearings reviewed them to assess what was being done at laboratories across the nation. Sandia's pulsed power machines were included in the review, conducted by the Joint Committee on Atomic Energy. At the conclusion of the review, the committee determined that electron-beam accelerators were as viable as lasers in the quest to create a controlled fusion reaction in small pellets of deuterium-tritium (weapons work had suggested the composition of the pellets). This recognition, coupled with the ongoing need for electron beams for weapons effects simulations, created support for electron-beam fusion research. The recognition also meant that Narath and Beckner had succeeded in gaining Sandia a place in the nation's fusion programs. Because inertial confinement fusion was funded for weapons applications, many details of the target work remained under tight security wraps. (In this history, the term fusion refers to inertial confinement fusion. If magnetic confinement fusion is meant, it will be called such. Controlled thermonuclear research encompasses both approaches.)

Soon after the review (mid-1972), Beckner and Narath hired Gerry Yonas into Sandia's research organization. Yonas had managed electron-beam physics work at Physics International, a major firm that made large electron-beam accelerators and performed weapons-related experiments with them. The Defense Atomic Support Agency, which was responsible for radiation-effects studies in the Department of Defense, was the firm's key customer at that time. (In fact, Sandia competed with Physics International and other Department of Defense laboratories in this field; see chapter one.) Beckner recalled that he and Narath hired Yonas specifically to gain a better understanding of the physics of intense electron-beam accelerators, especially the diode, and how to get the focus needed for an intense x-ray source.⁶

At the same time, there was a program using a small glass laser at Sandia for fusion studies, even though Livermore and Los Alamos were out in front with laser work and had been in the field for some time. Beckner said, "Livermore was already a powerhouse in glass lasers, Los Alamos less so, but a force, with their gas lasers. The designs Los Alamos and Livermore created for fusion targets were similar to what they did when designing nuclear weapons, so they had target expertise.

John Emmett at Livermore was a pioneer in fusion with lasers, as was Keith Boyer at Los Alamos. Sandia entered the laser fusion arena as a third party, as it were, to Los Alamos and Livermore. And we were using our electron accelerators for other reasons than fusion."⁷

In Yonas, Narath and Beckner found the ideal champion for Sandia's fusion program; however, not for laser fusion, but using the accelerators that he knew so well. As manager of a new Electron Beam Physics Division, Yonas joined Narath and Beckner in insisting to Livermore and Los Alamos that Sandia merited a place at the fusion table. It would prove to be a lengthy and at times volatile effort, naturally involving the Atomic Energy Commission and its national fusion program. Narath became Vice President of Research in 1972, and Beckner was promoted in 1973 to lead the Physical Research Directorate, with Yonas and Tom Martin reporting to him.⁸

Yonas recalled years later that when interviewing at Sandia, he had promised Narath that he would "bring LIFE (lasers, ions, fusion, and electrons) to the Sandia Pulsed Power Program," and said he was totally committed to pursuing fusion.⁹ Promoted quickly into increasingly higher management positions, Yonas would champion and lead the fusion effort inside the Labs and at the national level throughout the 1970s and into the 1980s. A universal acknowledgement among pulsed power veterans is that Sandia's fusion program is in large measure due to Yonas's tenacious pursuit of funding for the required facilities and his firm commitment to the pulsed power approach. In 1998, he would receive a special award for his work (see chapter four). However, Yonas credits Narath and Beckner with having had the vision to initiate Sandia's inertial confinement fusion program in the early 1970s. (Please see following sidebar on these men.)

Just as fusion research in the weapons community was beginning to ramp up, the United States and the Soviet Union signed two treaties that had the effect of reducing the need for many kinds of weapons work in the national laboratories for a time. Because both countries had intercontinental ballistic missiles bearing nuclear warheads and extensive anti-missile capabilities, it became obvious that, in a shoot-out, no country could win. As a result, after lengthy negotiations, in 1972 President Richard Nixon and Soviet leader Leonid Brezhnev signed the Treaty on the Limitation of Anti-Ballistic Missile Systems and the Strategic Arms Limitation Treaty (SALT). The Anti-Ballistic Missile Treaty, as it became known, limited deployment areas for anti-ballistic missiles in each country to two and made it impossible for either country to have or develop a nationwide anti-ballistic missile defense system. SALT limited strategic offensive and strategic defensive weapons systems. The United States and Soviet Union were now equally open to attack, and the balance of nuclear weapons assured—a concept known as mutually assured destruction.¹⁰ The treaties eased tensions in the arms race and called into question the need for increased efforts at US weapons laboratories. If no nuclear weapons were deployed, weapons effects studies were of less importance than during the arms race. As a consequence, defense funding for weapons effects simulations became tighter, including dollars for fusion.

*Ev Beckner**Gerry Yonas**Al Narath*

Beckner, Yonas, Narath



by Sandia artist Jim Walston

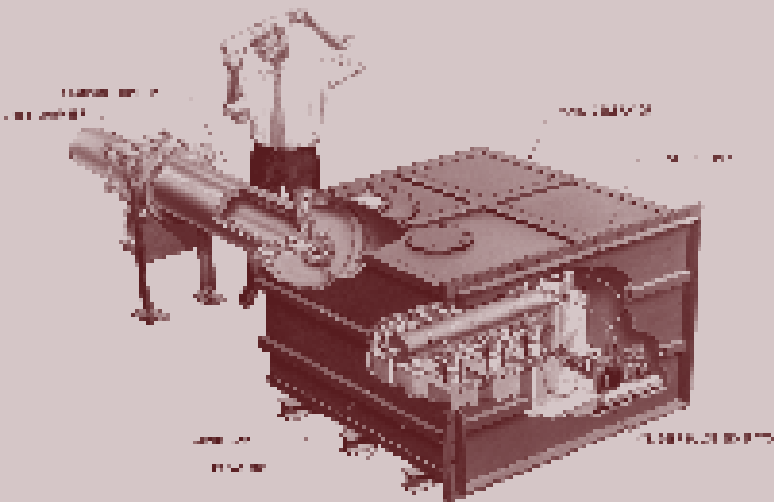
“Sandia had three programs in the early 1970s: lasers, plasma physics, and high-power pulsed electron accelerators. It was Al Narath’s insight to try to combine those three areas. That was the thrust when I became a director reporting to him. The decision to use pulsed power as our main capability made us different; that set us apart from Los Alamos and Livermore. A lot of it was coincidental, that it was all here at the same time—the people and the technology. Narath and I developed a strategy for turning this technology into a fusion program. And Gerry Yonas was the right person at the right time. We had this technology that was advancing and being supported for other reasons (weapons). We needed those x-ray sources—and we had the opportunity to use the same accelerators to try to make fusion.”

Everet Beckner, 2006.

Despite some funding reductions, weapons effect simulations and fusion studies continued at Sandia, Los Alamos, Livermore, and elsewhere. Sandia was now concentrating on using its pulsed power accelerators to produce electron beams capable of irradiating fusion pellets, an approach similar to lasers. Sandia intended to implode the deuterium-tritium pellets by focusing intense electron beams on them, heating them to the point that they imploded and fusion reactions occurred. Experiments on the accelerators Nereus and SLIM introduced the concept of wire-on-axis pinched electron beams, and for the first time, computer codes were used to guide the work. As a result, Sandia's team pushed its claim that it could focus electron beams for fusion applications. In January 1973, Sandia researchers published a paper titled "Electron Beam Focusing Using Current Carrying Plasmas in High- v/γ Diodes" in *Physical Review Letters* and the results were announced later that year at the European Conference on Controlled Fusion and Plasma Physics.¹¹ (Please see following sidebar on Wire-on-Axis Research.) At the conference, the United States learned that Russian scientists at the Kurchatov Institute, notably Leonid I. Rudakov, were also working on electron-beam fusion using a concept similar to Sandia's; i.e., using electron beams to compress and implode spherical pellets of fusion fuel. Yonas and Rudakov began a long professional association at this time, in spite of the limitations on sharing information that security issues posed.¹²

Fusion began to attract national interest at this time, but not for reasons of national defense. In 1973, an international oil crisis made energy a rallying cry in the United States and brought additional pressure on the national laboratories to identify secure, environmentally safe sources of energy. Because of the need to reduce dependence on foreign resources, the laboratories cast a wide net of possibilities for creating energy sources at home. Beginning then, research into harnessing fusion for energy became a major US effort. Interest in renewable energy was high as well, and major programs evolved at the national laboratories devoted to solar, wind, and geothermal technologies, many of them at Sandia. As reported in a *Sandia Lab News* article on September 7, Senator Joseph Montoya, senior senator from New Mexico and a staunch supporter of the Labs, visited Sandia in August. At that time, he warned of reductions in defense spending and increasing emphasis on energy and the environment, urging Sandia to apply its "tremendous reservoir of experience and capabilities" to the energy crisis. In foreseeing funding reductions ahead at all the weapons laboratories, Montoya told his Sandia audience, "The honeymoon is over for Congress and the Atomic Energy Commission in the easy funding of Atomic Energy Commission [weapons] programs."

As a consequence, at weapons laboratories such as Sandia, the fusion energy effort for awhile overshadowed the weapons-related fusion work, though both continued in parallel. The fact that funding for defense was decreasing and the interest in fusion for energy rather than weapons effects was increasing factored into events at Sandia soon after Montoya's visit. Intended primarily for weapons effects studies



NEREUS

Wire-on-Axis Research

The facilities available for electron-beam research when Gerry Yonas arrived were REBA, Nereus, and SLIM (the diodes were still being developed). Yonas immediately started electron-beam pinching experiments on Nereus and conceived the idea of using a wire on axis to provide an additional magnetic field for pinching the electron beam.

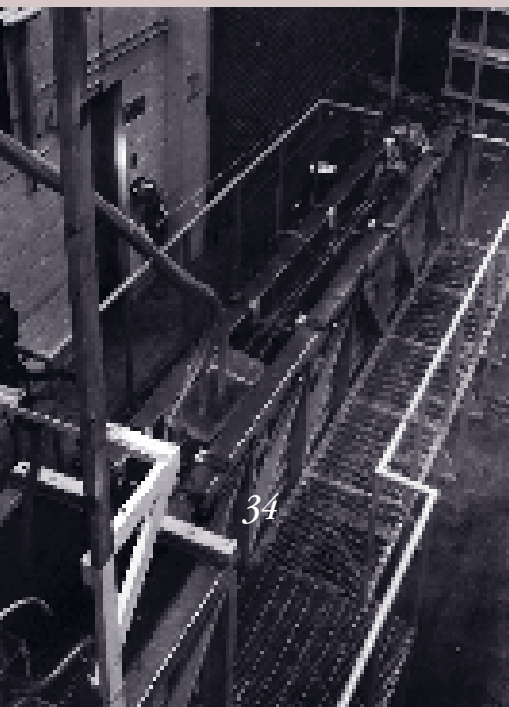
These experiments were transferred to Slim, a machine with the unique feature that it did not have a prepulse voltage. In essentially all other pulsed power accelerators, a voltage appeared across the diode while the pulse-forming lines were being charged. In experiments on SLIM with a 17.7-cm-diameter cathode, electron beam densities of several megamps/cm² were achieved. Although there was some uncertainty as to the accuracy of

the radiographs, these current densities were never exceeded. The wire-on-axis pinched electron beam concept was patented by Yonas, Ken Prestwich, John Freeman, and Jim Poukey.

Poukey and Freeman developed codes that described the physics of electron beam diodes. The code physics evolved by comparison with the experiments performed by staff members in what became Yonas's division. By 1975, Poukey and independently Shyke Goldstein from the Naval Research Laboratory showed that it would be very difficult to get enough energy in the self-pinched electron beam to achieve fusion conditions. The problem was that in order to get several megamps of current, the cathode had to be the order of 1 m in radius. The magnetic field of the large current generated at the outer edge of the cathode caused the electron to flow radially to the axis of the large cathode. During the rising portion of the current pulse, the magnetic field was not large enough to cause the electrons to flow to the axis. Substantial energy was deposited in the anode during this phase, heating the anode, causing gas to evolve, and producing an anode plasma. Ions from this anode plasma were accelerated across the gap. In non-pinching diodes, the ion current is only a few percent of the total current. In these pinched diodes, it can become greater than 50 percent of the current, thereby substantially reducing the efficiency of the pinched beam diode.

Sandia and other organizations started ion beam research immediately after these papers were published, but it was nearly 10 years before pinched electron beam diode concepts were abandoned. This research involved experts in plasma theory as well as pulsed power and electron beams. Funding came from the Atomic Energy Commission/Controlled Thermonuclear Research and from the Atomic Energy Commission/Department of Military Applications. The Department of Defense provided funding for research at the Naval Research Laboratory, Maxwell Labs and Physics International.

[Information from Ken Prestwich, summer 2006.]



SLIM, 1971.

using x rays to rip apart microcircuits, a facility named Ripper designed by Tom Martin's department was proposed to the Atomic Energy Commission/Division of Military Applications, which funded the majority of pulsed power work at the Labs. Even though Sandia said Ripper would increase by a factor of ten the power from its existing accelerators, Ripper was turned down.¹³ Ripper, envisioned as a much more powerful facility than any at Sandia at the time, was proposed both for radiation simulation and for fundamental research with electron beams for fusion.

Fortunately, the Atomic Energy Commission's now independent Division of Controlled Thermonuclear Research approved Sandia's request for \$250,000 for a year to do research into compressing and heating thermonuclear fuel using electron beams. Initially, the research was to be in the physics of beam focusing and energy absorption in solids (important in being able to heat the outer layer of the pellet of fusion fuel). A *Sandia Lab News* article on September 23, 1973, titled "Fusion and Electron Beams" explained that three divisions were now involved in the work, all of them under Yonas. Plasma Theory under John Freeman, Electron Beam Research under Al Toepfer, and Pulsed Power Research and Technology under Tom Martin were going to work together on the difficult goal of igniting a fusion pellet in the laboratory, drawing upon specialized capabilities of other Sandia organizations when necessary.

Eclipsed in later years by the accelerator effort, between 1973 and 1982 a significant laser program existed at Sandia. (The origins of the laser program go back to 1966.) Laser activities existed within the overarching Physical Research area, where the Pulsed Power Program was being created using staff from several divisions. In some ways the laser effort was competing with the goals of the electron-beam fusion program. However, the tie-in was that virtually all advanced lasers required pulsed power sources to supply energy to the laser. In a quest for more efficient lasers for a laser-driven inertial confinement fusion reactor, the Atomic Energy Commission/Department of Military Applications funded an advanced laser research program, some of it at Sandia.

Jim B. Gerardo headed laser physics research beginning in the summer of 1971, and most of his lasers used electron beams to excite the laser gas. At first, REBA was used for the research, and then other electron-beam accelerators. LILI, Rayito, and Rayo were developed by Juan Ramirez and David L. Johnson specifically for this kind of work, where the beam is not required to focus. The laser group was responsible for a considerable number of studies related to electron-beam generation, deposition physics, and transport of electron beams. In 1974, laser and electron-beam fusion issued a combined progress report for Sandia's Directorate of Physical Research; the next year, the programs were separate and remained so henceforth, yet still in the same directorate.¹⁴ In the early 1980s, laser fusion activities were transitioned into laser-triggered switching and ion source research and the laser program diminished in size. With the emphasis on electron-beam development for fusion at Sandia, and



Gerry Yonas and Tom Martin with model of Ripper.

given that Los Alamos and Livermore had large laser programs, choices had to be made in funding requests, and the laser fusion activities elsewhere were too large to compete with directly. Laser fusion work continued at Sandia largely in support of accelerator work and to provide information to other laboratories.¹⁵

The US inertial confinement fusion programs were overseen by the powerful Laser-Fusion Coordinating Committee, which would make funding recommendations to the Atomic Energy Commission after hearing proposals. The Atomic Energy Commission would then draw up and annually submit a budget to Congress for approval. The committee's name—laser fusion—suggests where the breakthroughs in fusion work were anticipated, and also why Sandia faced an uphill battle to gain recognition for its electron-beam approach. However, Sandia was beginning to gain acceptance as part of the Atomic Energy Commission's inertial confinement fusion effort because of its electron-beam programs. The far less expensive electron-beam technology was unique to Sandia (at this time, the Department of Defense laboratories had a smaller effort in applying the accelerators they had been developing for weapons effects simulations to fusion experiments, since the military viewed fusion work primarily as an energy program with applications to weapons effects simulations).¹⁶

Having jettisoned its proposal for Ripper, in 1974 Sandia outlined to the Atomic Energy Commission a long-range program to develop a new Electron Beam Fusion Facility. Such a facility would have an accelerator capable of much more power and energy than anything yet available and specifically designed to ignite a fusion reaction. The estimated cost was \$15 million, and Sandia wanted it included in the FY 1976 Congressional budget.

As described to the Commission, the facility would be built in a new area, away from Area V where all the radiation facilities (including, for example, Hydra, Hermes, and REBA) were then operating. Safety concerns were the main reason for not adding the new accelerator and its additional staff to Area V, which was by that time considered overcrowded. Since it would be by itself in an as-yet-unoccupied part of Sandia's desert landscape, plans for the Electron Beam Fusion Facility called for constructing office and laboratory space in addition to building the accelerator. Sandia bolstered its proposal by stating that the facility would have multiple uses: the accelerator could be used as an x-ray simulator in addition to its fusion experiments and thus fill a need in weapons work. In addition, it would contribute valuable information to the Atomic Energy Commission's laser fusion research program.

In promoting the idea for the Electron Beam Fusion Accelerator (EBFA), which would go into the facility, Sandia said it was addressing three major technical concerns about electron beams and fusion using theoretical studies and experiments on existing machines. These concerns were whether the beam of electrons could be focused on a specially designed and very small pellet of fusion fuel, whether the beam could be made to irradiate the pellet with near-perfect

symmetry, and finally, whether a pellet could be constructed so that it would implode efficiently, given success in the first two areas. The pellet design was in fact an area common to laser and electron-beam fusion and was being worked on at all the Atomic Energy Commission laboratories; however, steering committee minutes reveal that sharing of information could be a problem, particularly because Los Alamos and Livermore did not think that Sandia's electron-beam approach would work given the difficulties with focusing the beam. The approach was also competing with theirs for Atomic Energy Commission money.¹⁷

At this time, fusion research at Los Alamos centered on a carbon dioxide laser, Helios, and an eight-beam facility named Antares was scheduled to be completed in May 1975 at a cost of \$22.6 million. Lawrence Livermore was building the 20-beam glass laser, Shiva, with a ceiling cost of \$20 million. Sandia's proposal for the new electron-beam facility was slightly less than \$15 million. The fusion targets Sandia would use in its electron-beam approach were made at Los Alamos and Livermore because of the material they contained.¹⁸

At the national level, a shift in emphasis toward energy research within the US government was seen in January 1975, when the Atomic Energy Commission was abolished and the Energy Research and Development Administration (ERDA) and the Nuclear Regulatory Commission (NRC) were established to take over its functions. The NRC took over responsibility for commercial reactor safety (and for Sandia's reactor safety assessments as well). The ERDA assumed responsibility for weapon and energy research, with an organizational structure similar to that of the Atomic Energy Commission. Funding requests and oversight of the weapons and fusion programs continued much as in the past under the new agency.

At Sandia, the plan forward toward the EBFA was developed carefully and systematically, though obtaining funding for it continued to be problematic. Physics studies on beam focusing and energy deposition in targets would continue on Hydra, in particular using low-energy electrons for energy deposition without deep penetration. Research had demonstrated that the high magnetic fields of high-current electron beams could focus them to millimeter size. Using this self-pinch effect, one beam of Tom Martin's Hydra heated two-part metal targets and caused the inner part to implode and concentrate the beam's power. At the same time, studies were being made to determine whether the implosion was symmetrical, since uniformly heating the spherical fusion pellet was a critical requirement for fusion ignition. Because of favorable results from this work, Sandia decided to use Hydra in a two-beam configuration and evaluate the results.¹⁹

In addition, Sandia's ability to diagnose the results of its experiments and optimize the configuration of fusion targets would soon improve in several areas, including developing computer codes and collaborating with Los Alamos and Livermore to obtain needed calculations using their enormous computer capabilities. Jeff Quintenz was hired into John Freeman's group at this time (1975) to work with Jim Poukey to advance Sandia's "rudimentary simulation capability" using computer codes,



HARP, 1972-1973.

then being run on thousands of punch cards with a CDC-7600 computer.²⁰ It was during this period that electrostatic particle-in-cell computer codes began to be developed at Sandia, codes that were soon used to understand electron beam focusing and the role ions played in focusing electron beams. To this point, an empirical approach had prevailed, and veterans of the program acknowledge that the new theorists had to prove themselves to somewhat incredulous experimentalists and machine designers. Quintenz became known as the “unprincipled advocate for theory,” an advocacy that was vindicated in later years, when theory served to lay firm foundations to explain and predict experimental results.²¹ (Please see following sidebar on early computer codes.)

To prove the need for EBFA, Sandia outlined to the Congressional Joint Committee on Atomic Energy detailed plans calling for not one, but two successively more powerful prototypes to be developed and operated between 1974 and 1979. EBFA would follow in late 1979 or early 1980, designed using information derived from operating the prototypes. The presentation to the committee showed the first prototype producing 2 trillion watts of power, with the planned EBFA producing 40 trillion watts, an enormous gain in only five years.²² Beyond that, and looking years ahead, Sandia was already envisioning a successor to EBFA; its design would depend on how well EBFA performed. Calculations were indicating that fusion might require more power on target than had been believed in the past.

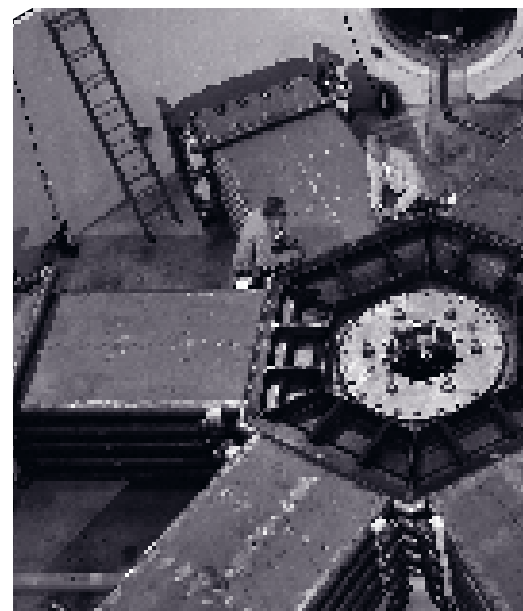
In contrast to Sandia’s other machines with their evocative names, the first prototype for EBFA was called simply Proto I and it began operation in 1974. In fact, Proto I was an upgrade of a slightly earlier machine named HARP—an acronym for “Here’s Another Ripper Prototype.” HARP/Proto I was designed by Ken Prestwich, with John Corley and Art Sharpe on his team. (Please see following sidebar on Proto I and Proto II.) Proto I was Sandia’s first machine designed specifically to irradiate fusion pellets. Created in the wagon-wheel configuration that has become a hallmark of Sandia’s fusion machines, Proto I had 12 transmission lines linked into two beam sources, like spokes converging on an axle. The trick was that the 12 transmission lines had to be triggered so that the pulses of power from all of them would be delivered simultaneously to create a beam in the central diode. The beam would then irradiate a fusion pellet positioned at the heart of the wheel’s axle inside the diode. Sandia’s expertise in developing switches again paid off. Prestwich is credited with developing the precise switches that enabled Proto I to produce a very short pulse of power by synchronizing the pulses from the 12 transmission lines. The transmission lines were submerged in transformer oil to insulate them, and the switches had to operate in this environment.

In November 1975, Sandia hosted the first International Conference on Electron Beam Research and Technology with Yonas as chairman and organizer. It drew some 200 participants, one of whom was Charlie Martin from the UK, the man who in many ways was responsible for starting the technology that was the subject

of the conference (see chapter one). Even Russian scientists were present, and the conference was regarded as a signal of détente in relations between the West and Russia. Certainly, exchange of scientific ideas began to increase beginning at this time. Because fusion for energy held out hope to solve a major need facing mankind, scientists everywhere wanted free discussion of the myriad challenges in fusion work. Proto I was at center stage during the international meeting. In talking about the conference and the status of electron-beam fusion at Sandia, Yonas told a *Sandia Lab News* reporter that the program now numbered 50 people with a budget of \$4.7 million, expected to rise to \$7 million in 1976.²³ Although the machines that generated the power were fundamental to success in fusion, other specialties brought into the organization, such as plasma studies and diagnostics for the electron beams, were vital to understanding and mastering this complex technology.

Results from operating Proto I and data from a test bed machine called Ripple convinced the pulsed power team to try a slightly different approach when designing the second prototype, dubbed Proto II. The water lines in Hydra and experiments using Ripple in 1974/75 indicated that the synchronized multi-channel switching needed to form the power pulse could in fact be done better in water than oil. Water lines facilitated the lower voltages and high currents required to achieve the power densities. Earlier, water switching had been thought to be impossible. Sandia decided to base Proto II on using water as insulation for the transmission lines and to further develop water switching. Although the change sounds simple, it presented many technical challenges, not the least of them how to reduce losses in power when the switches were triggered. At this juncture in the program, a new staff member named Pace VanDevender was hired into Tom Martin's group in 1974 to work on the Ripple test bed. Like Yonas, VanDevender would soon be promoted into upper management, contributing to Sandia's pulsed power effort and to other Sandia programs for many years to come. VanDevender and Martin worked out the feasibility of water switching for Proto II, which began operating in early 1977.

For the US and international non-weapons community, fusion research was primarily of interest as a source of energy, and national media coverage of advances in inertial confinement fusion concentrated on that application. In reality, many crucial scientific details of inertial confinement fusion, in particular the target designs, were at that time classified and confined to the weapons community and therefore received almost no popular attention. Foreshadowing international technological competition that was shaping up both inside and outside that community, the *New York Times* of January 15, 1976, reported that the Soviets were turning from lasers for fusion to electron beams, which the *Times* said was "a method that, in this country, is receiving only modest support." The *Times* said that 90 percent of US funding was for laser fusion, with approximately 1000 people working on it nationwide and estimated that only 50 to 100 were in electron beams, most of them at Sandia.²⁴



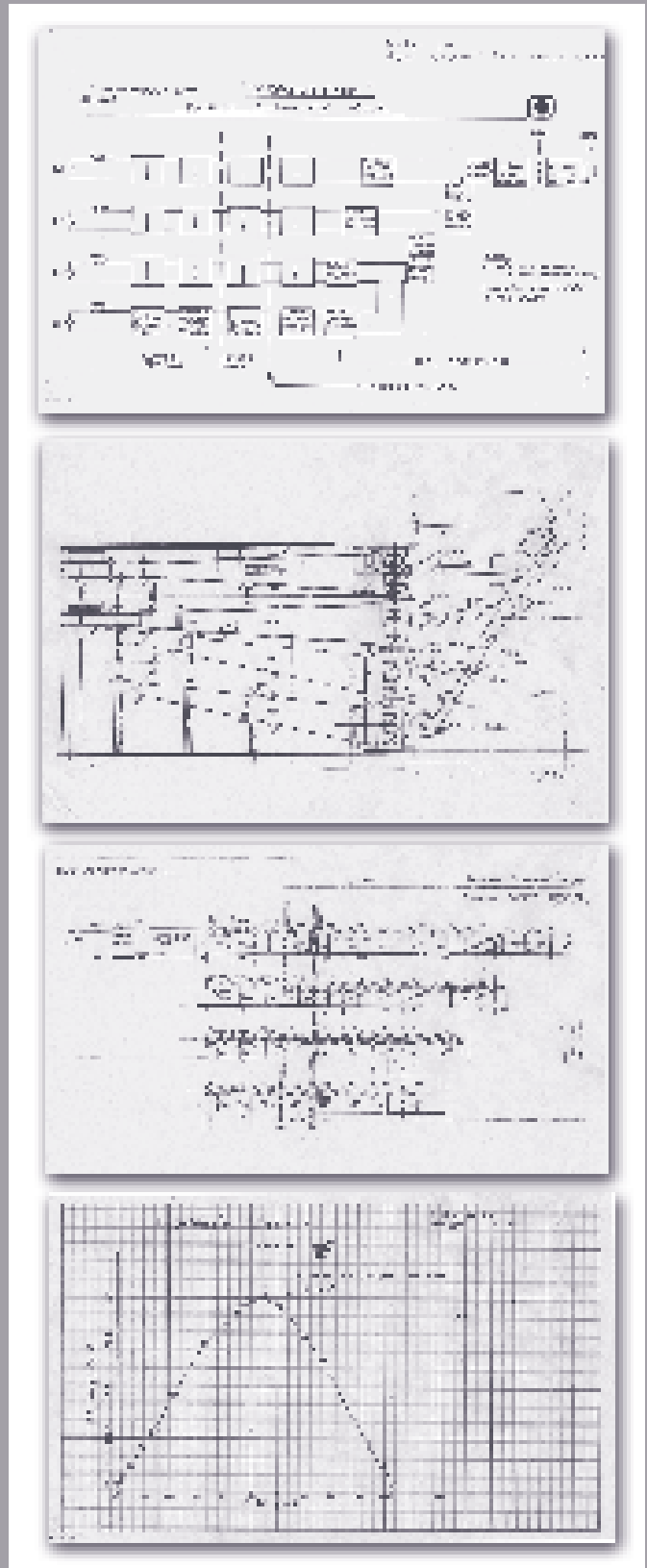
View of Proto I, a pulsed power machine built at Sandia during the 1970s for research into inertial confinement fusion.

Early Use of Computer Codes in Pulsed Power Work at Sandia

In an interview in 2006, Sandia computational physicist David Seidel likened experiment, computer modeling, and theory in scientific research to a three-legged stool: all three legs are complementary and necessary to make the stool stand. Two of those elements were lacking in the earliest days of fusion work at Sandia, when experiments on accelerators and test beds sufficed for much of the needed weapons effects simulations. Because of the demanding scientific nature of inertial confinement fusion using particle beams, by the mid-1970s Sandia staff found they needed to be able to understand, explain, and finally improve on increasingly complex machines and experiments. As a consequence, new kinds of diagnostics and computer codes were needed to try to ascertain what was happening and why—in a new field of research worldwide. Fusion work required expertise in engineering and in both experimental and theoretical physics at a laboratory only newly involved in basic research.

Each area demanded increasing sophistication—the three-legged stool analogy again—better diagnostics of experiments required more computer power to model what was going on, and then better theory to analyze the models and the data. This in turn suggested improvements in the experiments; one complex area in particular involved improving the diode, the heart of ion-driven fusion. In the early to mid-1970s, pulsed power at Sandia was machine-oriented, with experimentalists trying to get higher voltages and currents from new and larger accelerators for various applications. With the increasing complexity of inertial confinement fusion work, the front end of the machine, the target and beam-forming area (the diode) and their associated elements, became of paramount importance and the intricacy of experiments increased enormously.

Computer codes were first used in pulsed power at Sandia to model accelerators and were applied after the fact to model how the accelerator design had worked. Experimenters, used to back-of-envelope drawings and estimates, were leery of using computer codes as predictive tools for machine operation because this was a fundamentally new approach. Electrical circuit codes model integrated accelerator operation (called system modeling); the earliest circuit code



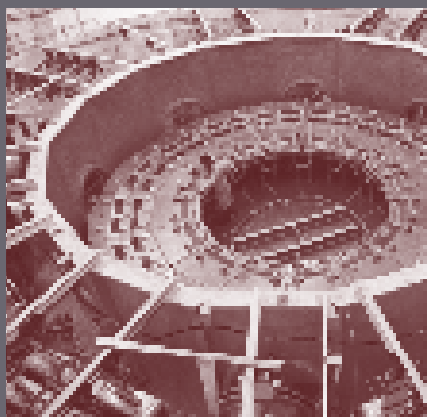
Proto I and Proto II

Proto I was the first high-power, short-pulse electron beam accelerator designed specifically to heat and compress the fuel pellets used in fusion experiments. It was Sandia's first step in an accelerator program estimated in 1976 to be leading toward a 100-terawatt capability.

Proto I began operation in 1974 (it used elements from an earlier machine called HARP, initially built as part of the proposed Ripper program, which was not funded). Before the accelerator could become a reality, a new high-voltage switching technique (a rail switch using an oil dielectric), a novel pulse-forming transmission line, and a dual diode especially suited for target interaction studies had to be developed. The modular construction of Proto I was designed to allow adaptation in the development of much higher energy systems of this type.

Although the power level of Proto I was known to be well below that required for fusion, the machine enabled Sandia to explore a number of questions before such experiments could be envisioned. Proto I was useful for studying the generation and focusing of electron beams initiated in large-diameter cathodes, and for investigating electron beam energy deposition in solids that would be used in fusion targets. Target compression experiments were advanced on this accelerator. Proto I was also used to study the generation and focusing of ion beams.

Proto I was constructed with two Marx generators located in an oil-filled tank and connected to trigger circuits, transmission lines, and diodes in an adjacent oil-filled tank. One generator charged the transmission lines, the other provided precision triggering to the rail switches. (Sandia developed an oil-dielectric rail switch that would work for this application, since no such switches then existed.) The transmission lines were in a tank measuring 9.1 m in diameter and 2.4 m deep filled with 30,000 gal. of transformer oil during operation.



Electron beams were generated from the surfaces of cathodes that were between 25 and 300 times larger in diameter than the fusion targets. The fusion target was attached to the common anode for compression experiments. It was found that spherical targets could be uniformly irradiated with only two beams.

The intent of Proto I was to deposit large amounts of energy in a small target, with the hope of producing thermonuclear neutrons using an electron beam to irradiate a fusion target—a first desired step in Sandia's particle beam fusion program. The Proto I approach was a conservative extrapolation from existing technology using an oil dielectric and triggered multi-channel switches. Proto I was designed by Ken Prestwich and built with the assistance of Art Sharpe.

However, at the time Proto I and II were being built, it was known that for fusion reactions to occur, megajoules of beam energy would be needed delivered on target in 10 to 20 nanoseconds. Sandia decided to use a more advanced and riskier approach on the 8-terawatt **Proto II**, which used a water dielectric and untriggered multi-channel switches. It began operation in 1977. Proto II was designed by Tom Martin, and the team included Johann Seamen, Dillon McDaniel, Dave Johnson, and Pace VanDevender.

Sandia wanted to ascertain how well high-purity water would work as an insulator, and a new approach to switching was again required before a water-insulated accelerator could be considered at the power levels desired. Sandia developed its technique for switching in a series of experiments on Ripple, a test configuration that modeled the electrical energy storage, switching, and transport concepts for Proto II. (The technique was first developed at Maxwell Labs; the UK's Charlie Martin suggested it to Sandia.)^a The generated voltage rise times were so short that multiple breakdowns occurred, in effect creating many switches by producing numerous current-carrying channels between the electrodes of each switch.

Proto II was housed in a tank that was 2.74 m high and 13.4 m in diameter filled with 60,000 gal. of transformer oil. It had eight Marx generators, which discharged into 16 intermediate storage capacitors, also in the oil-filled tank. The intermediate capacitors

released energy into pulse-forming and transmission lines arranged near the center of the tank and submerged in 35,000 gal. of water. The new switching technique came into play at this point, and the first set of pulse-forming lines self-switched in 16 current-carrying channels to charge the second set of pulse-forming lines in 70 nanoseconds. The voltage rise was so rapid that the second set of lines switched, with about 200 channels, and launched a wave down the converging transmission line transformers toward the diode. At the center of the tank was an evacuated chamber, or diode, whose outer wall of Lucite separated the diode from the surrounding transmission lines.

At peak energy, the electromagnetic wave from the transmission lines passed through the insulator, applying a strong electric field to two carbon-coated metal rings, parallel to each other and about an inch apart. Electrons flowed out of the rims of these rings, or cathodes, and drifted toward the fuel pellet, which was suspended in the center of the chamber between the cathodes. By injecting ionized gas (plasma) into the diode and by using the magnetic forces generated by the flow of electrons, the electrons could be focused and the pellet uniformly irradiated.

Proto II was used to develop improved methods of switching high-current pulses so that short bursts of electrons were produced, and to study the power flow through the insulating wall separating the transmission lines and the diode. It was also used to test energy storage. When PBFA I began operation in 1980, Proto II continued to be used for research into imploding foils. In 1984-85, Proto II was upgraded, became a successful test bed for the multiple ring diode concept envisioned for and implemented in Saturn, and had a reduced inductance driving z-pinch loads. The upgrade was implemented by a team including staff from Pulse Sciences, Inc. (headed by Phil Spence), Rick Spielman, McDaniel, Tom Wright, Warren Hsing, and Mark Hedemann. This was one of many collaborations between Sandia and Pulse Sciences, Inc. beginning in 1980 when the latter was founded.

Important work related to developing and improving Proto I and Proto II was summarized in a *Sandia Lab News* article of October 31, 1975, concerning the first International

Conference on Electron Beam Research and Technology hosted by Sandia in November of that year, summarized here.

Sandia had improved its ability to predict test results, record test data with increased precision, and analyze those data later. The goal was to determine the degree of symmetry of loading and subsequent compression of the spherical fuel pellet after irradiation by the electron beam. The key to symmetry was the "beam pinch," or the tight focus that could be achieved.

The speed of focus was also critical—ideally the beam should pinch to 1 mm early, not late, in the exposure period.

Al Toepfer, head of the Electron Beam Research department, explained that Sandia could now obtain up to four high-resolution holograms of target response within 15 nanoseconds because of work done by Paul Mix. Jim Chang was obtaining high-quality flash radiography of imploding targets, and Mel Widner used those data and optical measurements of implosion times done by Frank Perry to determine the beam energy deposition characteristics.

John Freeman, head of Plasma Theory, said the theoretical work was a combination of studies instigated by experiments and more speculative feasibility studies, such as current flow in diodes carried out both by ions and electrons, which James Poukey was doing. At the time, his code was state of the art in its field. (Please see related sidebar on early codes in this chapter.) In related work, Milt Clauser was studying the benefits of ions instead of electrons in pellet implosions. Both of these theoretical programs were tied in to experiments on spherical ion diodes being done by Paul Miller.

[Based primarily on the article "Particle Beam Fusion Accelerators" in *Sandia Technology*, Vol. 2, No. 3, October 1976, which fully covers the technology and machines for the fusion program from Proto I to the concept for EBFA. Information was also derived from "E-Beam Machine Will Advance Fusion Research," *Sandia Lab News*, February 25, 1977, and from comments by Ian Smith in January 2007.]



Standing atop the diode of Proto II, where x-ray laser experiments were performed for the Strategic Defense Initiative in 1984, are Keith Matzen, Rick Spielman, and Warren Hsing. Proto II then was used in an experimental program to develop a pulsed-power-driven x-ray laser. 1984 photo.

a Fast-charged multi-site switching in water was first developed by Richard Miller at Maxwell Labs. He explored the approach extensively in early 1974, after seeing some initial work at the Naval Research Laboratory in 1973 that was published in November 1973. Maxwell's Blackjack 3 ¾ was the first operating machine that used the technique, and it came on line in late 1974. Physics International built PITHON, which came on line in 1975, using the same technique, on the basis of what it heard about Maxwell's work. Miller later was awarded the Erwin Marx award, which recognized this multi-site switching in water among other work of his. (Information kindly provided by Ian Smith in January 2007.)

Electron-beam research in the Soviet Union was headed up by Leonid Rudakov at the Kurchatov Institute in Moscow. Because the target designs in the United States and Russia were classified and weapons-related, it was somewhat ironic that the *Times* said only as an aside, “Because of potential military applications, there are also secret efforts in the United States and presumably in the Soviet Union.” The truth was that the non-secret aspect of fusion work was only the tip of an iceberg. The newspaper said that a new approach was being pursued in the United States that even the Soviets did not know of—ion beams. In fact, at Sandia and at the Naval Research Laboratory, experiments with electron beams and fusion targets were revealing that the ions created inside a diode might work better than electrons in igniting fusion. Consequently, in electron-beam experiments at Sandia, ion beams were also being closely studied.²⁵ Laser fusion research, of course, continued as the nation’s major approach to inertial confinement fusion.

In 1976, Yonas and Narath went to Washington to sell Sandia’s fusion program and try to obtain funding approval for the long-planned EBFA. The Sandia team promoted its electron-beam work and emphasized its merits as compared to the laser approach, seeking line-item Congressional approval for \$14.2 million at a time of tight appropriations. Sandia was able to convince Senator Montoya of the merits of its proposal and the need for the machine. Montoya testified at the Joint Commission on Atomic Energy, and the funding was finally approved. In later years, Yonas recalled that to get the sums needed for large pulsed power machines at Sandia, “it took a lot of politics and a lot of Congressional support. It’s never easy to get money for big machines. For fusion, many times it looked like the end of the world: it was always a hairy edge.”²⁶

That same year, while visiting several US laboratories and giving presentations, Rudakov, whom the *New York Times* had mentioned in January, publicly revealed that he and his Russian laboratory were using electron beams to create soft x rays to compress fusion fuel at low energy levels, confirming what the *Times* had reported. He said an enormous follow-on electron-beam accelerator named Angara 5 was being proposed at a cost of \$55 million. In an assessment written in 1976 comparing the Russian approach to Sandia’s, Sandia said that the Soviets were using conventional pulsed power technology, that is, multiple beams with beam transport, thus focusing the beams at a distance from the generator. Sandia was then attempting to focus the beams within the diode itself, emphasizing an “in diode” approach to ignition, and avoiding the need for beam transport and compression systems. Separating the fusion reaction from the accelerator (stand-off), as the Russians were doing, had the advantage of allowing larger reactions, but Sandia predicted problems with concentrating the beam onto the target. It was generally believed that larger reactions and stand-off would be favorable aspects in developing the technology into an energy source, once fusion had been attained.

However, during the course of his talks, and totally unexpectedly, some of the information Rudakov revealed about inertial confinement fusion—dealing with

the fusion targets—was classified and known only to certain scientists within weapons programs in the United States and United Kingdom. And even there, because of the mandate that discussions of classified material be limited to people who had a need to know, certain details about the fusion targets were unknown, for example, to the accelerator builders. As Tom Martin explained it later, “The target folks just kept asking me for a bigger hammer but they did not say exactly what it was for.”²⁷ Many pulsed power veterans at Sandia who were in the program in 1976 recall that the bombshell Rudakov set off dealt with how the fusion target should be constructed and irradiated so as to ignite the fusion reaction. Because aspects of this information could pertain directly to the design of nuclear weapons, most of it remained classified in the United States until 1993.²⁸

The flavor of the disclosure is mirrored in the following write-up, by a source with a clear bias:

October 1976. *New Solidarity*. Disclosures by the Soviet electron-beam fusion researcher Dr. L.I. Rudakov, first reported here earlier this month and now known in greater detail, leave no reasonable doubt that Soviet scientists have mastered scientific-technological capabilities which at a minimum would permit them to improve the efficiency of their thermonuclear weapons . . . Rudakov has demonstrated that an electron beam directed against a metal foil, which shields a pellet of fusionable material, produces a highly non-linear plasma configuration beneath the shield. Through interaction with that plasma, hard x rays are converted into soft x rays, which can produce isentropic compression of the pellet of fusion fuel.

Efforts to declassify information about inertial confinement fusion target research being done in the United States stepped up at this time; classification not only shut out certain foreign collaboration, but much of US industry as well. Nevertheless, declassification would prove to be an uphill battle until the early 1990s. The implications of Rudakov’s breakthrough were not confined to basic high-energy-density physics; if true, the capability could position the Soviet Union as the leader in weapons work. The result of the Soviet disclosure was a somewhat ironic bolstering of the US electron-beam effort, because of fears the United States might be behind.

At this time (1976), a new area of accelerator technology—pulsed power accelerators for repetitive operation—was begun in Sandia’s Pulsed Power Program. Prestwich was named supervisor of a new division where the work would be carried out. Because lasers that were sufficiently efficient to be used as potential reactor drivers would require electron beams to excite their gases, the program was justified as being related to Sandia’s inertial confinement fusion program. Prestwich remembered attempts at the time to try to make repetitive-rate accelerator development a significant part of the national fusion program, but said it ended up as a four-person effort.²⁹ Malcolm Buttram and Juan Ramirez, who had been in

Martin's division, were assigned to the new group; both men would be important to the overall program for many years. Among his many accomplishments, Ramirez was responsible for leading development of the innovative Hermes III accelerator in the 1980s. Buttram had helped develop a repetitive pulsed power generator for a cloud chamber beam diagnostic tool at Argonne National Laboratory before joining Sandia in 1975. In 2001, Buttram would be given the prestigious Erwin Marx award.

A small pulsed power program had been under way at Sandia Livermore, but because of Yonas and Narath's efforts to concentrate the work under one roof, its staff was transferred to Albuquerque, at first under Martin. From California, Gene Neau remained in Martin's group and Gerry Rohwein joined Prestwich's new group when it was created.³⁰ At Livermore, Rohwein and Neau had built Trace I, an electron-beam machine similar to Nereus but using a transformer to multiply the voltage, a design attractive for repetitive pulsed power work. Part of Prestwich's responsibilities was to develop reactor concepts, and Don Cook was hired that same year for his experience at the Massachusetts Institute of Technology in doing magnetic fusion reactor design. (Cook would become director of the Pulsed Power Program in 1993.)

With a new administration in the White House under President Jimmy Carter beginning in 1977, attitudes toward fusion work changed. In the first year of its existence, the Carter administration (1977-1981) abolished ERDA and created a cabinet-level Department of Energy, which began operation in October. The new department had a strong leaning toward renewable energy and conservation programs as answers to the nation's energy situation. It did not favor nuclear breeder reactors for power plants, as they were regarded as a dangerous stimulus to proliferation of nuclear weapons. The first Department of Energy secretary, James R. Schlesinger, Jr., was alarmed by what he considered a huge increase in the overall budget for fusion compared to what it had been in 1973 when he left the Atomic Energy Commission. He wanted to trim \$100 to \$200 million from fusion and reassign it to other programs. As part of that effort, he established an Office of Energy Research in the Department of Energy with John M. Deutch as the head. Deutch's priority was to assess the nation's fusion programs, and he saw to it that both magnetic and inertial fusion would come under the microscope of a lengthy review by a panel headed by John S. Foster.³¹

Sandia broke ground for the Electron Beam Fusion Facility on January 21, 1977, a festive occasion on a cold day in a barren location south of Sandia's main campus, with Sandia's president Morgan Sparks and a crowd of 150 looking on. The *Sandia Lab News* reported on the event on January 28, noting the \$14.2 million facility would be home to a 40-terawatt accelerator that could create either electron or ion beams. The facility was designed with a laboratory, basement for equipment, two adjacent annexes, and an associated office building, and was to be the heart of a new technical area of the Laboratories known as Area IV. The huge EBFA and the equipment needed to operate it were estimated to cost \$8 to \$9 million of the total.

The facility and accelerator were scheduled to be completed late in 1980. (Please see following sidebar on EBFA-PBFA.) A month later, the *Sandia Lab News* reported that testing had begun on Proto II, one of the two accelerators built to help develop technological concepts for EBFA. Proto II was designed to produce 8 trillion watts in a pulse lasting 24 billionths of a second; when completed, EBFA would produce 40 trillion watts in the same brief instant. In full operation at the time Proto II started up, Proto I was producing 2 trillion watts.

Not in the *Sandia Lab News*, however, was a development that would change the course of Sandia's technology within a few years. The *Electron Beam Fusion Progress Report* for October 1976 to March 1977 shows that Sandia was considering light ion and heavy ion beams at this time, in addition to electrons. The report states that because of discoveries made since the electron-beam fusion program began, “. . . the program can now be described as a triad with pulsed power central to each approach. . . . Our program is therefore best described as one following a primary direction, namely the use of electron beams, but with other alternate paths considered through the EBFA I stage.”³²

Sandia's pulsed power machines were versatile enough that they could be reconfigured to produce a number of different types of particle beams. Although the reconfigurations were complex and demanding, they typically involved reusing and improving existing facilities, and planning to build new machines, such as EBFA I and II, only when a great increase in power was required.

Pulsed power accelerators could be configured according to the desired use: irradiating a weapons component with x rays or heating a fusion pellet to ignite a fusion reaction. The requirement was to drive a defined load (e.g., the pellet) reliably and efficiently—meaning the machine had to be configured at a certain voltage and current to cause a specific effect. In the case of driving a fusion pellet, unheard of power was required; hence the need for a much larger and more powerful accelerator. Sandia's accelerator designers were asked to provide increasingly bigger hammers, as Tom Martin put it; it was then up to the target teams to configure the load, whether that was a diode for fusion pellets or a device for weapons tests. Consequently, target design was increasingly a concern; the beam had to be precisely matched to the load. No one had been able to come up with a credible electron-beam target and ions seemed more promising. (Electron beams preheated the fusion fuel in the target, and the targets did not work as designed. The targets needed to implode, compress the fusion fuel, then heat the fuel very quickly to work.)

In June 1977, fusion neutrons were detected from a reaction produced by Sandia's Rehyd accelerator,³³ and this success was reported as opening up new hope for using controlled fusion in commercial power generation. On June 17, the *Sandia Lab News* reported that electron beams from an accelerator, unnamed in the article, had irradiated a deuterium-filled fusion pellet to a temperature sufficient to make

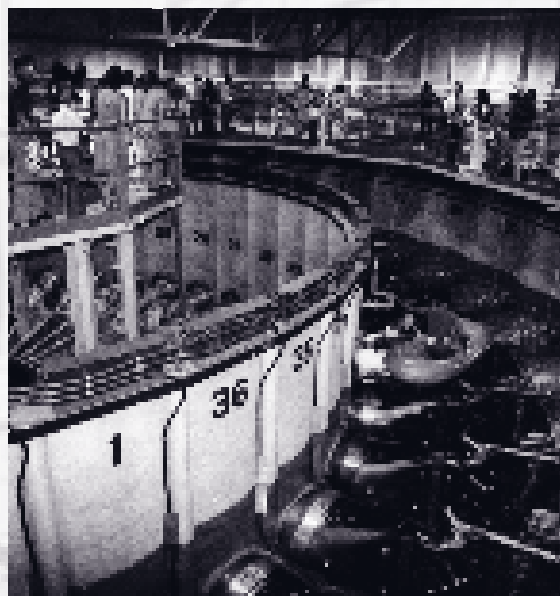
Countdown to EBFA make that PBFA I

Groundbreaking ceremonies took place for the Electron-Beam Fusion Facility in January 1977, marked by a photo in the *Sandia Lab News* on January 28, 1977. A year later, on January 6, 1978, a photo in the paper shows the EBFA labs and office buildings approximately 50 percent complete, with plans for the accelerator buildup to be in October and the offices occupied by Christmas of that year. The new site for the facility was called Area IV, about a mile and a half due south of the main Sandia campus in Area I. EBFA and associated structures were the initial occupants of what had been vacant desert.

Another *Sandia Lab News* photo, on November 27, 1978, shows the circular, wheel-like support structure for EBFA I being constructed in the new building. The EBFA I project mechanical design team is pictured with the skeleton structure, including George Hiett, Tiny Hamilton, George Staller, and Marlin Aker. The caption predicts the accelerator assembly will be complete and the accelerator operational by June 1980. Construction of the nearby laboratory building was almost complete and would be occupied in mid-January 1979 by the Fusion Research Department and the Pulsed Power Systems Department.

In November 1978, Sandia was projecting that after experimenting with EBFA I for two years, the machine would be shut down and upgraded to EBFA II, with funding for the preliminary engineering of the second machine expected in FY79-80. Completion was hoped for by 1983. In an article for the November 1978 issue of *Scientific American* titled "Fusion Power with Particle Beams," Gerold Yonas said EBFA I was designed for a capability of 30 trillion watts to the target area and that the upgrade to EBFA II should double the power level. At this level, he thought pellet ignition experiments could begin as early as 1985. At this time, he said that EBFA I could be adapted to produce ion beams for fusion research.

A timeline titled "Significant Events in Pulsed Power Fusion, Sandia National Laboratories" dated January 1980 indicates that the ion-beam baseline approach was chosen in 1979 over the electron-beam approach for PBFA I and II. (The timeline is in many of the archival



The crowd assembled for the 1980 dedication of Sandia's Particle Beam Fusion Accelerator (PBFA I) watches technicians at work in the water around the machine. It accelerated light beams for Sandia's internal confinement fusion experiments aimed at producing abundant, economical energy during the 21st century.

collections and a copy is in the Van Arsdall folder for the 1970s.)

Memos from May 1979 onward indicate that the decision whether to commit fully to the ion-beam approach was needed by the end of the year. (See Yonas notebooks for 1979 in the Sandia History Archives for these memos.)

Documentation on the actual change in name from EBFA I and II to PBFA I and II is scarce; but the decision to switch to light ions and the associated change in names occurred in the second half of 1979, as revealed in the *Particle Beam Fusion Progress Report* for July-December 1979 (SAND80-0974, January 1981). The name change may have been as informal as Yonas recalled in an interview in 1984 with Sandia historian Necah Furman: "We were not so pleased with our electron-beam accomplishments, but we were very impressed with the ion results we had achieved. In 1979, we had a sign out here on the road that said Electron Beam Fusion Facility and one day in 1979, we took the sign down and changed it from electron beams to particle beams, which meant we were now changing our emphasis to ions." Beginning in 1980, reference is made to PBFA I and II.

many deuterium nuclei fuse. The report explained that when two nuclei fuse, a new atom is created, and a neutron is released. In the experiment, the newspaper said that about a million fusion neutrons were produced per pulse—the first time in the United States such a device had produced neutrons. Although neutrons were certainly detected, the ability to monitor the event was limited, and the technique was not repeated. (This was the Φ target, which relied on magnetic insulation in the fuel to keep the fuel hot enough to produce fusion. The behavior of the Φ target was also hard to analyze computationally because the ability to model the system in two or three dimensions was necessary, but not readily available.) In fact, the Pulsed Power Program was already moving toward ion instead of electron beams, and so nothing more came of the event at that time.³⁴ Others, notably the Soviets, claimed the ability to produce fusion neutrons using various techniques, but there were problems with all of them. Proof of producing fusion neutrons is important because it is a first step toward being able to use controlled thermonuclear fusion for energy. The extra neutrons can be absorbed in a material and then used to produce heat and electrical power. However, numerous other considerations and innovations will be needed after fusion neutron production before the dream of a fusion reactor can be realized.

In a development that affected pulsed power, events on the national scene during 1977 brought to the fore ideas that had long percolated in the minds of researchers about the possibility of using particle beams and lasers as weapons. It was an obvious capability to which both technologies might be suited. In April 1977, Major General George Keegan, former head of Air Force Intelligence, alleged in public reports that the Soviets were 20 years ahead of the United States in developing a technology that would neutralize the ballistic missile weapon as a threat. He confirmed that he was talking about a charged particle beam. At this time, missiles were the heart of US military strategy, although kept in check by the ABM treaty and SALT. The Carter administration debated the implications of such a weapon, though not denying it might exist. Keegan justified bringing the threat of a Soviet beam weapon out in the open because he claimed his information was being swept under the rug and he felt the nation was at risk.³⁵ The fusion work at Sandia using particle-beam accelerators and elsewhere using lasers would naturally be at the center of any national beam-weapons activities. Nothing immediate resulted from Keegan's allegations, but the seed of a concept had been planted.

In September 1978 a major reorganization at the Laboratories placed Gerry Yonas at the head of a new directorate of Pulsed Energy Programs under vice president Al Narath.³⁶ The directorate contained four departments: Laser Physics under Jim Gerardo, Simulation Technology under M. Cowan, Fusion Research under Glenn Kuswa, and Pulsed Power Systems under Tom Martin. Hermes II, REBA, and other machines primarily used for weapons simulation were in the simulation division. Also at this time, results of the Foster Committee review were presented to

Particle Beam Weapons Make Headlines in 1977

Aviation Week and Space Technology published an editorial on the “Beam Weapon Threat” in its May 2, 1977, issue. It was a follow-up to the magazine’s March 28, 1977, story in which Maj. Gen. George Keegan’s allegations about Soviet advances in the field of beam weapons were made public for the first time. The editorial called for an end to the secrecy surrounding the topic:

The Soviet Union has achieved a technical breakthrough in high-energy physics application that may soon provide it with a directed-energy beam weapon capable of neutralizing the entire United States ballistic missile force and checking this country’s strategic doctrine.

The hard proof of eight successful Soviet tests of directed-energy beam weapon technology gives new and overriding urgency to bring these developments into the public domain and rip the veil of intelligence secrecy so that this whole matter of vital national urgency and survival will finally be brought to the attention of the President of these United States, the Congress, and the citizens of this republic whose future is at risk.

It could be a fatal error for this country to continue to put its major strategic reliance on a single type weapon for which an effective counter is already looming on the horizon.

At issue were US intelligence reports on tests the Soviet Union had made that suggested work on directed-beam weapons. The intelligence reports could not verify how far along this work was, nor when a Soviet directed-beam weapon could be deployed. Keegan, believing that the threat was imminent, made the issue public because he felt it was being swept under the rug in official circles.

A May 2, 1977, article, also in *Aviation Week and Space Technology*, was titled “Soviets Push for Beam Weapon: USSR developing charged-particle device aimed at missile defense, exploring high-energy lasers as satellite killer.” The article outlines the evidence that prototype directed energy weapons (using both particle beams and lasers) were under way in Russia and provides the evidence and arguments both supporting and rejecting Keegan’s conclusions.

Science News writers John Douglas and Dietrick Thomsen came to the conclusion that the threat was highly overrated after talking with US scientists and military personnel. Their article “The Great

Russian ‘Death-Beam’ Flap: News reports of Soviet advances toward a weapon-sized charged particle beam seem based on good intelligence, fair physics, and poor strategy considerations” appeared on May 21, 1977. The article explains why “serious questions can be raised about the feasibility of a charged particle beam weapon.” The authors assert that “Even graver doubts can be brought up about its capacity to protect a nation against intercontinental ballistic missiles.” One major reason they cite in debunking the threat was the fact that US and Soviet scientists had been sharing information about beam physics for several years and that they were familiar with each other’s capabilities. “To be useful as a weapon,” they write, “a beam must be able to burn a hole in the atmosphere—heating the air along a column long enough to create a temporary vacuum for the passage of the rest of the beam. Leading American physicists say that simply hasn’t been done—either in the Soviet Union or the United States.”

Science magazine laid out the issues involved on April 22, 1977, under the title “Particle Beams as ABM Weapons: General and Physicists Differ.” The magazine said that the United States had experimented with using an electron beam as a directed energy weapon in a program named Seesaw, which was abandoned in 1973. Keegan had alleged the Soviet Union was successfully using proton beams, not electrons. *Science* said that Jeremy Stone, director of the Federation of American Scientists, had told the Senate Arms Control sub-committee in March that the idea of using particle beams as weapons “has been invented and reinvented almost every year since there were these particle accelerators.”

As to the technical feasibility of using particle beams as weapons, *Science* quoted a scientist knowledgeable about military affairs as saying, “Just getting the beam to propagate over the long distances has been thought of as the principal difficulty. You have high current beams of relativistic particles. No matter how you slice it this means very large powers. Also the design of a suitable accelerator is rather problematical.” In a May 27, 1977, commentary, “Charged Debate Erupts over Russian Beam Weapon,” *Science* concluded that there was not enough evidence to support Keegan’s claims and took the stand that opening discussion of intelligence matters to public debate might “jeopardize sources and reveal the extent of American knowledge about Soviet activities.”

the House Committee on Science and Technology.³⁷ The committee had examined the Department of Energy's magnetic confinement and inertial confinement approaches.

The report began by saying the Department of Energy's total budget for applied research in fusion energy in FY 1979 was \$481 million. (That same fiscal year, the total budget requests to fund inertial confinement fusion at all three weapons laboratories ranged from \$76 to \$80 million.³⁸) Although the intent was a report card on progress toward the prospects of using fusion for energy applications, the findings of the committee bolstered a desire on the part of the Office of Energy Research that all approaches toward fusion be equally funded. With the number of technologies being tried (lasers, electron beams, tokamaks, and other contenders, including heavy ions at Berkeley), the report said that when one or several technologies were successful in producing fusion in the laboratory, then and only then should power plants be designed. As in earlier reports, specific concerns were voiced about the classified status of much research in inertial confinement fusion. The secrecy inhibited collaboration among scientists, constraining progress. The report highlighted a need for more funding in the inertial confinement fusion area for breakthroughs to occur.

Construction of EBFA was well under way at this time, with a target date for completion of July 1, 1980. However, results from experiments using the Proto II and HydraMite machines were indicating that ion beams irradiated the fusion pellet in a way much more conducive to compressing the gas and setting off a fusion reaction, just as the *New York Times* had reported back in 1976 and confirming what many researchers at Sandia and elsewhere had suspected. (Please see following sidebar on Magnetically Self-Insulated Transmission Lines.) Electron beams heat both the shell of the fusion pellet and the gas inside it, whereas ion beams deposit their energy in the thin outer wall of the pellet, causing it to heat very rapidly. The heated outer surface blows away, and as it does the gas in the center of the pellet is rapidly compressed and heated; theoretically this will create the conditions needed for fusion more efficiently than if electron beams are used. By the summer of 1979, theoretical predictions indicated that the electron-beam approach could not succeed. Recognizing that ion beams were much more promising for this application, midway through the project the name was changed to Particle Beam Fusion Accelerator (PBFA), and the thrust of the work shifted to configuring the accelerator for ion-beam technology.³⁹ (Please see following sidebar on EBFA/PBFA: Electron Beams vs. Ion Beams.)

As the Labs had done earlier when planning for EBFA and trying to sell the concept to the Department of Energy, even while EBFA/PBFA was under way, Sandia was formulating plans for a successor, an accelerator capable of 60 trillion watts envisioned for the 1983/85 timeframe.⁴⁰ In fact, the Department of Energy decided rather at the last minute to fund EBFA II in 1979, and Yonas and Narath had to

Chapter Two

rush to Washington, DC, to get the requisite signatures for the \$56 million facility. A sensitive issue in selling PBFA II was that after having argued for upgrading EBFA/PBFA into a more powerful electron-beam machine, this was a proposal for an upgrade using an as-yet-unproven technology: ion beams. Research at Sandia and other places, in particular Cornell, showing the promise of ion beams was invoked, and the head of fusion work at the Department of Energy was swayed into approving Sandia's request. (Please see following sidebar on PBFA II funding.)

By 1979, Fusion Research at Sandia was divided into Particle Beam Fusion Research and Pulsed Power Systems; that is, the targets and the "hammers" that drove them. That year, the Department of Energy named Sandia the lead laboratory for pulsed power development and also designated Sandia, Los Alamos, and Lawrence Livermore as national laboratories. ♦

Magnetically Self-Insulated Transmission Lines

At the voltages and energies being used in Proto I and II and in the later PBFA machines, the vacuum transmission line between the water/vacuum interface and the reaction chamber had to be unusually long (6 m). A discovery about how to control electron flow between metal conductors in the transmission line enabled Sandia to develop the concept of magnetically self-insulated transmission lines. Without magnetic insulation, it would have been impossible to transmit efficiently these high-voltage pulses in a vacuum over the required distances. Used in PBFA I and II, this technology was the key to producing modular accelerators that are scalable. (Physics International and the Kurchatov Institute were also working on this technology at the same time as Sandia.)

A magnetically self-insulated transmission line carries the power pulse to the reaction chamber. The magnetic field induced by the movement of the electrons provides insulation by inhibiting electrical breakdown of the vacuum gap separating the internal cathode from the surrounding anode. Ahead of the pulse, where the magnetic field is weak, some electrons can escape, resulting in an energy loss. Within the central region of the pulse, however, the strong, self-generated magnetic field forces the electron flow to remain near the surface of the cathode virtually without loss.

Without this self-insulation feature designed into the transmission line, it would be impossible to deliver terawatt power levels efficiently over a distance of several meters. Because of magnetic insulation, as early as 1982, 2-megavolt pulses were routinely transported with nearly 100 percent efficiency along the 6-m distance from the water/vacuum barrier to the reaction chamber containing the diode. The vacuum interface between the pulse-forming network and the vacuum insulated power feed to the load has been the persistent limiting bottleneck for pulsed power accelerators.^a

Unfortunately electron-beam fusion and z-pinch fusion require large currents and work best with a short rise time. Although Sandia could have built EBFA I with a conventional vacuum insulator like on PROTO II, that approach would not scale to EBFA II for electron-beam fusion, so Sandia developed self-magnetically insulated power flow to provide the 2-megavolt “extension cords” to connect the pulse-forming networks to the vacuum insulated load. The current in each

The development of a concept for magnetically self-insulated transmission lines involved the Kurchatov Institute, Physics International, and Sandia. It involves using the self-magnetic field of a powerful electromagnetic pulse to inhibit breakdown and is central to power concentration. Without the self-field approach, the power that could be transmitted in a reasonably sized transmission line would be less than 0.1 terawatt. On the other hand, at high power levels, the self-magnetic field of the traveling wave causes the emitted electrons to return to the high-voltage electrode, and power levels of 1 terawatt or greater can be transmitted. (From Particle Beam Fusion, Pulsed Power Program, Sandia National Laboratories, 1980)

module was modest and the currents from all modules were added in series/parallel combinations with convolutes in vacuum.

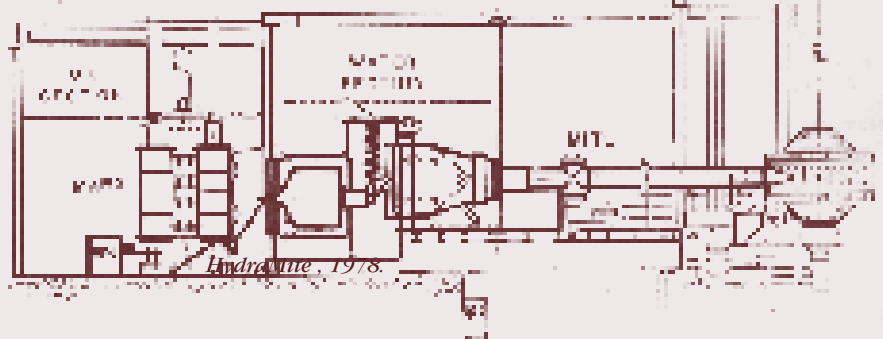
Magnetically insulated power flow works even though the negative conductor (cathode) copiously emits electrons, because the loss current makes a self-generated magnetic field that bends the electron trajectories to keep them away from the positive conductor (anode). Sandia knew that this effect worked in an electron beam diode but did not know what would happen in a long transmission line. The power flow technology was inefficient until experimenters learned how to launch the electron flow smoothly and avoid electron instabilities. The successful technology gave a scalable high-current technology with long magnetically insulated transmission lines.

By the time EBFA I was built, the program had moved to ions. Ion diodes have a very high initial impedance so that a lot of energy is lost at the end of the magnetically insulated transmission lines before the impedance falls to match the impedance of the line. However, the change from EBFA I to PBFA I and the decision to build a new and higher voltage PBFA II (instead of adding another 36 modules to PBFA I) allowed Sandia to build PBFA II with a conventional vacuum insulator and a short magnetically insulated transmission line.

A magnetically insulated transmission experiment, known as MITE, was a test bed used in the late 1970s for PBFA I. Its team included Pace VanDevender, Johann Seamen, and Bill Moore.

[From *Sandia Technology*, Vol. 6, No. 3, October 1982 (SAND82-1398) and from information provided by Pace VanDevender and Cliff Mendel, August 2006.]

^a The relatively low electric field (voltage per unit interface length) of vacuum-insulator flashover means that high voltage requires long insulators, which means a large volume to fill with magnetic field energy. That volume is an inductor in series with the load and the voltage across the insulator becomes the load voltage plus the inductor voltage—i.e., inductance times the current divided by the rise time of the current. If the current were low or the rise time were long, then the additional voltage is small compared to the load voltage.



EBFA-PBFA: Electron Beams vs. Ion Beams

Part of an earlier machine called Hydra was turned into a prototype for EBFA. It was named HydraMite, meaning one module of Hydra and the Magnetically Self-Insulated Transmission Experiment (MITE) were combined into a test bed.

HydraMite provided a full-power test of a PBFA I module in 1979, producing an 0.8-terawatt, 2-megavolt, 400-kiloamp, 35-nanosecond pulse for PBFA-type experiments. This result permitted the final design to be released to build PBFA I. That same year, results from experiments on pulse inversion and stacking using MITE and HydraMite were important to the decision to make the change to an ion-beam baseline approach for PBFA I and II. As a result, construction began that year on SuperMite, a full-scale module of PBFA II on which concepts for the more powerful machine would be tested using ion-beam experiments.

In the fall of 1979, the decision was made to switch to ion beams and to change EBFA I into PBFA I not only in name but by altering the technology. In a 1984 interview with historian Necah Furman, Gerry Yonas said about the change: “When PBFA I was completed in 1980, it was a machine which had lived through a transition—it had been built as an electron-beam machine and at the eleventh hour had been converted to an ion beam machine through some clever inventions of Pace VanDevender and Tom Martin. Basically, when the machine was finished, it was a machine with a big gaping hole in the middle because we still had not developed an ion gun—we had the electricity but no ion gun. The reason why is that we had built this machine all along toward the electron beam approach and in the eleventh hour we switched, so we were unprepared.”

A Sandia publication of January 1980 titled *Particle Beam Fusion* issued by the Pulsed Power Program (with no official SAND

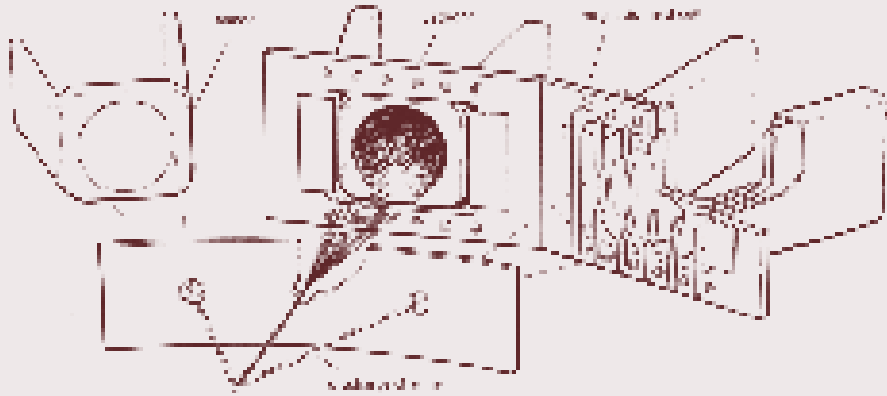
number, but in color) describes PBFA I and the plans for PBFA II as follows:

The 36 separate beam lines of PBFA I will be able to deliver 30 trillion watts of power and 1 million joules of energy to electron or ion sources when it begins operation in mid-1980. In the design of PBFA I, the eventual need to build an upgrade was recognized, so the tank containing the accelerator was designed with sufficient room to contain the modified accelerator. The parameters of this accelerator are to be optimized for ion beam fusion, but the accelerator will also be ideal for radiation effects experiments using electron beams. PBFA II will have 72 beams, operate at nearly 4 million joules output energy, and will supply 4 million volts instead of the 2 million volts specified for PBFA I, which itself will be the world’s largest pulsed power accelerator.

The flexibility of pulsed power technology allows us to change the voltage from 2 to 4 million volts and to reverse polarity within the volume of the PBFA I tank. Thus a machine designed to supply one million joules to electron sources will be upgraded to supply four million joules to ion sources.

Issues with Electron Beams and Ion Beams in the mid-1970s

Early in accelerator development at Sandia and elsewhere, researchers realized that the diodes in electron-beam accelerators produced intense ion beams as well as electron beams. In these diodes, the anode is bombarded by electrons throughout the beam pulse. If the density of the electron current is high enough—several kiloamperes per square centimeter or more—then the anode material and anode surface contaminants are heated and turned into a plasma sheet before the end of the pulse. The electric field of the diode then pulls positively charged ions from this anode plasma and accelerates them to the cathode. The result is that a very powerful ion beam can be generated.



Light ion beams are generated with the same pulsed power technology as for electron beams. But here, the goal is to suppress the flow of electrons and to extract from the diode a converging light ion beam. Drawing from Particle Beam Fusion, Pulsed Power Program, Sandia National Laboratories, January 1980.

Researchers began to believe that intense ion beams had several advantages over electron beams in trying to ignite fusion targets. Ions lose energy more rapidly near the end of their path than at the beginning, so the peak in the energy deposition profile occurs deep within the target shell rather than near its surface. This manner of energy deposition increases the hydrodynamic efficiency of fuel compression and thereby lowers the ignition power requirements significantly.

On the other hand, electrons interacting with the shell of the target generate Bremsstrahlung (a type of radiation), which is absorbed by the pusher and fuel, producing a very low level of energy deposition throughout the target. The inner part of the target is preheated and the heat builds pressures that resist the compression of the target implosion. This detrimental preheating effect does not happen with ions because they produce essentially no Bremsstrahlung as they slow down.

Another difference between electrons and ions is that many of the incident electrons can backscatter from the surface of the pellet, whereas ions do not backscatter appreciably. Depending on the electric and magnetic fields surrounding the target, electron backscattering could lead to a significant decrease in the fraction of beam energy that is deposited on the target.

Sandia researchers reasoned that the desirable energy-deposition characteristics of ions might reduce the power requirements for fusion ignition using ion-driven targets by as much as a factor of 5 or 10 below requirements for electron-driven targets. In addition, ions had the advantage that the power for ignition could be obtained at lower currents and higher voltages than was the case for electrons.

In 1976, the ion-beam approach to fusion was looking promising, but little was known at the time about problems that might be encountered. The assumption was that eventually, ion

beams could be generated as efficiently and focused as tightly as electron beams. At the time, ion beams had a much lower efficiency than electron beams, but techniques using magnetic forces were being developed to improve ion beam efficiency.

In one approach, a strong magnetic field was applied parallel to the anode and cathode surfaces, bending the orbit of electrons and keeping them from crossing the anode-cathode gap, thus greatly suppressing the flow of the electron beam. Because the ions associated with the beam were massive, their trajectories were only slightly bent by the magnetic field, improving the beam's efficiency.

Another technique used the self-field of a pinched electron beam to provide the magnetic insulation. In a normal focused-electron-flow diode, the flow of electrons off the axis is inhibited by the self-field, but ions cross the gap in nearly straight lines. The overall efficiency of ion-beam generation can be high in a focused-electron-flow diode.

Once ion beams could be generated efficiently, researchers knew the next challenge would be focusing them onto a small target. High-current electron beams tend to be focused by their self-magnetic fields, but this process is ineffective with ion beams because ions have a greater mass than electrons. In 1976, Sandia was considering using concentric, spherically shaped anodes and cathodes as a means to focus the ions.

[Condensed from "The Particle Beam Fusion Program" in *Sandia Technology*, Vol. 2, No. 3, October 1976 (SAND76-0615). Editors listed are J.A. Mogford and W.L. Garner, with G. Yonas listed as the primary contact.]

Winning Approval for PBFA II Funding

PBFA II was sold to the Department of Energy as an upgrade of PBFA I. But, as the ion program proceeded, it was obvious to us that the original idea, which was born of the electron-beam program, wouldn't really work. That was a critical period in the program. We realized we would have to build a much more difficult machine, and the story of how we were able to make that transition is interesting. We continued to talk to Washington about the need for a new machine, and it didn't seem to go anywhere.

One day, I was in San Francisco at a meeting and received a phone call from Washington saying we had three days to sell this new machine—the upgraded PBFA II. I called Al Narath and we went to Washington and met the head of the program, who at that time was Greg Canavan. We never knew what had changed his mind, but clearly there was now a deadline. The machine had to be sold by Wednesday—and by then we had to have a piece of paper from John Deutch (head of the program) approving the upgraded machine. But first, on Tuesday, we had to sell this to Duane Sewell. We made our presentation to Sewell and he rejected it. We sat in the hall, glum and depressed, and in walked Canavan. He asked what the problem was—and we said our upgrade proposal had gone down in flames.

I think he called Don Kerr (head of Los Alamos National Laboratory), and I think Kerr called Sewell and turned him around. By lunchtime we had Sewell's signature.

Canavan, Narath, and I rushed up to Deutch's office without an appointment and ran into his secretary, Luanda—Luanda was a very impressive and forceful woman with an imposing personality—and she said, “no way we were going to get to see John Deutch.” We said, “but we have to get his signature. If we don't get his signature, we can't go to OMB (Office of Management and Budget), we miss the deadline, and we lose the whole year.” She didn't care. Greg tried something and I tried something, and Narath finally reached into her candy dish and offered her candy. I think she was beginning to come around. At this point, Deutch heard the commotion and came out to see what the heck was going on. That gave Canavan an opportunity to explain to him what we were trying to do. Deutch looked at me and said, “This upgrade, is it going to be for electrons?” I said, “No sir, I'm negative on electrons, I'm positive on ions. We're going to go for ions.” He said, “I'll sign it.” And he signed it.

Gerry Yonas

[Furman Interview with Gerry Yonas, 1984; Van Arsdall interview with Yonas, 2003.]

endnotes

- 1 The Department of Defense had a number of accelerators designed for the new high-current technology, notably Casino, SNARK at Physics International, and Black Jack at Maxwell Labs (a follow-up to Gamble II at the Naval Research Lab). These accelerators were scheduled to come on line at about the same time as Sandia's Hydra, Nereus, and SLIM, that is in the 1971/72 time frame, and were reasonably successful in meeting their goals. Another side to the story that comes out strongly in the literature and in discussions with Sandia engineers who recall this time is the competition, at times extremely heated, between the Atomic Energy Commission and Department of Defense laboratories, particularly at the upper levels, over funding and approaches. For a more in-depth overview of this subject, see N. Furman, Interview with G. Yonas of June 22, 1984, in the Sandia archives, Furman Pulsed Power Collection.
- 2 Van Arsdall interview with Al Narath, June 2006. In Van Arsdall Collection, Narath folder.
- 3 In 2006, Dillon McDaniel, a manager in the Pulsed Power Program who has been with the program since the early 1970s, said that by 1976 both the United States and Russia were doing foil implosions, a fusion target technique highly classified at the time and thus absent from the open literature on pulsed power. It was the target type used in the classified Scorpio program that later evolved into z pinches. Dillon McDaniel folder, Van Arsdall Collection.
- 4 Accelerators would now have to be configured for low voltage, high current, and low impedance instead of the high-voltage, high-impedance machines used for Bremsstrahlung.

Chapter Two

- 5 Gerold Yonas, "Fusion Power with Particle Beams," *Scientific American* 239:5, November 1978, pp. 5-6, outlines the emergence in the early 1960s of the idea to try to use electron and ion beams to ignite a fusion pellet. In 1967-68, US and Russian scientists came up independently with quite similar approaches. The issue was whether pulsed power machines could be scaled up to the required power for pellet ignition and whether the electron beams could be focused so as to heat the fusion pellet symmetrically.
- 6 Van Arsdall interview with Everet Beckner, August 2006. Van Arsdall Collection, Beckner folder.
- 7 Ibid.
- 8 Narath later became president of Sandia (April 1989-August 1995). Beckner became the first Vice President for Energy Programs at Sandia, after serving in several high-level management positions. Beginning in 1991, Beckner joined the Department of Energy and served in its and later the National Nuclear Security Administration's upper-level management of Defense Programs.
- 9 Gerold Yonas, *A Pulsed Power Inertial Confinement Fusion Journey*, SAND2004-2653P, Sandia National Laboratories, Albuquerque, NM, 2004, 3.
- 10 Federation of American Scientists Website on the Anti-Ballistic Missile Treaty (<http://www.fas.org/main/home.jsp>, consulted in October 2006).
- 11 The authors were G. Yonas, K.R. Prestwich, J.W. Poukey, and J.R. Freeman. Prestwich, who had built Nereus and SLIM, recalled that the wire-on-axis approach can be said to have cemented in place the accelerator fusion program at Sandia. Later that year, John Kelly patented an electron-beam generator used with REBA that concentrated the area of the beam by a factor of 10 by achieving a pinch in the beam. Kelly was in A.J. Toepfer's Electron Beam Research group, and the device was said to point the way toward some promising approaches for future work (*Lab News*, November 16, 1973).
- 12 Sandia's paper for the conference was G. Yonas, J.W. Poukey, J.R. Freeman, K.R. Prestwich, A.J. Toepfer, M.J. Clauser, and E.H. Beckner, "High Current Density Electron Beam Application to Fusion Studies." The Russian paper was L.I. Rudakov and A.A. Samarsky, "On Initiating the Impulsed Nuclear Fusion Reaction by Means of DT-Mixture Compressing by the Shell Heated with a Strong Relativistic Electron Beam." Both were published in the *Proceedings of the Sixth European Conference on Controlled Fusion and Plasma Physics, Moscow, 30 July 1973*.
- 13 Casino, in fact, was funded through the Department of Defense. It too was an electron-beam accelerator envisioned to have multiple beams, like Hydra and REBA. In an interview in 1984, Yonas said Sandia had been skeptical about its chances for success (skepticism that proved to be well founded). In the interview, Yonas reviewed territorial disputes between the Atomic Energy Commission and Department of Defense about who should be developing the new high-current machines for x-ray simulations, a feat Yonas termed "formidable" no matter who did the work. At this time, ca. 1970, the Defense Atomic Support Agency (Department of Defense) and Sandia embarked on separate design programs with the same goal, and communications were less than open between the competing laboratories.
- 14 Report titles reflect the split: SAND75-0262, *Laser-Fusion and Electron-Beam Fusion Progress Report, July-December 1974*, June 1975; SAND76-0148, *Electron-Beam Fusion Progress Report 1975*, June 1976.
- 15 See Yonas Notebooks, 1973-1976, containing letters and reports about this development. Senator Montoya asked repeatedly why Sandia had both a laser and an electron-beam program. The issue, as always, was funding and competing priorities.

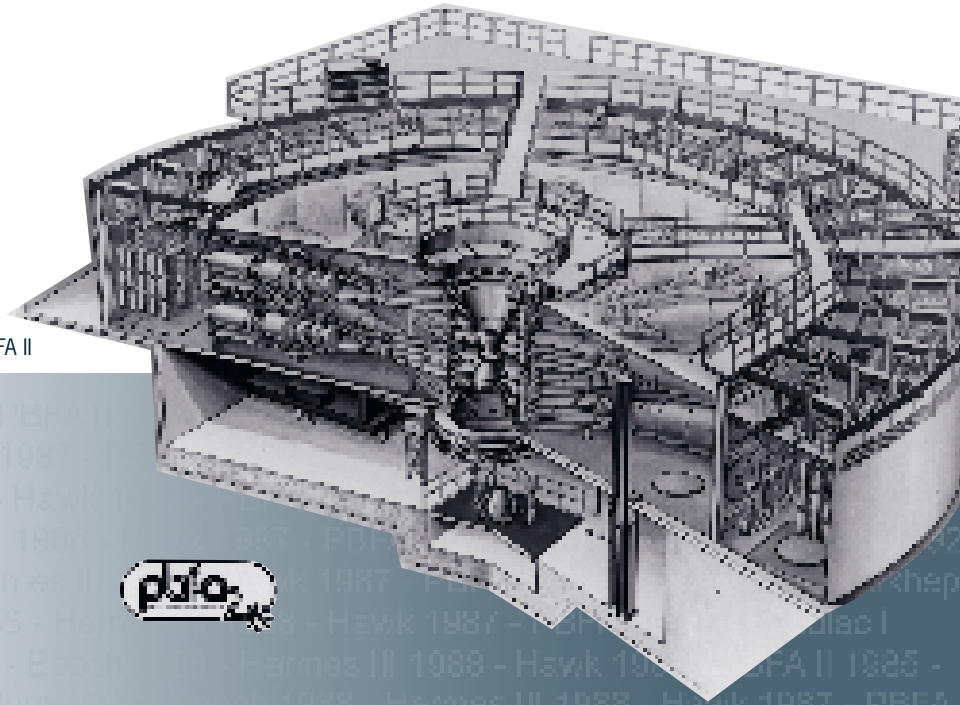
- 16 Information on the Atomic Energy Commission/Department of Military Affairs is from “Minutes of Atomic Energy Commission Laser-Fusion Coordinating Committee, April 2-3, 1974” in the Yonas Notebooks, SNL Archives; Atomic Energy Commission, “Atomic Energy Commission Laser and Electron-Beam Programs: FY 1976-FY1980, July 15, 1974,” WASH 1363-UC-21, USGPO.
- 17 See Laser Fusion Coordinating Committee minutes and related correspondence in the Yonas Notebooks for 1974 ff in the Sandia Corporate Archives.
- 18 See Yonas Notebook for 1973-76.
- 19 As reported in the *Sandia Lab News* of April 12, 1985, Steve Shope used Hydra at this time to develop an improved cathode for inertial confinement fusion research. Using an extension of the self-pinch concept, the cathode allowed extremely high current densities and the tightest focus ever produced by that time.
- 20 See “Jeff Quintenz Notes,” dated September 5, 2006, in Quintenz Folder, Van Arsdall Collection. Quintenz credits Poukey and John Freeman with pioneering this early work.
- 21 Pace VanDevender gave Quintenz that moniker, as Quintenz called it (see reference 20). Quintenz was subsequently promoted into several management positions and became Director of the Pulsed Power Program in 1999. He recalled that Yonas was initially quite skeptical of the role of theory.
- 22 Presentation to the Joint Committee on Atomic Energy by Gerold Yonas, Manager of Fusion Research, February 1975. Copy in Yonas Notebooks for 1970s, Sandia Archives.
- 23 *Sandia Lab News*, “Sandia to Host E-Beam Meeting,” October 31, 1975. In the November 14, 1975, issue, two photos from the conference show French, Russian, and British scientists at Sandia visiting Proto I. Among others, Yonas, Prestwich, VanDevender, and Valentin Smirnov from Russia are shown with Proto I.
- 24 Physics International, the Naval Research Laboratory, and Cornell were reported in the article to be also doing electron-beam work.
- 25 Yonas Notebooks, 73-77: March 30, 1976, Memo from G. Yonas to A. Narath and E.H. Beckner has a list of highlights in the electron-beam fusion program indicating ion-beam work was going on in 1975. The Pulsed Power Progress Reports beginning in 1975 demonstrate a growing interest in ion beams and an intent to generate them. *Electron Beam Fusion Progress Report* for 1975, SAND76-0148, Sandia National Laboratories, Albuquerque, NM, states, “. . . electron beams should be viewed as competitors to lasers for applications to inertial confinement fusion. We now recognize that it may be possible to include ion beams in this listing, and will discuss this approach for the first time in this report,” p. 9.
- 26 Van Arsdall interview with Yonas, September 5, 2003. In the same interview, Yonas told a story about Montoya and this funding. Yonas said he was on his way home from work and stopped in at Powdrell’s (a popular restaurant featuring barbeque) near Kirtland Air Force Base, where Sandia is located. He intended to pick up supper and take it home to his family. He noticed Senator Joe Montoya there eating by himself—and Yonas said he ordered dinner and sat down with the Senator instead of getting dinner to his family. “We talked,” Yonas said, “and Joe backed me.” Later behind the scenes, Yonas said that Sen. Montoya worked to sway Sen. McCormick, who opposed Sandia’s funding for EBFA. “McCormick finally asked why Montoya wanted his support. Joe said he was a little guy from a little state and it was only a little money.” That is how Yonas said the measure was successful.
- 27 Telephone interview of January 23, 2006, with Tom Martin. Van Arsdall Collection, Tom Martin folder.

Chapter Two

- 28 Furman interview with Yonas, June 22, 1984. Yonas recalled that the disclosure was made in July 1976 at the Gordon Conference in Santa Barbara, California. Sandia manager Ray Leeper, who joined pulsed power at this time, recalled Rudakov also giving a talk at Sandia's Coronado Club in which he revealed the material about how fusion was being attempted that was classified in the United States at that time. (Leeper interview of January 20, 2006). *Aviation Week and Space Technology*, May 2, 1977, stated that the technology Rudakov outlined in California was "... considered highly secret in the US and 'those seated there [at the California meeting] had to sit with their mouths open and not respond to Rudakov's outline.' " In the journal *Fusion* dated August 1978:38-39, the Fusion Energy Foundation said when Rudakov made his 1976 presentation in which he said that he had used soft x-rays for compression of fusion fuel to generate the first electron-beam induced fusion, the US Government classified his presentation as top secret.
- 29 Ken Prestwich, August 2006. See Van Arsdall collection, Prestwich folder. Prestwich added, "Even with these limited resources, substantial progress was made in a relatively short amount of time."
- 30 Their supervisor, Jim Mogford, also came to New Mexico, but went elsewhere at Sandia. Information from Ken Prestwich, August 2006, in Prestwich folder, Van Arsdall collection.
- 31 See Joan Lisa Bromberg, *Fusion: Science, Politics, and the Invention of a New Energy Source*. Cambridge MA: The MIT Press, 1983; and Van Arsdall, "Milestones," a document in the Van Arsdall Collection outlining more detail about this committee with references to sources.
- 32 See SAND77-1414, p. 11.
- 33 *Aviation Week and Space Technology*, July 1977, reports that Rehyd produced the neutrons; Rehyd was one of the famed "Tinker Toy" machines and it combined a line from REBA and a line from Hydra. Tom Martin and Ray Leeper confirmed in separate telephone queries in December 2005 that Rehyd was the machine in question.
- 34 Ray Leeper, a manager in pulsed power at Sandia, provided information beyond that in the *Lab News* and *Aviation Week* in an interview on January 20, 2006. Hired into the program in 1976 specifically to design and operate neutron diagnostics, Leeper said there is no doubt there were neutrons, but whether from the thermonuclear plasma is uncertain to some of the researchers involved. He said a report of what was done was published by J. Chang, M.M. Widner, A.V. Farnsworth, Jr., R.J. Leeper, T.S. Prevender, L. Baker, and J.N. Olsen, "Neutron Production from Advanced REB Fusion Targets," in the *Proceedings of the 2nd Topical Conference on High Power Electron and Ion Beam Research and Technology*, October 3-5, 1977, Cornell University.
- 35 Yonas notebooks.
- 36 Other organizations under Narath were Weapons Systems Development, Nuclear Fuel Cycle Programs, Nuclear Waste and Environmental Programs, and Energy Programs; all were in Organization 4000. In the *Lab News* of September 1, 1978, where the reorganization was announced, Yonas's directorate was called Pulsed Power Programs. By November, it was called Pulsed Energy Programs.
- 37 John M. Deutch, Director, Office of Energy Research, Department of Energy, "Statement of Fusion Energy: House Committee on Science and Technology," September 18, 1978. Copy in Yonas Notebooks.
- 38 Letter from Martin Stickley, Laser Fusion Office, Department of Energy, to the heads of inertial confinement fusion programs at the three laboratories, October 16, 1978. In Yonas notebooks.

- 39 Yonas notebooks. Furman interview with Yonas in 1984 for Sandia History. *Sandia Lab News*, April 12, 1985, "History of ICF at Sandia." Telephone interview with Dillon McDaniel, December 13, 2005, concerning a *Sandia Lab News* article of November 16, 1979, where it is reported that EBFA was designed to produce either electron or ion beams. McDaniel said once the decision was made to change to ions, it was irrevocable, but before the decision was made, it could theoretically have gone either way.
- 40 A feature article in *Scientific American* 239(5), November 1978: 50-61 by Sandia's Gerold Yonas titled "Fusion Power with Particle Beams" outlines Sandia's progress to date, describes the goals of EBFA I, acknowledges that ion beams were being considered as alternatives to electron beams, and outlines the proposed upgrade to a more powerful accelerator soon after EBFA I was running. Also see *Sandia Lab News*, November 27, 1978, page 1, containing a photo of the support structure for EBFA I and announcing plans for EBFA II.

PBFA II



CHAPTER THREE

the '80s

In the early 1980s, the new Particle Beam Fusion Accelerator (PBFA I) began to operate, while its more powerful successor, PBFA II, was being designed. For such large and complex machines and related facilities, and for the anticipated experiments to be performed on them, numerous specialized skills were required. Because of this, teams of specialists were assembled, including theorists and computer code designers, as well as the traditional machine designers and target specialists. From this point forward, the story of pulsed power at Sandia becomes more one of teams than of individuals and their technical contributions.

At this time, the Department of Energy was losing interest in making near-term plans for a power plant based on fusion. Research was indicating that inertial confinement fusion was much more difficult to achieve and much further away than had been believed. Instead, the Department began to emphasize first of all proving that fusion ignition could be achieved in the laboratory. Toward this end, it continued funding Los Alamos and Livermore to do fusion work with lasers and Sandia with pulsed power accelerators, urging all of them to achieve what they had

promised. As had been the case in the 1970s, these laboratories were competing for funding from the Department for this expensive endeavor. The presidency of Ronald Reagan spanned the 1980s (1981-1989), and under his leadership a new defense program began. The new program was the Strategic Defense Initiative, intended as an update in missile defense for the United States, and it brought added responsibilities to the weapons laboratories, including Sandia.

PBFA I fired its first shot on June 28, 1980, two days ahead of schedule and within its budget of \$14.2 million. All 36 modules fired simultaneously, as planned, producing 840 kilojoules of energy and 20 trillion watts of power in a 40-nanosecond pulse, but without a central diode or target chamber. (Please see following sidebar on PBFA I.) Following dedication of the facility on August 2, testing with electron and ion beams was scheduled for the rest of the year, with target experiments slated to start in 1981. The planned normal operating level for PBFA I was 1000 kilojoules and 30 trillion watts in the same short pulse length, a level it reached on November 7.¹

Sandia's expertise with pulsed power machines permitted changes to the intended type of beam. The team changed half of the 36 lines so they would be positively charged to produce positive ions; the remaining 18 lines were left negative for electron experiments. Both types of beams could be accelerated at 2 million volts, and, as another option, connecting the positive and negative 2 million volts would result in a 4-million-volt output either for ions or electrons. Because of lingering questions, particularly from its funding sources, Sandia had to substantiate its earlier decision to concentrate the fusion efforts on ion beams instead of electron beams. The problem with electron beams was their Bremsstrahlung (x-ray radiation) passed through the outer layer of the target, preheating the fuel within it. Ion beams would not do this.

By January 1981, the pulsed power team could report advances in its two approaches to inertial confinement fusion: imploding foils and ion beams. In the open literature at the time, including Sandia's internal newspaper, few details are given about the imploding foil work because it was classified and closely related to nuclear weapons designs.² On the other hand, the drivers (pulsed power machines) are fully described, as is much of the light-ion work. Magnetically imploded foil technology harked back to the mid-1970s at Sandia as part of a classified program named Scorpio.³ Research was performed in this program to create plasma implosions that stagnated on axis, creating x rays that could be used in weapons effects studies as well as to drive a fusion target.⁴ The technology avoided having to focus an electron (or ion) beam and was of interest for that reason. A decision whether to use imploding foils or ions for PBFA II was estimated to be two years away; both approaches used an intense burst of soft x rays to implode a target. Researchers were already discovering challenges in using ion beams; namely, limitations on their ability to focus the beams and difficulties in obtaining a pure, single-species beam of ions.

Recollections of the First Shot on PBFA I, June 1980

When the machine fired for the first time in June 1980 it was one of the most exciting things I've ever been involved in. The day before the promised deadline, we tried to bring the machine to a state of readiness for first tests and many things failed. Finally the machine was up and ready to run. We were well into the countdown; it proceeded rather well, it was close to midnight on Friday night, and a two-bit fitting exploded. And so, on Friday night we shut down and we were within a day of our long-term schedule of completing this machine, and we were out of money and time.

The next day, which was the last day, we got the shot off at noon but the adrenalin and excitement had been building for over 24 hours and it was a marvelous and exciting experience. The ground shook and the machine worked. We had arranged for a picnic after the first shot, but with the excitement and achievement, the notion of going somewhere else was ludicrous—everyone wanted to shoot again. We knew we had to diagnose the shot to make sure that everything was in good shape before we shot again, but everyone wanted to stay there. It was certainly the most exciting place in Albuquerque that day. For many of us, it was the most exciting thing we had ever done.

Gerry Yonas [Necah Furman interview, 1984. Transcript in Sandia archives.]

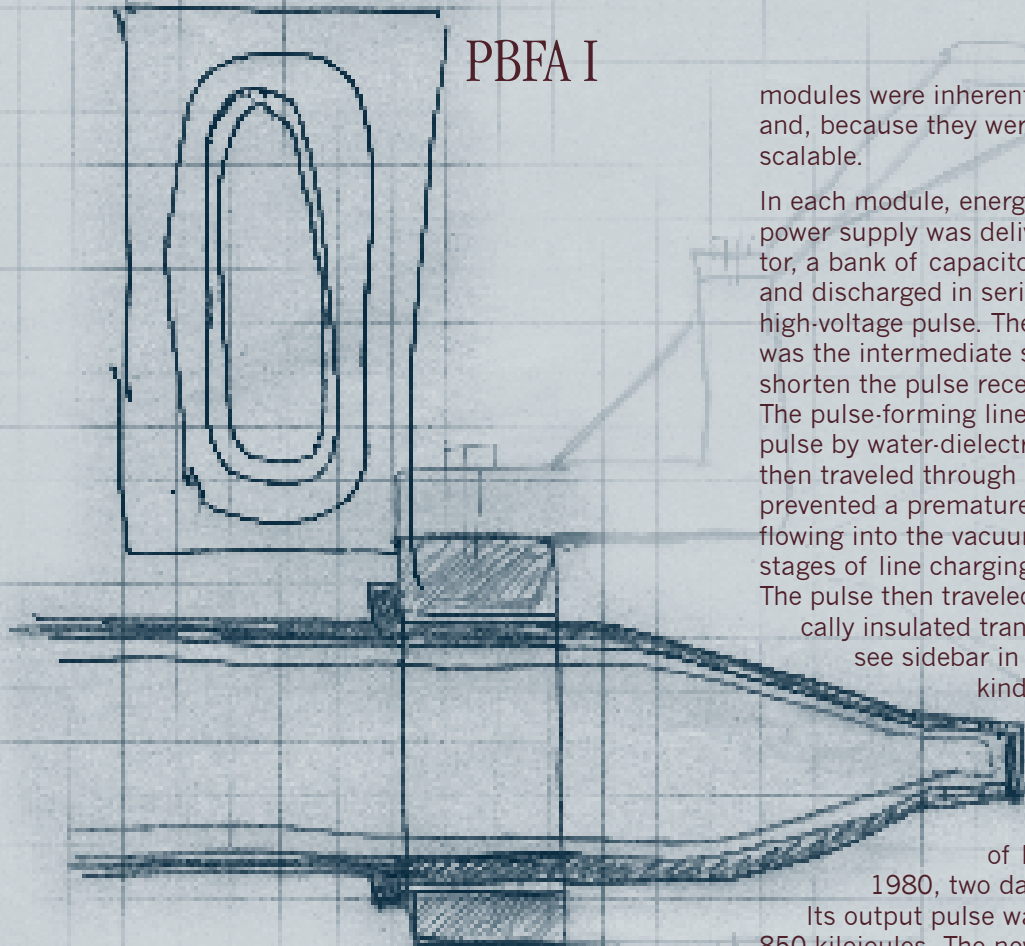
When we fired PBFA I for the first time, we tried the Friday night before the Monday deadline and failed. A small plastic coupling in the bottom of the accelerator tank had broken while we were charging the generator and we

had to stop for the night. The next morning, on Saturday, we tried again. Gerry Yonas and Rick Sneddon (from the Department of Energy) were there. This accelerator was made to operate most reliably at full power, so our first shot was also a full power shot, and that was unprecedented. It offered some hazards. A lot of energy was available if something goes wrong. We had some preliminary shots at lower volts that worked out fine. However, after long delays and making sure everything was OK, we did fire the accelerator and everything worked. Data came out and we were close enough to our milestone to be very happy. No one had really thought much about what was going to happen after the first shot, so people were running into the high bay before things could be adequately checked out, and it was a major concern because there appeared to have been sparks and maybe a fire on top, which was viewed from the outside. . . . The enthusiasm was so high that after the shot on that Saturday morning, we had a party, but what people really wanted was to fire the machine again, not have a party. Most of us left early and went home after firing the world's largest accelerator. As it turned out, that was the week that the movie "The Empire Strikes Back" was on. I went to this movie, walked inside the theater and noticed that many of the people who had been at PBFA I that morning were at the movie that afternoon, including Gerry Yonas and his family. Seeing a "Star Wars" movie seemed appropriate after the morning's excitement.

Pace VanDevender

[Necah Furman interview of July 16, 1984. Copy from Don Cook in Van Arsdall collection for 1980s.]

PBFA I



Progress spanning nearly a decade of work on focusing ion beams with ever-increasing power density contributed to the design of PBFA I. Cornell University pioneered the work in 1974 using protons, and the intensity of ion beams focused on a target increased over the years—from 10^6 to 10^{11} watts/cm² on several machines in the United States, including Sandia's Hydra, Hermes II, Proto I, Proto II, and Gamble at the Naval Research Laboratory. PBFA I was expected to better this and achieve 10^{13} watts/cm², with PBFA II projected to obtain 10^{14} watts/cm² on target.

PBFA I was envisioned as an intermediate step in the development of Sandia's fusion program. Operation of the accelerator showed that multiple accelerators could be effectively synchronized and their output pulses combined to drive a common load—thus a technology easily extendable to higher power levels.

PBFA I consisted of a circular array of 36 modular accelerators, each with a power level of more than 0.8 terawatts, resulting in 30 terawatts when combined. The accelerator

modules were inherently simple and efficient, and, because they were independent, were scalable.

In each module, energy from a conventional power supply was delivered to a Marx generator, a bank of capacitors charged in parallel and discharged in series to provide the initial high-voltage pulse. The next driver element was the intermediate store section, used to shorten the pulse received from the Marx. The pulse-forming line further shortened the pulse by water-dielectric switching. The pulse then traveled through a prepulse shield, which prevented a premature voltage pulse from flowing into the vacuum section during initial stages of line charging (known as prepulse).

The pulse then traveled through a magnetically insulated transmission line (please see sidebar in chapter two about this kind of transmission line) to the reaction chamber containing the electron or ion diode.

The first test firing of PBFA I was on June 28, 1980, two days ahead of schedule.

Its output pulse was 20 terawatts and 850 kilojoules. The new facility was dedicated on August 2, as reported in the August 8, 1980, *Sandia Lab News*. A series of five qualifying shots produced typically 30-terawatt, 1-megajoule power pulses at the end of the 36 magnetically insulated transmission lines. In the next phase, the output from all 36 modules were combined into a single power feed, or convolute section, to power the ion diode.

The following phase of development involved the ion diode. Diodes are devices that convert the electromagnetic energy supplied by the drivers into ion beams. Diodes generate, accelerate, and focus the ion beam onto the fusion targets located at the center of the accelerator. The beam is produced within a small gap, or diode region, between two plasmas that form and cover the anode and cathode surfaces in a few nanoseconds after the pulse arrives. Because the plasmas are separated in potential by several megavolts, ions are extracted from the anode plasma and are accelerated toward the cathode. Because the cathode typically is an open grid, the accelerator ions pass through the structure and are focused in ballistic trajectories or by self-pinch forces onto the target.

Electrons are ejected from the cathode plasma and, if allowed, would flow to the anode, resulting in loss of current in parallel with the ion beam, and thus a loss of efficiency. To avoid the electron loss, a strong magnetic field is used to prevent electron flow across the anode-cathode gap. The way in which the field is applied became an area of continued research, trying externally applied pulsed field coils, internally generated magnetic fields within the diode, or using a coil powered by the diode current itself.

By 1982, Sandia was studying three diode configurations for electron control: the magnetic field diode, the pinched-beam diode, and the hybrid-ampfion diode. In addition to the differences in how they controlled electrons, the diodes varied in details of how they produced plasmas at the anode. The purpose of the ion-diode experiments was to determine the best concept and develop it for PBFA II.

Advancing previous accelerator technology to the level needed for PBFA I required solving several fundamental problems, including synchronized switching, efficient transfer of energy to

the diode region over relatively long distances in the vacuum, voltage polarity reversal, operational engineering, and system-facility integration. For example, a fast-opening switch invented by Cliff Mendel in 1975, and further developed by the Naval Research Laboratory, was used on PBFA I to boost the accelerator voltage. The switch cut the pulse duration by a factor of 2 and reduced the input energy needed by a factor of 8. Boosting the voltage of PBFA I allowed testing some of the physics of lithium ion production.

PBFA I Team

Design: Tom Martin, Pace VanDevender, Dillon McDaniel, David L. Johnson

Assembly: Johann Seamen

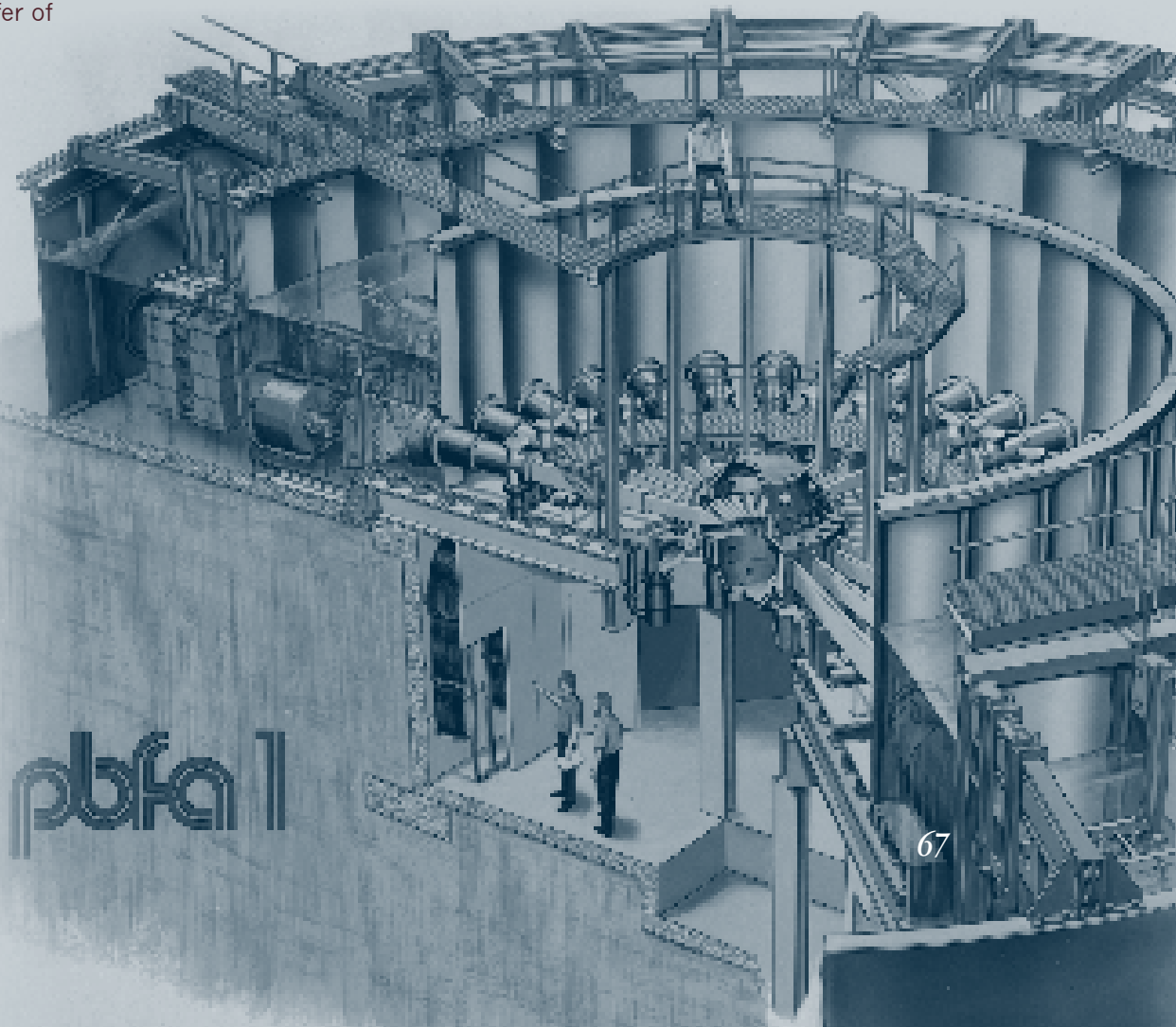
Operations: Steve Goldstein

Project Management: Gerry Barr

[Condensed from "Drivers for Pulsed Power Fusion," *Sandia Technology*, Vol. 6, No. 3, October 1982, SAND82-1398.]

Original sketch for PBFA I on facing page was submitted to Sandia's technical art department as the beginning for the later drawing on this page.

PBFA I



Experiments on PBFA I were designed to determine the best configuration for PBFA II, and initially, beams of hydrogen ions (protons) were used. Even though protons are heavier than electrons, they tended to be deflected by magnetic fields in the diode, affecting the beam's energy density possibilities. At the same time it was looking into the optimal type of beam, in mid-1981 Sandia decided against its initial plan to shut down PBFA I and upgrade it into PBFA II by adding an additional 36 modules, bringing the total to 72. A primary reason was loss of valuable research time while the machine was being rebuilt; another was improvements in machine technology that gave the voltage and current needed without additional modules. Instead, an entirely new machine was planned within the funds allocated for the upgrade, approximately \$48 million. Like PBFA I, it would have 36 modules delivering power to a central diode, but with triple the design power, totaling 100 terawatts. The goal of completing construction by the end of 1984 remained the same. Ground was broken the end of March 1981 for a \$2.68 million high bay laboratory building for PBFA II, east of PBFA I, even as the decision was being made whether to upgrade PBFA I or build a new machine.⁵ Either would fit into the new facility.

Multiple areas of research during the early 1980s were geared to improve PBFA II and its subsystems even as it was being designed and built. Increasing the power by a factor of three over PBFA I required new accelerator concepts and significant advances in component technology. Moreover, higher power implies higher voltages, making it difficult to provide a trigger for the multi-megavolt gas switches that would enable the 36 modules to fire simultaneously. Consequently, switches were also the subject of research. The primary goal was to create a facility and provide the understanding required to prove that inertial confinement fusion targets could in principle be ignited. A secondary goal was to develop the technology for a fusion reactor for commercial power.

Meanwhile, the national inertial confinement fusion program was slowly becoming more focused on military applications. A headline in the journal *Science* in May 1981 summed up the situation: "Ambitious Energy Project Loses Luster: Laser fusion, touted as a new energy source, has produced only fizzles; its military implications now predominate."⁶ As the article pointed out, the military focus of the program—which had always been there—had been revealed more clearly during budget discussions in Congress in the early 1980s. Whereas in the decade before, energy had been publicized as the primary focus for fusion work in the United States, *Science* predicted its true home—in weapons work—was becoming more overt.

Projections and promises about achieving ignition and building a commercial power plant within a relatively short amount of time circulated into the early 1980s, and the military side of fusion was of course not widely discussed in the open literature. For a brief moment in 1976, the Rudakov disclosure (see chapter two) about advances in this area had given a peek into the classified part of fusion

research, without making it known that this was a major thrust. Absent an energy focus, any news about work on inertial confinement fusion was largely confined to highly technical journals. Because of their complexity, details of the topic did not lend themselves to wide public interest.

The realization that creating fusion in the lab was further away than anticipated, the yearly increases in budget requests for expensive fusion facilities, and a string of overly optimistic predictions were beginning to take the luster off the national fusion program as a whole. Complicating the picture, work at Lawrence Berkeley Laboratory, Brookhaven National Laboratory, and Argonne National Laboratory indicated that heavy ions looked very promising for igniting fusion pellets. However, this approach was less attractive for military applications and very expensive. Although it was thought to be as viable as lasers or light ions for a commercial power plant, the issue was, of course, funding sources. The Office of Fusion Energy in the Department of Energy oversaw and funded most of the heavy ion work. (Magnetic confinement fusion, as always, continued to be funded through this office as well.) Defense Programs funded basic development of inertial confinement fusion using lasers and pulsed power machines at the weapons laboratories.⁷

A complicating factor for Sandia was the long-standing emphasis on lasers in the national fusion program because of their technical maturity. Lasers had already demonstrated their capability to focus a beam, whereas Sandia was still trying to suitably tame particle beams. Advocates of particle-beam fusion had to continually argue their case for funding, and the laser laboratories often objected, since all inertial confinement fusion funding came from the same pool of money. Results from Sandia's pulsed power accelerators for fusion work were as yet preliminary, and the jury was out in the scientific community about their possibility for success. Laser fusion received 70% of the funding and had totaled more than \$1 billion in the 1970s, largely based on promises that ignition would happen within a short period and that commercial power plants would operate soon thereafter. Conceptual designs for fusion energy reactors made it apparent that either a laser or particle beam fusion energy plant would have to be enormous and prohibitively expensive. Moreover, repetitive shots from the fusion driver would be needed to ignite a series of pellets in rapid succession (several times a second) inside the reactor—like pistons in a gas engine. The ability to fire repetitively and reliably had to be developed as well.

By 1981, the Department of Energy had committed large sums for long-term construction of laser facilities for fusion drivers: \$137 million for the glass laser, Nova, at Lawrence Livermore National Laboratory and \$62.5 million for Antares, the carbon dioxide (CO₂) laser at Los Alamos. Livermore was asking full funding, \$250 million, to build Nova, but had been approved for the lesser amount to build one stage of it. The argument Livermore made was that fusion ignition could only be proven with a machine providing adequate energy to the pellet. (A mirror fusion

test facility was also being built at Livermore at this time for magnetic confinement fusion at a final estimated cost of \$372 million.⁸) Sandia's request for \$48 million to build PBFA II fell into this time period and was from the same source of funding.

Because energy had been emphasized so strongly as a reason to fund fusion machines, and because any fusion energy plant seemed now to be many years away, Congress and the Office of Management and Budget began to ask pointed questions about the large budgets earmarked for inertial confinement fusion. In the spring of 1981, *Science* quoted R.L. Schriever, then head of the Office of Inertial Confinement Fusion at the Department of Energy, as saying: "It can be argued that the energy goal of the program is being put on the shelf. But it is more fair to say that we are setting aside either application—civilian or military—for the goal of proof of scientific feasibility." (Here, scientific feasibility means fusion ignition.) In contrast to earlier years when funding for inertial confinement fusion had been a separate item in the DOE defense budget, in 1981, it was part of a lump sum of \$162 million allocated for weapons research, development, and testing (\$236 million was requested for FY 1982).⁹ In a climate of restricted funding, Sandia's operating budget for particle-beam fusion was reduced below the needed level for the first time ever; from \$18.4 million requested to \$15.9 million, resulting in cuts and setbacks in plans.¹⁰ That same year, the House Armed Services Committee stated openly that inertial confinement fusion research was being funded primarily for military applications.

Sandia continued to insist upon the potential advantages pulsed power machines held out for inertial confinement fusion, whether used for energy or weapons applications. The advantage they had over lasers was much better efficiency and suitability for repetitive operation, the latter a requirement for fusion energy plants. However, a letter from the president of Sandia, George Dacey, to the directors of Los Alamos and Livermore in September 1981 clearly spells out the direction in which the inertial confinement work was going: "I believe that we are all fully agreed to cooperate in directing the various elements of the inertial confinement fusion program toward unified weapons physics orientation." Dacey also told the directors of the weapons design laboratories that rather than being concerned with the physics of ignition, Sandia was concerned with the efficient conversion of pulsed power sources into soft x rays, work that was relevant to weapons effects studies. Thus Sandia saw its primary role as being a return to laboratory simulation of weapons effects, a responsibility dating back to the earliest days of the nuclear weapons program.¹¹ To this end, Sandia had begun planning a Simulation Technology Laboratory project encompassing the accelerators not specifically designated as part of the fusion effort.

In laboratory experiments on PBFA I, continued problems with deflection of the light hydrogen protons in the diode convinced researchers to try to develop a stiffer beam. Even as parts of PBFA II were nearing construction, Sandia was investigating

a different kind of ion beam (lithium) for the new accelerator. The challenge was to develop lithium-ion sources at the same time as the accelerator was being built. Another challenge was to show that an ion beam could be focused on a target the size of a pinhead; to date this had not been accomplished. The classified magnetically imploding foil work continued in parallel with the ion-beam effort, and was considered a contender as a fusion driver.

With two different technologies being investigated at the same time PBFA II was being built, many issues had to be resolved to determine how PBFA II should finally be configured, among them the kind of ion beam the machine would use.¹² Moving rapidly from initial experiments with intense ion-beam diodes into fielding an optimum ion-beam system on PBFA II raised many physics issues in generation, transport, focusing, and deposition in targets that needed to be resolved. Sandia and its partners, the Naval Research Laboratory and Cornell University, were involved in an extensive research program to increase understanding of these issues. In addition, international interest in ion-beam-driven inertial confinement fusion grew at this time, and important advances were also achieved by researchers in Japan, France, Germany, and Israel that factored into decisions concerning PBFA II.¹³

Planning for the kind of capability Sandia needed—an entirely new technological and scientific endeavor—was different than planning and constructing a new facility designed to answer a known need. In the case of the new particle-beam fusion accelerator being built at Sandia, experiments were being conducted on existing pulsed power machines that pertained directly to it. Consequently, it was desirable to be able to modify construction plans when results indicated the need to do so.

Years are customarily required to obtain funding for major construction at Sandia and other national laboratories. Requests have to be submitted to the Department of Energy together with plans for a new machine often before all research questions have been adequately answered. In this case, researchers knew they needed more power and energy to drive fusion, but did not know the kind of beam that could best deliver that energy to the fusion pellet. Moreover, the design of the pellet itself was a subject of theoretical calculations and experiment.

For this reason, Sandia adopted an implementation method called ‘fast-tracking’ when PBFA I was being built, and because of its success, the method was fully implemented for PBFA II. Using the fast-tracking approach, one stage of the project was built while subsequent stages were being developed, ensuring that in the end, the machine would be state of the art. This approach was not without risk and deviated from the norm of freezing plans for a project at the time funds were requested. Since projects had to be planned and funded so far in advance, fast-tracking had obvious advantages for research machines such as those in pulsed power. They were being designed and used for cutting-edge experiments in areas

with which no one had much experience; fusion was as yet an unattained goal in the lab.¹⁴

In the spring of 1982, all of Sandia was reorganized, and the divisions within it were aligned according to two major functions: those with current responsibilities and commitments, such as energy and weapons, and long-range future capabilities involving research. Pulsed Power Sciences was placed in the research area under Al Narath, and Sandia's president, George Dacey, explained the reason to the *Sandia Lab News*: "Gerry Yonas' programs are futuristic devices and ideas and understanding, not, as yet, a deliverable product. Furthermore, I think the technology that's involved is closer to that of our other research activities, than for example to weapons development."¹⁵ The placement—outside both weapons and energy—did not make it easier for pulsed power either internal to Sandia or externally to obtain funding and support. In April 1983, Dacey modified his stance somewhat, saying that the inertial confinement fusion program had recently been given a multi-pronged approach including fusion, weapons effects simulations, and other applications needing large amounts of power in a small space. Close in time to when the laboratories' reorganization occurred, Pace VanDevender was promoted to head up the Pulsed Power Research Department and Don Cook, who had joined Ken Prestwich's group in 1978, was tapped to head the Pulsed Power Engineering group under Tom Martin. Both men came to play increasingly important roles at Sandia, inside the Pulsed Power Program and outside it.

On March 23, 1983, in an announcement that took many by surprise, President Reagan said that the United States was going to begin an extensive research and development program for missile defense for the nation. At the time he made the announcement, the President said the effort was consistent with US obligations under the 1972 ABM Treaty and that its goal was to render nuclear weapons impotent and obsolete. The program was named the Strategic Defense Initiative and its stated goal was to eliminate the threat posed by strategic nuclear missiles.

Because of Sandia's expertise in particle accelerators and lasers, the Labs immediately became involved in the effort, which soon was dubbed Star Wars. (The name came from the title of a popular 1977 movie depicting futuristic wars involving beam weapons.) One of the reasons for the Strategic Defense Initiative was to create an anti-ballistic missile system for the nation, in which armed missiles would be sent into space and detonated immediately following the launch of a Soviet missile. The US missile would explode in space and the radiation from it would disable the enemy's missiles. However, popular artists' concepts depicted beams of particles or light being aimed at the heavens to bring down an enemy missile or vehicle, with intergalactic "star wars" involving the beams as weapons. Even though the intent was not to use the particle beams as weapons, but as a way of wreaking havoc on enemy weapons, the idea that beams could be used as

weapons had been around since the early days of accelerator work, largely as theory.

Work for the Strategic Defense Initiative began to scale up in the nuclear weapons complex soon after the President's announcement. During the summer of 1983, Yonas headed a study team in Washington exploring the parameters of technologies for the Strategic Defense Initiative. While Yonas was in Washington, Narath realized the nation would need centers for strategic defense research and told VanDevender, who was acting director in Yonas's absence, to prepare a plan for the Strategic Defense Facility. Yonas then proposed this facility to Congress on his return to Sandia. The next year, in the summer of 1984, Yonas accepted the position of Chief Scientist in the Reagan administration's Strategic Defense Initiative Office, part of the Department of Defense, leaving Sandia for Washington, DC. (Please see following sidebars, Major Strategic Defense Initiative work and A 1984 perspective of the Strategic Defense Initiative.) On August 31, 1984, VanDevender was named director of Pulsed Power Sciences, and Cook took over the Fusion Research Department. VanDevender continued to push for the Strategic Defense Facility, which eventually was funded. Repetitive pulsed power work, the coil gun, and other largely classified activities related to beam weapons were carried out at this facility.

As had long been the case, part of the Pulsed Power Sciences organization was James Powell's Simulation Technology Department, whose groups operated the weapons effects simulation machines, some of which became part of the Simulation Technology Laboratory project. Some of the accelerators and test beds also helped with the inertial fusion development and included Proto II, Hermes II, Speed, and HydraMite.

A final design for the heart of PBFA II was determined that year, based on the decision to use lithium ions rather than protons to bombard the fusion pellet. Lithium was selected for its greater mass (seven times that of a proton), which calculations showed would minimize its bending in magnetic fields and make the beam easier to focus, with the focusing anticipated to boost beam intensity. Use of lithium ions also would allow target experiments to be conducted at higher voltages, resulting in greater beam brightness. The ability to focus was assumed to increase rapidly with increased voltage.

In theory, a key to fusion ignition was the ability to achieve enormous power density at the target, with the power density directly related to how precisely the beam could be focused on the target. Particle beams have to travel over a distance to their target—called propagation—and here is where some of the power density can be lost. Another key aspect is that the electrical energy must be converted efficiently to ions, minimizing loss of electrons, and the ion beam must be pure; i.e., only lithium must be produced. Related to the decision to configure PBFA II for lithium-ion beams was the choice of a diode, a key component of the accelerator that had been the subject of intensive research for some time. The Applied-B diode was the final choice. All of these requirements had to be factored into the final design of

Major Strategic Defense Initiative Work at Sandia: 1980s

The Strategic Defense Initiative, begun in 1983, had the mission to develop a defensive system for the United States that would destroy incoming ballistic missiles in space, soon after they were launched. Lasers or directed-energy beams appeared promising technologies for this endeavor, and some of the accelerator work Sandia was already doing made a good match to the national program. In fact, the possibility that electron beams might be developed as weapons was an idea that had existed for many years.^a Light, radar, x rays and other bands of the electromagnetic spectrum travel freely over great distances in space, since they are above the Earth's atmosphere. One idea was that orbiting stations carrying power sources could be stationed in space, and from these stations, lasers or directed-energy beams could be deployed to destroy enemy missiles being launched toward the United States.

The electron beam accelerators Sandia developed in the pulsed power and radiation simulation programs became key in Strategic Defense Initiative work. Used as directed-energy weapons, high-current electron beams could blow apart the body of re-entry vehicles; however, it was uncertain whether these beams could propagate the distances required to hit such a target. Early experiments showed that the electron beam became unstable within a few meters, and work ensued on making a weapons-grade beam go the required distance.

RADLAC I AND II

Two years before the official creation of the Strategic Defense Initiative, Sandia had begun a collaboration with the Air Force Weapons Lab in Albuquerque to develop the first radial linear accelerator in the United States, RADLAC I (radial pulse linear accelerator). First tested in 1981, RADLAC I adopted pulsed power technology to a linear accelerator to create high-current, high-energy particle beams that could be used for a number of applications, one of them potentially as a beam weapon. RADLAC I used the electromagnetic pulse created in a typical pulsed power accelerator to form a 2-million-volt electron beam that was accelerated through four cavities to achieve a final energy of 10 million volts. Project leader and machine designer Ken Prestwich likened it to a multi-stage rocket.^b

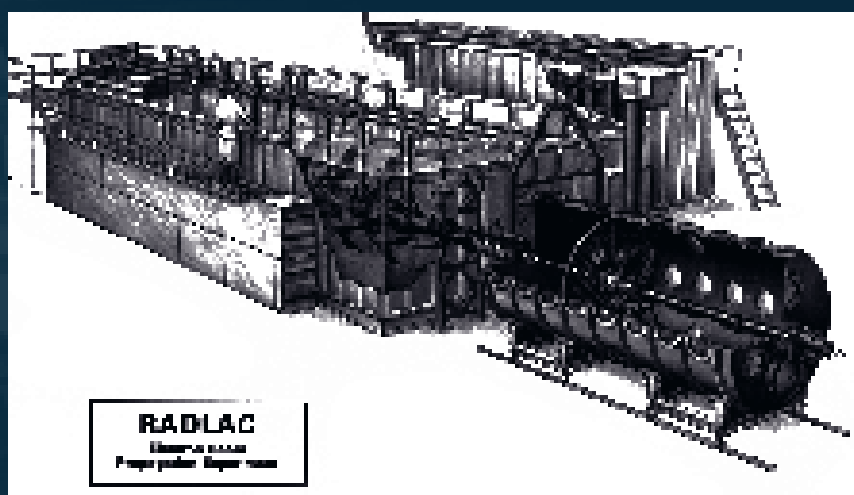


Development was already in the planning stage in 1981 for a second-generation linear accelerator, RADLAC II. When the Strategic Defense Initiative began in 1983, this second machine, by now well under way, suited its requirements. RADLAC II produced its first beam in the summer of 1985. Also a collaborative project with the Air Force Weapons Laboratory, RADLAC II was funded by the Department of Defense/Defense Advanced Research Projects Agency to address key issues in directed-energy weapons using electron beams. The physics of producing and propagating lethal beams of electrons in full-density air while keeping it stable was the primary subject of investigation. Laser-triggered switches synchronized the timing so that the electrons were given a series of pushes at just the right time. RADLAC II, fully completed in 1986, was used to successfully demonstrate stable propagation of a 10-megavolt, 40-kiloamp electron beam in open air for a distance of about 15 meters. The RADLAC II team included Ken Prestwich, its designer, Steve Shope, David Hasti, Dave Smith, Bruce Miller, D.L. Johnson, Art Sharpe, and Ray Clark. Having proved that the concept of beam weapons was feasible, and having made significant contributions to understanding beam propagation, beam conditioning, and diagnostics, RADLAC was subsequently dismantled in 1991.^c

X-RAY LASER

In early Strategic Defense Initiative efforts at Lawrence Livermore Laboratory, the concept for a "Stars Wars" weapon—an x-ray laser pumped by a nuclear weapon—caught popular imagination. However, such a laser was known to be difficult to make. Sandia contributed to the x-ray laser work through cooperation between its laser and pulsed power programs,

using Proto II to evaluate imploding plasmas as a source of photons to energize the laser. Proto II converted electrical energy into the kinetic energy of an imploding plasma, which was stagnated onto an annular shell or onto a central laser rod. The plasma energy was converted into x rays, which ionized and excited the laser medium. The experiments also investigated some of the physics of an x-ray laser and assessed its potential as a directed-energy weapon. Sandia's Keith Matzen headed up this work. Sandia also studied the possibility of deploying x-ray laser missiles on submarines



Schematic diagram of Sandia's EPOCH Facility used for directed energy experiments with electron beams.

and launching them from the submarines into space to intercept incoming Soviet weapons mounted on missiles. Related work ensued on how to detect enemy missiles as soon as possible following their launch.

DELPHI

In considering other options for the Strategic Defense Initiative, military strategists came up with the idea that, if attacked, the United States could deploy decoy missiles to draw fire from an enemy's "Star Wars" type weapons, depleting their fire power and allowing more US warheads to penetrate and arrive at their targets. However, the possibility existed that the enemy might be able to identify the decoys. Work began on several ideas as to how a decoy could be distinguished from an actual warhead in a project named DELPHI, honoring the Greek oracle who saw through Oedipus's

disguise and recognized him as the husband of his own mother. The name “Discriminating Electrons with Laser Photon Ionization” was force-fit into the acronym. The DELPHI team was led by Ron Lipinski, Bruce Miller, Milt Clauser, and Tom Lockner.

Somewhat later, the team realized that the same technology that detected and analyzed incoming missiles could be configured to destroy them. Instead of putting DELPHI in space, Sandia studied the idea of having the facility on the ground and sending the electron pulse into the upper atmosphere. Again, the difficulties involved in propagating electron beams any distance were problematic.

MIMI/EPOCH

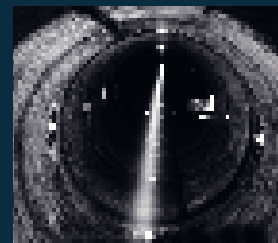
It was known that high-current electron beams generate huge electromagnetic fields, and so they become unstable, whip around, and do not travel long distances in a straight line. In 1985, Gordon Leifeste, Charles Crist, John Leija, and Charles Frost showed that an ultra-violet laser could create an ionized channel to guide an electron beam from the accelerator MIMI in a propagation tube.

To find out whether electron beams could be propagated over greater distances, Sandia built the EPOCH (electron propagation on channels) facility, consisting of the electron beam accelerator, Troll, a 56-m long, 0.9-m-diameter aluminum propagation tube, and instrumentation, all inside a concrete tunnel that was 106 m long, protected by a 7-m-wide semicircle of concrete that was 7 m wide and 3.6 m high. Troll, so named because it lived



Ron Lipinski gives a briefing on the EPOCH facility to SDIO director General James Abrahamson. Behind them is the 56-m propagation tube.

in a tunnel, was a 46-stage Marx generator with a high-voltage diode to convert the energy into electron beams ranging from 1 to 4 megavolts in pulses lasting from 0.3 to 2 microsec-



onds. Troll team members were Ray Clark, Malcolm Buttram, John Smith, and Ron Lipinski.

Subsequently, in EPOCH, the electron beams from Troll were coupled with a KrF laser beam, which made a path for the electron beam to follow. In another method, the propagation tube, first evacuated, was surrounded by coils that created a plasma channel to serve as a guide for the electron beam. By 1988, electron beams were propagating some 50 meters.^d The goal was to use the same technology to get a beam into space.

The EPOCH experiments indicated that high-energy electron beams were more efficient than lasers for transporting pulsed energy between widely spaced points. Electron beam accelerators are typically lighter and simpler than lasers, producing a beam of equal energy. Since the electron penetrates deeply into the target, deposits its energy throughout the depth, and produces x rays, other uses were suggested, such as flash x-ray radiography, welding, and research on the properties of materials. Ron Lipinski headed up this effort, which included Tom Lockner, George Kamin, Malcolm Buttram, and Ray Clark.

[General information for this sidebar from L. Johnson, *A History of Exceptional Service in the National Interest*, SAND97-1029, 251-252. Additional information from Van Arsdall interview with Malcolm Buttram, July 2006; Steve Shope collection in Sandia archives; boxes 32-37 in Prestwich collection, Sandia Archives; in particular Box 32.]

a J.P. VanDevender, “Pulsed Power, ICF, and SDI,” *Journal of Fusion Energy*, Vol. 5, no. 1, 1986, pp. 33-39. An appendix to the technical article contains VanDevender’s personal comments on implementation of the Strategic Defense Initiative.

b See Sandia Lab News, April 17, 1981, “RADLAC: For High-Current, High Energy Particle Beams.” The configuration was first investigated by Soviet physicist A.I. Pavlovskii in 1979 on their LIU-10, a 13-million-volt radial pulse line accelerator.

c Information on the outcome of RADLAC provided by Steve Shope in a telephone interview December 15, 2005. For RADLAC I and II, see Sandia Lab News, April 17, 1981; August 16, 1985.

d “Epoch: Unique Facility for Study of Electron-Beam Propagation,” Sandia Lab News, July 29, 1988.

A 1984 Perspective of the Strategic Defense Initiative*

In 1984, the political situation between the United States and the Soviet Union was growing tense: arms control discussions had broken down and the Soviets were testing a Ballistic Missile Defense System, and were known to be working on ground-based lasers. It was difficult to determine whether the United States had adequate defensive capabilities because the offensive technologies the Soviet Union possessed could only be surmised from available data.

The challenges faced by the Strategic Defense Initiative faced included the need to develop technologies for an evolving threat: an offensive Soviet capability that could change qualitatively and quantitatively. Hitting and destroying an intercontinental ballistic missile in flight, for example, would be difficult, but an even greater challenge would be managing the battle. That would take massive computer systems managing hundreds of thousands of data points and computer structures capable of making decisions and of engaging weapons and keeping track of targets—that is, which targets are alive, and which dead. The whole process would need to be fast—no more than 30 minutes.

Yonas described it at the time as “the most massive software job that man has ever faced, requiring new methods of artificial intelligence to write the software.” He said such a capability could have enormous benefit to, for example, air traffic control on a global scale or anything else where real-time data comes in and, if it were managed properly, could be used to control large, complex processes and events. Other technologies related to the Strategic Defense Initiative that Yonas saw as potentially benefiting other endeavors included reliable portable energy supplies providing hundreds of megawatts of power on command where it

was needed and for a short amount of time and new materials developed for the Initiative but adaptable for other needs.

Yonas said the immediate strategic goal of the Strategic Defense Initiative was to strengthen US deterrence with respect to the Soviet Union. The long-term goal, however, was to make ballistic missiles, both US and Soviet, militarily useless “through a combination of enlightened policy and breakthrough technology.” Proponents of the Strategic Defense Initiative saw it as a way to bring the United States and the USSR back to meaningful arms negotiations, forcing both sides to think more clearly about strategic weapons. Yonas said he envisioned a day when offensive nuclear ballistic missiles would be negotiated away. Such negotiations would be possible after a period when each side had single warhead deterrent missiles and substantial ballistic missile defenses so that neither side would have any benefit from a preemptive strike. He saw the Strategic Defense Initiative effort as a first step toward reaching such an optimal state.

Pursuing the research needed for the Strategic Defense Initiative was seen as a hedge against developments in the USSR, which was believed to be developing a ballistic missile defense system. The long-range goal of the Strategic Defense Initiative, as Yonas outlined it at the time, was to create a defense-dominated rather than an offense-dominated, nuclear deterrent. The technologies being developed were designed to destroy missiles, not people. The intent was to move away from the long-standing policy of mutually assured destruction and toward a situation where defense predominated on both sides of the globe.

[Condensed version of a *Sandia Lab News* article of November 9, 1984, that is based on an interview with Gerry Yonas, soon after he began his duties as chief scientist with the Reagan administration's Strategic Defense Initiative Office, part of the Department of Defense.]

*See also Nigel Hey, *The Star Wars Enigma: Behind the Scenes of the Cold War Race for Missile Defense*, Potomac Books, 2006. Hey is a retired Sandian.

all the elements of PBFA II. (Please see following sidebars, PBFA II: Technical Timeline and PBFA II.) The decision to base PBFA II on lithium-ion beams meant that the imploding foil approach, the Scorpio program, would be suspended, at least as part of the inertial confinement fusion effort. In November 1983, VanDevender sent a letter to the head of a committee that had recently reviewed the program to explain his decision. After outlining the merits of lithium ion-beam technology, VanDevender wrote:

Under the constraints of constant or declining funding for the light ion fusion portion of the Inertial Confinement Fusion Program, growth in one area necessarily means a reduction in another. The Scorpio Program has had some outstanding success in past years, and Proto II had been modified as an experiment to make a lower inductance diode and increase the energy available in the foil implosion. Had this experiment in power flow worked, the relevant concept for using imploding plasmas to drive ICF [inertial confinement fusion] targets could have been investigated in time for the PBFA II decision. However, breakdown in the water feed and flashover of the vacuum insulator have been persistent problems during the last year. We have now redesigned the power flow section of Proto II to avoid these problems. The new hardware will not be available until spring, and there will not be time to investigate the promise of Scorpio for PBFA II before we would have had to choose the PBFA II option in May 1984. . . . The Scorpio option will be revived only if the plasma opening switch for pulse compression on PBFA II does not scale to the high voltages required, and if double shell targets are shown to be not viable for PBFA II.¹⁶

Imploding foil technology was not completely abandoned, however, but continued under Dillon McDaniel in a new Strategic Defense Initiative endeavor, the X Ray Laser Program.¹⁷ Some staff remained in the ion-beam inertial confinement fusion area, and others went with McDaniel.¹⁸ (Perceptive readers will know that this technology would re-emerge in Sandia's fusion program more than 10 years later as the z pinch. However, in most of the open literature of the time, it was not called by that name. In the meantime, the imploding foil technology continued to be used in weapons effects work.)

Before the scheduled start of operations on PBFA II in early 1986, researchers had to develop a reliable source for lithium-ion beams. The source would be a plasma formed in the diode of the machine, and more than a score of possibilities existed for creating it. (Please see following sidebar on later computer codes for fusion.) Another area being intensively investigated was focusing the beams. Significant success was being reported using the Proto I machine and an Applied-B diode to repeatedly focus intense ion beams onto a spot the size of a pinhead. Researcher David J. Johnson discovered that particle beams can be focused like optical beams to concentrate the power in the diode onto a target a millimeter across, and Ray Leeper developed a

technique to verify the achievement.¹⁹ It was hoped that the focusing ability could be scaled up from small machines, such as Proto I and PBFA I, to the much larger PBFA II.²⁰ The *Sandia Lab News* likened the accomplishment to “focusing—for an instant—all the electrical power generating capacity of the United States onto an area less than the size of a fingernail.”²¹

One pulsed power test module for PBFA II was SuperMite. Also, as part of its usual careful process, Sandia opted first to build and test one of the 36 modules before ordering the remaining 35 to make sure they would work as predicted. Demon was the name given to this demonstration module built in Area IV, and it was a full-scale (15-m-long) experiment to verify computer projections of how a module would work. By early 1985, tests on Demon were strongly suggesting that PBFA II would be able to meet its design goals. Predictions were that PBFA II would be able to deliver 1 to 2 million joules of ion-beam energy onto a fusion pellet target with a final power of 100 trillion watts at a minimum. These levels of energy and power were thought to be equal to igniting fusion in the pellet. The *Sandia Lab News* reported that “PBFA II is now believed to be the only fusion experiment in progress anywhere that has the possibility of igniting thermonuclear fuel in the laboratory,” predicting implosion experiments by late 1988.²²

The Demon tests neared an end, the additional modules were ordered, and finally all 36 Marx generators were installed. The generators had also been rigorously tested, at first the one on Demon, then each one individually. These 36 Marx generators made up the outer circle on the wagon-wheel shape of PBFA II and had to be extremely reliable because they were designed to fire simultaneously. Synchronized switching would be the key to making this work, an area in which the Labs excelled. Sandia’s long experience with Marx generators, beginning in the 1960s, culminated in this fourth generation of the pulsed power energy source.²³ By the fall of 1985, several years of tests had come to successful conclusions, and PBFA II was being assembled in preparation for its first shot. Funding for PBFA II had been such that money for the building had become available before the accelerator was designed. A shell building was constructed, then the basement was dug out, and the accelerator had to be sized to fit within the existing building shell.

At this time, Sandia decided to begin converting PBFA I into the world’s largest laboratory x-ray source primarily to support a major weapon program, the W88. The pulsed power staff held a contest to determine a new name for it, since it was desirable to distinguish it clearly by name from PBFA II and because, once reconfigured, it would no longer be the same machine. Saturn was the name chosen, suggested by its multiple-ring diode. The \$5 million conversion was scheduled to be completed by 1987 and was part of the Simulation Technology Laboratory project.²⁴ (Hermes III, a large gamma-ray simulator, was also planned as part of the project.) Saturn was intended for radiation-effects research and weapons-component hardening and to support the Strategic Defense Initiative.

PBFA II: Technical Timeline

Demon

The energy storage section for PBFA II involved a Sandia-designed Marx generator, which was extensively tested in 1983/1984 at Sandia's Demon accelerator facility in Area IV. (Demon stood for 'demonstration.') Demon was one complete module, built so it could be tested before the 36 identical modules that would make up PBFA II were constructed. Measuring 15 m in length, it had all the components needed to operate one module, providing a full-scale experiment on which to verify computer projections of performance.

By 1985, as reported in the *Sandia Lab News* of April 12, the tests had shown the module provided the necessary voltage, energy, power, and pulse length. The Demon experiments also showed that the high-voltage, low-jitter gas switch, which was triggered by a laser, performed reliably at high voltage without suffering significant energy loss or breakdown. (A transfer switch connects the energy storage section's high-voltage output with the driver's first pulse-forming section.) These switches would synchronize all 36 of the modules in PBFA II, making them act in unison. The switch was a major advance in pulsed power technology, and its developers were Rich Adams, Joe Woodworth, Charles Frost, Roy Hamil, Bob Turman, Russ Humphreys, and Jay Penn.

At this time, Pace VanDevender was the division supervisor for Pulsed Power Research. He had the responsibility for the architecture of PBFA II, and worked with David L. Johnson to complete it. Dozens of Sandians also contributed to the design and testing of the Demon module including managers Tom Martin, Bobby Turman, and Don Cook; Gene Neau, who designed the pulse-compression system; Russ Humphreys, Jay Penn, and Jerry Cap, who developed the gas switch; Johann Seamen, director of the Demon test facility; Darrell Green, Jeff Christofferson, Greg Mann, David Mares, Guy Donovan, and Zeke Ziska, all making up the test crew; Larry Schneider and Tom Woolston, who designed the Marx generator; Mike Wilson, designer of the firing system and high-voltage switching system; Ed Constantineau, design of the work platforms; Duane Burgeson, designer of the insulating fluids supply and processing system; Keith Tolk, designer of the Demon tank; and Bert Arnold, manufacturing liaison.

Switching Technology: Comet test bed

Increasing the power by a factor of three over PBFA I required new accelerator concepts and significant advances in components. Higher power implies higher voltages, making it difficult to provide a trigger to the multi-megavolt gas switches that determined the simultaneity of the 36 modules. Therefore, a special type of laser-triggered, 5-megavolt gas switch, the Rimfire Switch, was developed, and a krypton fluoride laser was developed in industry for Sandia to power these switches. A magnetic switch was developed as a possible replacement for the water switches in the pulse-forming transmission lines. The Sandia management team was interested in this switch because it would eliminate the shock waves from the water switches that had caused damage in PBFA I and Proto II and because these switches could be operated repetitively in a pulsed power driver for a reactor for energy production. The invention of a metallic glass material (Metglas) by Allied Chemical provided the possibility for magnetic switches for pulsed power devices. Neau, VanDevender, and Marilyn Stockton developed the first of these switches to operate at up to 6 million volts on a facility called Comet. Comet had two magnetic switches and was one prototype module for PBFA II.

In parallel with this effort, higher voltage water switches were developed and incorporated into another prototype module. For cost reasons, PBFA II was built using modules with water switches. The work on



Comet provided background for development of RHEPP II, a 3-million-volt electron beam generator with several magnetic switches that was completed in 1993. This machine was a demonstration of repetitively pulsed technology that could be used in a reactor driver. The initial concept for RHEPP and component testing was led by Malcolm Buttram and Jerry Ginn and included extensive contributions by a research team from Westinghouse Corporation. The final design and full system development was done by a team headed by Neau and Kim Reed.

In a paper delivered at the 1983 Beams Conference, VanDevender said the target design issues indicated a 10-nanosecond ion pulse was needed to create the conditions for fusion. PBFA II modules were designed to produce a 40-nanosecond pulse; efficient energy transfer was not possible for shorter pulses because of switching and inductance limitations. VanDevender indicated that the final pulse compression would be done with plasma erosion switches, for which the Naval Research Laboratory was responsible in both PBFA I and PBFA II.

The plasma opening switch is located near the ion diode and is designed to be a short until the load current in this short circuit is a maximum. At that point, a large amount of energy is stored in the inductance of the vacuum transmission lines and vacuum insulator stack. The plasma opening switch was designed so that the combination of removal of charge from the plasma and magnetic forces caused the switch impedance to increase to a value much higher than the ion diode impedance in a few nanoseconds. The design calculation at this time indicated that the

rapid decrease in current

would increase the ion diode voltage by a factor of 2 to 4 times the voltage without these switches and would decrease the pulse width to about 10 nanoseconds. Although

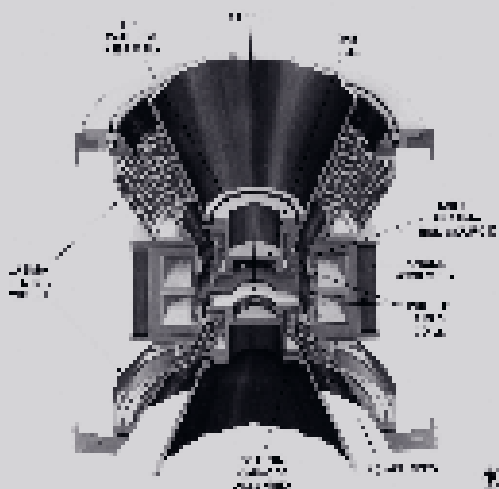
important progress in understanding these switches was made in experiments on PBFA I, at the Naval Research Laboratory, at Physics International, and at Maxwell Laboratories, tests using them on PBFA I were not successful because of the turn-on time limitations of the lithium ion diodes and the efficiency of energy transfer to the ion diodes.

Although plasma erosion switches were not used for the bulk of the ion diode research on PBFA II, Sandia continued to research their operation through the 1980s and 1990s. Cliff Mendel and Mark Savage were major contributors to understanding these switches and invented a triggerable switch. In the early 1980s John Farber, the Defense Nuclear Agency Program Manager for developing new weapons effects simulators, decided that plasma erosion switches offered a technology that would be considerably less expensive than the modular approach used on PBFA I and Saturn. The Defense Nuclear Agency and contractors supporting its efforts, the Naval Research Laboratory, Physics International, Maxwell Laboratories, and Pulse Sciences, Inc., worked on developing systems that had plasma erosion switches that would conduct for several microseconds and then provide a 0.1-microsecond pulse when the switch opened with a voltage gain of about a factor of 10. If this could be accomplished, it would decrease the three or four stages of pulse compression in Sandia's modular approach and the only components that would need to support high voltage were inside the vacuum insulator stack.

The impact of that decision had two effects on the Sandia pulsed power program: first, Sandia now had the only program in the world that was developing high-power modular accelerators and their components, and second, extensive advances would continue to be made in opening switch technology and systems that could be beneficial for future generation of machines beyond PBFA II.

In the 1990s, the Centre d'Etudes in Gramat, France, implemented a program on its z-pinch research program that made extensive use of opening switches and a version of inductive cavities that were developed by the Institute of High Current Physics in Tomsk, Russia, following work by Sandia in this area on Hermes III and RHEPP. Dillon McDaniel was an advisor for the Gramat program throughout the 1990s and arranged joint Sandia support of Russian work in this area.

PBFA-II ION DIODE REGION



(Please see sidebar on International Collaborations in chapter four). The Sandia triggerable plasma erosion switch was successfully demonstrated in one of the high-current z-pinch drivers developed at Gramat.

Diodes and focusing

Sandia explored three major ion diode concepts that differed in how the magnetic field, needed to stop electron flow, was created. Pinched-beam diodes used the self-magnetic field of the beam. Ampfion used some of the current delivered to the diode to power the magnetic field coils and the Applied-B diode used energy from a capacitor bank to power the coils. Problems from the beam interactions with the self-generated and applied magnetic fields limiting the power density existed in all of these diodes. The source of ions for these diodes was usually an anode plasma that was not always uniform and thereby contributed to these energy-density limitations. In addition, many species of ions were accelerated, and beam focusing and target configurations could only be optimized for one species. This phenomenon was characterized as an efficiency problem.

After the decision to use lithium ions, a great deal of research ensued on several types of ion sources to find a technique that would produce a pure lithium-ion beam. The extensive ion diode experimental program included developing sophisticated diagnostics to make better measurements of the beams, plasma conditions, and the power delivered to the diode. These experimental efforts and thorough theoretical studies advanced Sandia's understanding of such diodes, but not quickly

enough to ensure success in its fusion goals on PBFA II.

Many of the issues identified during this period proved very difficult to resolve. A considerable number of the shots during the first two years operating PBFA II were to help resolve problems with the pulsed power system and to find the best operational configuration for the ion diodes that were being evaluated.

In March 1984, the Applied-B diode was chosen for PBFA II because of an experimental discovery that had been made during testing, allowing a dramatic improvement in the focusing ability. The diode had been invented at Cornell nearly 10 years before and Sandia had been developing it for high power. Experimenters showed for the first time that intense ion beams behave like optical elements: a small change in the curvature of the lens produces a precisely defined change in the focal spot. Before this discovery, beam spreading was blamed on a number of different effects.

The Applied-B diode (or barrel diode) was a shortened form for 'Applied Magnetic Field Diode,' in which a so-called virtual cathode was created by electrons caught in the field lines from an electromagnet. The cathode performed the job of attracting and accelerating ions, impelling them from the anode surface to the fusion target.

In May 1984, Sandia formally announced that it had focused an intense beam of ions to the smallest spot size ever achieved—roughly the size of a pinhead. Such a size was crucial to being able to focus an ion beam on a fusion pellet of about the same size. The result had been achieved repeatedly in proof-of-principle experiments that spring (reported June 8 in the *Sandia Lab News*). The earlier focusing problem had been corrected by slightly reshaping the diode's cylindrical anode. Carefully changing the interior surface from a simple curvature to a compound curvature gave a two-and-a-half-times tighter focus, the article said, and provided a breakthrough in beam optics.

David J. Johnson was the lead investigator for the focusing experiment and Ray Leeper developed the technique to verify the achievement, which was a milestone on the way to experiments with PBFA II, slated to begin in 1986. The beam-focusing experiments were made on Proto I, now 10 years old, using a smaller diode but a higher-current density than would be used on PBFA II. The focus was onto a

In 1985, Pace VanDevender explains the ion diodes of PBFA II to Adam Klein, counsel for the House Armed Services Committee.



spot 1.3 mm across, and if scaled up to the three-times-larger PBFA II diode, the focus was calculated to be 4.4 mm, a tighter focus than the 6-mm-diameter targets being considered for the new machine. The remaining research, then, was to use PBFA I to scale to higher power in preparation for tests on PBFA II.

In 1985, John Maenchen was project leader and chief experimentalist for tests proving that earlier focusing achievements could be scaled up to larger accelerators. He used PBFA I and the Applied-B diode for the tests, which matched the focal intensities achieved the year before on Proto I. A high-intensity focused beam was achieved by solving problems connected with ion-beam aiming and transport without many of the hardware improvements the team had planned.

The high ion intensities were attained with the help of a transparent plastic mesh covering the metal cathodes, which allowed electrons to be emitted uniformly and form a virtual cathode fast enough for the 40 billionth of a second ion pulse to shoot forward as needed. Plastic mesh assisted with aiming the beam. A second mesh inserted behind the cathode in the area where the beam propagated across a strong magnetic field toward the central target aided the transport. The double mesh arrangement dramatically increased the ion power density on target. At this same time, Joe Woodworth was working on a means to use extreme ultraviolet radiation to create a uniform plasma layer above the anode surface that could emit an ion beam immediately when the power pulse was applied, enabling peak power to occur at the same time as peak voltage. Maenchen's team included Tom Mehlhorn, chief theorist; Carlos Ruiz, diagnostics chief; and Leeper, who helped with diagnostics. (See *Sandia Lab News*, April 12, 1985.)

Countdown to completion

By September 1985, the circular array of 36 Marx generators—the source of power for PBFA II—had been successfully test-fired in the accelerator, as the accelerator itself neared completion. The tests were run after normal work hours so that the “downstream” or interior portion of the machine could continue construction. During the tests, the Marxes were immersed in 500,000 gal. of insulating transformer oil, just as they would be when operating normally. During the tests, the generators performed as expected, and

with their certification, a major portion of the new accelerator was checked out. Jitter—the unpredictable difference in time of firing for each Marx—was quite small, approximately 3-5 nanoseconds and resulted in a 36-Marx timing spread of only 35 nanoseconds. That spread was expected to be sufficient because the laser-triggered gas switches between the generators and the target provided final synchronization.

Over time, approximately 40 to 50 people from a number of Sandia organizations worked on some stage of the design, assembly, test, and operation of the PBFA II Marx generators. For a *Sandia Lab News* article of September 27, 1985, highlighting the successful tests, Tom Martin singled out a number of them for special mention: Larry Schneider, Tom Woolston, Mike Wilson, and their colleagues in Ed Burgess's group; Bob Johnston, Gerold Ziska, and Dan Jobe of Steve Goldstein's Ktech group; and members of Gerry Barr's Pulsed Energy Projects group.

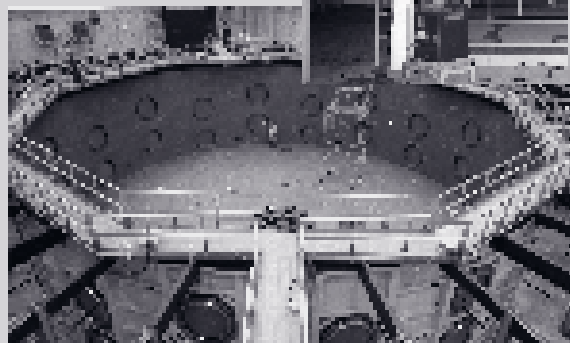
The first shot on the completed PBFA II was December 11, 1985.

[Sources used include comments by Pace VanDevender, Don Cook, Ken Prestwich, and Michael Cuneo on this sidebar; articles from the *Sandia Lab News* from the period, and material on specific topics in Sandia's archives.]

PBFA II, basement looking at stack, 1984.



Top of PBFA II around 1985.



PBFA II, stack with jaws, 1985.

PBFA II

The accelerator was built in four layers of nine modules each, with every layer arrayed like the spokes of a wheel measuring 32.9 m in diameter. Each module contained capacitors, switches, and transmission lines and all converged on a central hub, where a vacuum chamber with the Applied-B diode was located. The diode contained the fuel pellet. Electric current, charged into giant capacitors (the Marxes) and released simultaneously by all 36 modules, shot into the diode and produced a beam of particles. Efforts were made to focus the beam so that it would impact the surface of a pea-sized pellet of fuel and implode the pellet, making it crush upon itself. The goal was to compress the fuel in the pellet to about 1000 times solid density and heat it to some 100 million degrees Celsius, approximately six times the temperature at the center of the sun. This implosion would spark fusion reactions in the deuterium-tritium fuel.

In the outer, oil-insulated section of PBFA II, a Marx generator in each module accumulated electrical energy for 1-2 minutes, charging a bank of capacitors to 95,000 volts. At the proper instant, a computer sent a trigger signal, and switches in each Marx generator close to connect the capacitors in series and produce a 5-million-volt pulse of electricity lasting about 1 millionth of a second.

This pulse entered the middle, water-insulated section. In each of the 36 modules, an intermediate storage capacitor began the process of forming a compressed pulse. Compressed to about one-third its previous duration, the pulse left the capacitor through a high-voltage gas switch. The switch, one in each module, operated by laser-triggered breakdown of an insulating gas. Precise, computer-controlled triggering of the 36 gas switches synchronized the 36 pulses.

Next, still in the water section, a series of three pulse-forming lines in each module shortened and shaped the pulse. Self-breaking switches, operating by breakdown of the deionized water, let the pulse pass from each pulse-forming line to the next. After leaving the third pulse-forming line, the pulse entered a transition section where the shape of the conductors changed from cylindrical to flat.

Meeting near the center of the accelerator were 36 flat-plate transmission lines and about 12 million volts at the midplane. At this point, the 36 synchronized power pulses were combined into one.

This united pulse passed through an aluminum-and-acrylic vacuum interface that kept water out of the center section, which was in vacuum. The pulse then traveled



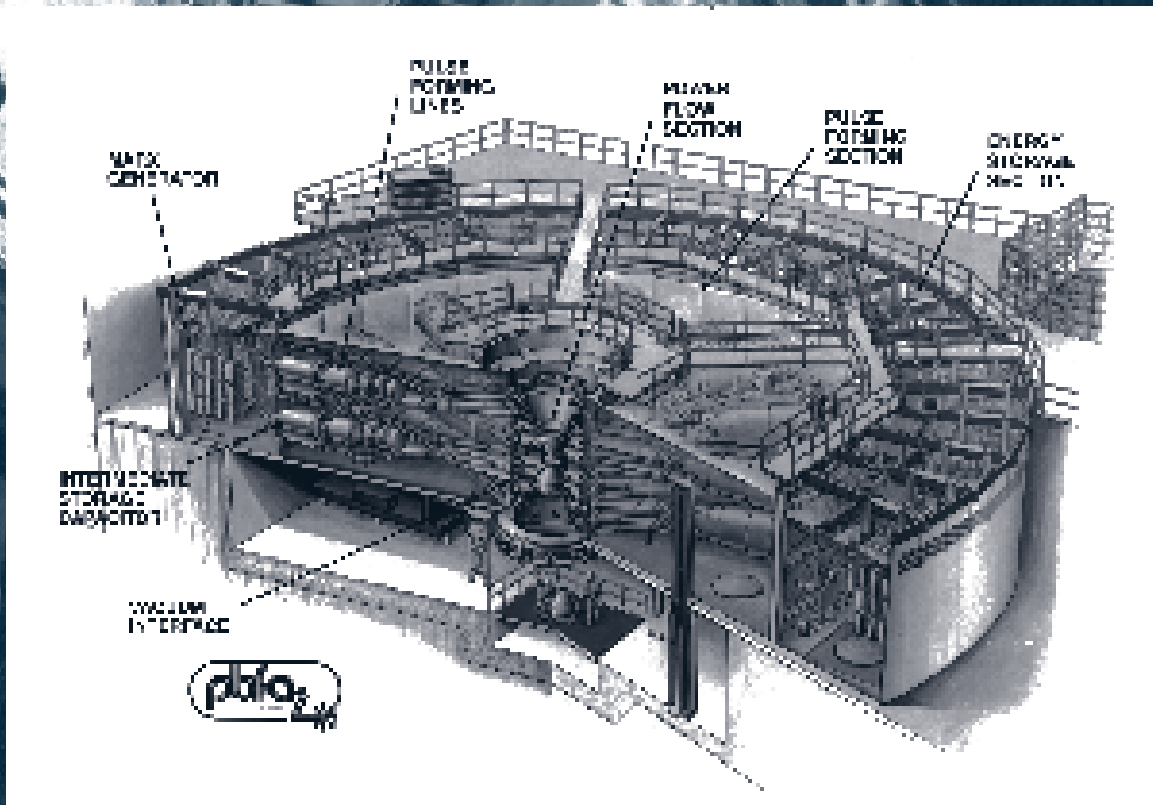
along magnetically insulated transmission lines toward the center point of PBFA II. Just before the pulse reached the center, one more switch, the plasma opening switch, boosted the output to 30 million volts. Finally, the pulse reached a diode

measuring 0.3 m in diameter, where the particle beam was produced (protons or lithium ions) and focused onto a target.

PBFA II operated using a data acquisition system and control/monitor system, both of which coordinated hundreds of actions before and during a shot and detected the results. The control/monitor system was highly automated, allowing procedures to be repeated exactly, reducing error, and monitoring the system for hazardous conditions. The data acquisition system was state-of-the-art for the

time, including more than 100 waveform recorders, computer hardware and software to control the recorders and analyze data, and more than 25 miles of cable linking monitors and recorders.

[Based on *Sandia Lab News* articles of April 12, and September 27, 1985, and the color booklet titled *Particle Beam Fusion Accelerator II*, SAND86-0861.]



PBFA II

Later Computer Codes for Fusion

Former Pulsed Power Center Director Jeff Quintenz recalled that one of the review boards visiting Sandia during the early days of the inertial confinement fusion program had called pulsed power an 'arcane endeavor,' meaning it was really more black art than science, not easily explained even to interested scientists. Marshall Sluyter, who headed the Department of Energy's Inertial Confinement Fusion Program for many years, echoed this sentiment, saying that even though he was a physicist, Sandia's Don Cook had to spend many hours explaining pulsed power's approach to fusion to him. Laser fusion is in some ways more straightforward and comprehensible than the generally less-well-known particle-beam approach, and reviewers were much more familiar with laser-beam fusion.

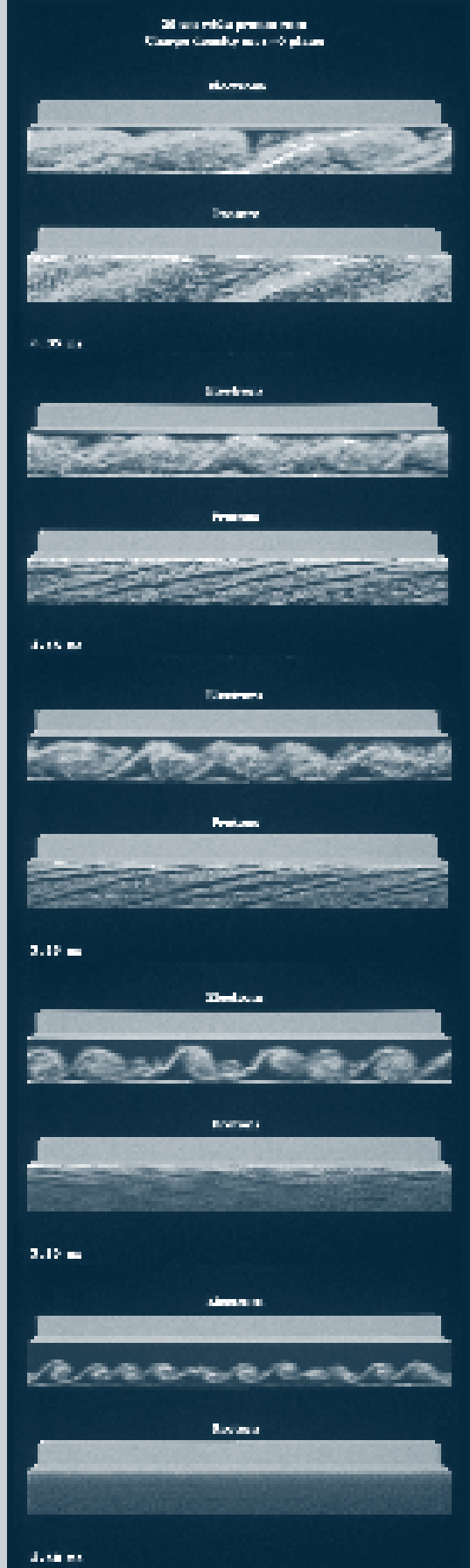


Photo of Dave Seidel and computer with graphic on screen.

After developing the capability to visualize simulation results, Sandia developed the capability make video animations of those visualizations. The time series of visualization results on the computer to the left were copied in sequence to a videodisk unit and then captured on video tape by controlling the videodisk playback with a computer. This allowed video animations to be created quickly and easily. Before, 16 mm film had been used. It was a very slow process because the computer output was sent to a central photo service within Sandia, a few frames at a time, where it was output on 16 mm filmstock. These short segments then had to be spliced together to produce finished animations.



Rebecca Coats and Mark Kiefer and three-stage system.



Despite the complex nature of pulsed power fusion, throughout the 1980s and 1990s, review panels increasingly praised Sandia for its progress in various areas, praise Quintenz attributes in great part to the contributions of theoretical work, which enabled Sandia to explain scientifically its problems and successes with particle beams, in particular ion beams. When experiments did not show great progress, theory could say why, and point to how improvements could be—and were being—made. In this way, Quintenz said Sandia was able to evolve from an ‘arcane endeavor’ to being recognized for world-class science.

The MAGIC code and was a state-of-the-art modeling tool until about 1990 (see sidebar on early codes in chapter two). In 1984/1985 Sandia made the commitment to ion-beam technology for fusion based in part on theoretical predictions of how the diode would work. Lithium was the ion of choice. However, continued problems with the diode being used, the Applied-B diode, signaled the need for new computational and theoretical tools, because the MAGIC code was proving inadequate. Paul Miller, one of the experimentalists, noticed a limiting voltage on the diodes and realized that the desired voltages could not be achieved with that particular configuration. That limiting voltage was not observed, and consequently could not be explained, in MAGIC simulations, although it was the most advanced code Sandia had. Soon after arriving at Sandia in 1986, theorist Mike Desjarlais began working on the problem of limiting voltage and, working hand-in-hand with experimentalists to iterate the problem, developed a model that explained the origin of the limiting voltage (the V_* theory).^a

His theoretical explanation helped diode research worldwide, and allowed researchers to understand other non-ideal effects on diode behavior. The theory explained the relationship between the limiting voltage and the magnetic field. It provided a framework to understand what was happening inside the diode and broke what Steve Slutz later called a logjam—many advantages followed from breaking it, including new understanding of diode instabilities by Slutz and Ray Lemke. Simulations could then be made that were more faithful to reality, and experimentalists were able to use this information to make progress in improving diodes.

Despite these advances, the quality of the ion-beam spot was not as good as had been hoped, and instabilities in the beam were suspected. Theorists knew that three-dimensional (3-D) computer codes would be needed to help analyze such instability problems. At that time, the computers in the Pulsed Power Center were not powerful enough to handle such codes. Like the transition from 2-D static particle-in-cell to the 2-D electromagnetic particle-in-cell capability, the transition from 2-D electromagnetic particle-in-cell to 3-D electromagnetic particle-in-cell codes would require much more powerful computers. Pace VanDevender, who headed pulsed power then, backed funding such computers for the ion beam work, but funds came in slowly. As a consequence, David Seidel and Mark Kiefer remembered Sandia staff having to slowly and carefully develop the first 3-D particle-in-cell-type code as funding permitted. The third dimension would allow fully general electromagnetic fields and motion of charged particles.

Rebecca Coats, one of the developers, named the code Quicksilver, an acronym for Quintenz, Coats, Kiefer, and Seidel, who developed it. All the developers vividly remembered that at that same time, SAIC was also trying to write a 3-D code, Argus, which would be a competitor to Quicksilver. As it happens, quicksilver is another name for mercury, and in mythology, Mercury (also called Hermes) slays the many-eyed monster Argus. Just as in mythology, Sandia’s Quicksilver code beat out Argus. Quicksilver was designed to be relatively easy to use and, although created to solve the problem of instabilities in the ion diode, was subsequently used to model general plasma physics problems.

In the mid 1980s, codes were run on CRAY 1S, the fastest computer in the world, but even it could not handle a 3-D code by itself. After two years of development, Tim Pointon used Quicksilver to run the first simulation in 1988 using the additional memory and four parallel processors offered by Sandia’s CRAY-XMP. The 1988 simulation illuminated the instabilities that were causing ion diodes to produce a poorly focused beam. From the beam energy and momentum diagnostics, Desjarlais saw that there were indeed clear indications of instabilities in the beam; the beam was wavering and had too much width. It was supposed

to focus down to a tiny area. The obvious next step was to study the instabilities to see if they could be eliminated or somehow overcome.

Using the Quicksilver code, instability analysis, and experimental data, Desjarlais and Pointon found after years of work that just before the ion instability began to develop, there was a high-frequency electron instability. Only when it died out did the ion instability begin. They surmised that if the electron instability could be controlled, the ion instability would never develop, or would be lessened. After working on this problem for nearly a decade, they thought it had been solved.

The German Forschungszentrum in Karlsruhe (FZK) was researching another kind of diode, the extraction diode, using proton beams at this time. Sandia's Applied-B diode was a barrel type, which was not as suitable for fusion work. To test Sandia's theory about ion beam instability, in 1996, during an exchange program orchestrated by Quintenz on the US side, Desjarlais worked with Peter Hoppe in Karlsruhe using codes he and Coats had designed, and developed an extraction Applied-B diode in which the electron instability could be controlled, inhibiting the growth of the ion instability. Desjarlais later called it a great success—the best diode yet. He said that they were able to prove with protons that the diode worked, but a pure source of lithium was lacking and nobody knew when or if it would ever happen. But by this time, when the instability problem was solved, the ion-beam fusion program was being phased out in favor of z pinches (Please see sidebar on successes with lithium-ion beams and closeout of this research in chapter four.) In addition, and complicating the chances for success with ion-beam fusion, Sandia was never able to develop an ion source with the needed purity.

The code Quicksilver has been improved many times and is still being used at Sandia and externally, notably by the French pulsed power program and at the Naval Research Laboratory.

It has been employed for various applications, such as high-power microwaves, high-frequency microelectronics, system-generated electromagnetic pulses, and the physics of magnetically insulated transmission lines. Quicksilver has, in fact, been used for the latter application to design the refurbished Z. However, further large-scale improvements to Quicksilver are proving difficult to implement. One reason is that in the late 1990s, Sandia pioneered a new approach to computing, switching from running complex computer programs on increasingly large monolithic computers to using massively parallel systems composed of tightly integrated, simple computers—sometimes as many as 1000 small computers at one time. This innovation allowed significantly more powerful codes to be developed and enabled better comprehension of complex events; but new types of codes had to be written to accommodate many small computers operating in parallel. Quicksilver was not designed for such operation.

In addition to the change to massively parallel computing, another new approach at Sandia funded by the Advanced Simulation and Computing program has created a framework that physics software development teams use as a foundation for advanced codes. Individual teams then overlay the physics specific to their needs onto this framework. For pulsed power applications, the EMPHASIS (electromagnetic-physics-analysis systems) code using this 'framework with physics overlay' as the newer approach to physics code development to better accommodate the increasing complexity of the science involved. Most recently, EMPHASIS has been used to analyze some of the refurbished Z's pulsed power components, and it will eventually replace Quicksilver.

[Based on interviews with Mike Desjarlais, Mark Kiefer, Jeff Quintenz, and David Seidel in 2006. See Van Arsdall collection of folders in Sandia archives.]

a M.P. Desjarlais, "Impedance Characteristics of Applied-B Diodes," *Physics Review Letters* 59, November 20, 1987.

An option was included to continue the magnetically imploding foil research on Saturn that had been excluded from the inertial confinement fusion project when the ion-beam approach was chosen for PBFA II. The imploding foils could supply needed soft-x-ray testing in weapons effects simulations and power laboratory x-ray laser experiments for the Strategic Defense Initiative.

After weeks of coordinated effort by a large team of scientists, engineers, technicians, and project managers, PBFA II was completed in December 1985, seven weeks ahead of schedule. Early in the evening of December 11, Sandia's pulsed power team and invited guests celebrated the accelerator's first shot with all 36 modules being fired.²⁵ (Please see following sidebar, "On the scene at PBFA II.") The shot ended Phase 1 of the mammoth project, which was construction. Subsequent phases were planned to unfold more or less simultaneously: during Phase 2, the accelerator's capabilities would be tested and analyzed; in Phase 3, the lithium-ion source for the beam would be developed; and in Phase 4, the target pellets would be optimized. These final phases were envisioned to last several years. The state of the art in inertial confinement fusion was constantly changing—it was a marriage of pure theory and expensive hardware about which the textbooks had not been written, as the *Sandia Lab News* wrote after talking to Cook, the PBFA II project scientist.²⁶

While Sandia was celebrating the successful completion of its newest particle accelerator, Congress asked for a review of the Department of Energy's inertial confinement fusion program. The review committee, commissioned by the National Academy of Sciences and informally called the Happer Committee for its chairman (physics Professor William Happer of Princeton), was supposed to measure progress toward the program's overall objective. That sole objective was to achieve a small thermonuclear explosion in the laboratory. The general conclusion contained in the final report of March 1986 was that it was too early to predict whether the objective could be met and that at least five more years of research were needed before any decisions should be made about the direction of the program. The committee recommended continuing experiments using lasers and accelerators to give all the technologies a chance to prove themselves. It also strongly recommended that Los Alamos and Lawrence Livermore collaborate with Sandia in the area of target design, an area traditionally belonging to the weapons design labs. Related to the target design issue, the committee advocated funding classified, collaborative programs of collaboration between the weapons and inertial confinement fusion groups on the design characteristics of targets. These secret programs were Centurion at Los Alamos and Halite at Lawrence Livermore. At this time, it was estimated that as many as 10 million joules would be required to trigger ignition, and these secret tests were aimed at verifying the amount of energy needed to ignite fusion in a pellet.

The committee said that it believed PBFA II offered a more efficient and lower cost approach to ignition than lasers, and gave the Sandia program thumbs up to

continue its work. It also recommended level funding at \$155 million a year for the entire national inertial confinement fusion program for five years, leaving that sum as a line item in the nuclear weapons research and development budget. During that time, the committee hoped some basic questions could be answered so that feasibility of fusion ignition by inertial confinement could be assessed realistically. The Happer Committee recommended that the Department of Energy establish an Inertial Confinement Fusion Advisory Committee to provide advice and guidance to the Secretary of Energy through the Assistant Secretary for Military Applications.²⁷ It was recommended that the advisory committee meet on a regular basis to assess progress in the national program. The recommendations assured Sandia of five years of funding for its inertial confinement fusion work, but PBFA II was as yet untried and the stakes were high. It was encouraging that in September 1986, PBFA II won an IR 100 Award from *Research and Development Magazine* for its technological innovation. This prestigious annual international award is given to the best technological innovations worldwide.²⁸

While PBFA II was being readied to test its abilities to ignite a fusion reaction, two new simulation machines began to operate as part of the Simulation Technology Laboratory. Saturn, which had been PBFA I, became the world's most powerful x-ray source when it successfully began firing in the fall of 1987. Meeting the highest expectations of engineering, Saturn was on time, on budget, and performed exactly as predicted. Saturn would be used to simulate the x-ray effects created by the detonation of a nuclear weapon and thus would serve as a complement to underground shots at the Nevada Test Site.²⁹ (Please see following sidebar on Saturn.) A few months later, in the early spring of 1988, Sandia proudly witnessed the first shot on Hermes III, a more powerful gamma-ray simulator than Hermes II, which was still operating and nearing its 30,000th shot.

Gamma-ray simulators provide another spectrum of radiation for weapons effects testing, supplementing the x rays on Saturn. An advantage such aboveground laboratory machines had was that they could be fired often and were much less expensive than the full underground tests in Nevada. Continuing work that began back in the 1960s in Sandia's early pulsed power group, the two powerful new machines were built to help weapons designers better understand x-ray and gamma-ray effects on weapons systems and components.³⁰ (Please see following sidebar on Hermes III.) Later that year, in reviewing the state of the Laboratories, President Irwin Welber acknowledged the importance of all the pulsed power capabilities in weapons effects simulation and in the Strategic Defense Initiative, and hinted at their even more important role should a rumored ban take place on all weapons testing. However, Welber, like many others at the weapons laboratories, stressed that none of the machines should be seen as substitutes for underground tests.³¹

Important behind-the-scenes developments that had been in the works for several years in the national inertial confinement fusion program and would affect its

future direction were revealed on March 21, 1988. In a front-page story on that date, the *New York Times* discussed the full implications of the classified Halite-Centurion experiments the Happer Committee had mentioned, whose details the *Times* could only hint at. The newspaper acknowledged it had obtained the details of the results largely from unnamed sources, but their truthfulness was not questioned by any in the weapons community. In fact, wishing to shed the cloak of secrecy in this line of work was a continued theme among weapons scientists beginning in the 1970s; it impeded communication in the scientific community, hence also progress. Titled “Secret Advance in Nuclear Fusion Spurs a Dispute Among Scientists,” the *Times* article made public the fact that at last fusion had been ignited in a fusion pellet—however, not using a laser or particle accelerator, but an exploding nuclear weapon. The accomplishment had been achieved during a secret underground test at the Nevada Test Site in 1986. Scientists had long wanted to perform the experiment to finally confirm the feasibility of inertial confinement fusion events, or what the *Times* called microfusion.³²

The implications of this classified work for the future course of the national fusion program were radical: fusion ignition in the pellet had required much more energy than predicted, on the order of 100 million joules, when 10 million joules had long been the working number. Nevertheless, the Halite-Centurion experiments had proved that the inertial confinement approach to fusion did work. Now that scientists knew the huge amount of energy needed for ignition inside a pellet, it was obvious that none of the current machines being built and tested for fusion were adequate. The *Times* assessed the situation in this way: “At issue is whether to press ahead with lasers and targets in the range of five to 10 million joules, or to shift to include lasers big enough to mimic the conditions of the underground achievement. Experts agree that the current generation of microfusion lasers are unsuited for producing such high energies, the cost being prohibitive.” Sandia’s particle accelerators are not mentioned in the story, because lasers were at the center of the national program, but what the *Times* said about lasers applied equally to particle-beam accelerators.

Before this public revelation, the secret results had been circulated within the nuclear weapons complex and inside the Department of Energy. Based on the knowledge that none of the current machines in the national program were powerful enough for ignition, the Department had begun to formulate a plan to build a Laboratory Microfusion Facility, estimated to cost between \$500 million and \$1 billion. It would be constructed on a much larger scale than current fusion facilities, with the sole goal of demonstrating ignition. Now that the secret results upholding the concept of inertial confinement fusion were out in the open, while seeking approval for the concept of a microfusion facility, the Energy Department told Congress on March 21, 1988, “we are now to the point where all but the most severe critics agree that the basic target physics has been proven.”³³

On the Scene at PBFA II

It is 7:23 p.m. on December 11, 1985. Building 983, home of PBFA II, is bustling with a hundred or so Sandians and Ktech contractors performing last-minute checks and operations designed to bring the giant machine to its first firing.

"This is not just a test shot," says Tom Martin. "If it works, we'll get some physics data."—If it works.—"We've practiced this many times before, but if the control room people feel anything like I do, they're scared to death," notes Steve Goldstein, head of Pulsed Power Operations.

It's been a long day. Some of the shot team members had arrived at 2 a.m., the rest between 6 and 7 p.m.. The shot had been scheduled for 2 p.m., but problems with the laser triggering system had caused postponement after postponement. There was a vote whether to wait until the next day, and the whole crew wanted to continue into the night.

At 7:23 p.m., there is one last test of the balky laser system, which Roy Hamil oversees. Tension builds. When the laser test results are analyzed nine minutes later, Mike Wilson, test integrator, announces "We are go!" The announcement is punctuated by the theme music from Star Wars on the PA system with voice-over reminding the listeners that Sandia "boldly goes where no man has ever gone before."

The waiting seems interminable as each of the interrelated systems that make up PBFA II is charged, dumped, checked, and charged again. "Eight minutes to go," comes the announcement at 7:59 p.m.

At 8:06 p.m. the visitors breathe a sigh of relief—the shot is going to go. They know that because Pace VanDevender, 1200 director, has placed a conference call to former 1200 director Gerry Yonas and Gen. Kenneth Withers, Deputy Assistant Secretary for Military Applications. They will listen to the final minutes of the countdown from Washington.

It's 8:07 p.m. The giant Marx generators are finally being charged. 8:08 p.m. Voices from the control room are shaking a bit now. Then it's 8:09 p.m. and Dennis Nations, control room coordinator, is saying "Fire!"

A few seconds later, the CCTV camera above PBFA II sends a flash of light to the monitors, the building rocks, and a flat "Whap!" hits listeners' ears. Everyone has been told to keep quiet, so the team members in charge of safety alarms can do their work if necessary. But it's tough not to shout. And some do.

Once assured that the shot had gone off successfully and no alarms were needed, the shot team and visitors release the exhilaration that had been building for hours, if not for days. The scene resembles the winner's dugout after a World Series except for the lack of real champagne.

Yonas stays on the line long enough after the shot to tell the *Lab News* that he's speechless. After being told that that fact was as remarkable as the PBFA II shot itself, Yonas regains control: "I'm incredibly thrilled. And proud of everybody. I could feel the machine's vibrations up my spine all the way across the country. That's got to be the best pulsed power team in the world!"

Marshall Sluyter, Department of Energy Headquarters Pulsed Power program manager, had flown in just to be with the team for the first shot. And Sandia Vice President for Research Bill Brinkman had spent most of the afternoon shuttling between his desk in Area I and the visitors' room in Area IV.

At the time, VanDevender said it was the most exciting day of his life. When interviewed a few days later, he said, "The event and the impressive and professional way in which the team carried it out demonstrate we are on the road with a winner of an accelerator. I'm very thankful for the engineers, experimenters, theorists, and sponsors who together have made it possible."

[Condensed from the *Sandia Lab News*, December 20, 1985.]

Asserting that the target physics was now well understood, the Department said all that remained was to determine the facility's driver requirements. Naturally Los Alamos and Lawrence Livermore advocated a laser of some kind as the driver at the proposed facility, and Sandia backed its accelerator approach based on the technology of several of its particle-beam accelerators.³⁴ At the time the Department of Energy began its plans for a Laboratory Microfusion Facility, the goal of PBFA II was to determine the utility of light-ion beams to drive inertial confinement fusion targets. In view of the much greater energy the fusion driver for the microfusion facility would require, Sandia decided to pursue its stated goal, and said that only if it believed that ignition was possible on PBFA II would it upgrade the energy in the accelerator and attempt ignition.³⁵ Sandia also began to look at the technology in its other accelerators as possibilities for designing the larger driver needed for the Laboratory Microfusion Facility. When it would be feasible to build such a facility remained debatable.

Reviews commissioned by the Department of Energy and by Sandia itself were beginning to pinpoint specific areas of concern with the pulsed power light-ion approach in the 1988/89 timeframe, particularly in view of the fact that the Department said it planned to choose a driver for the Laboratory Microfusion Facility within the next three to five years. Many issues had to be resolved, not only for the particle-beam approach, but for lasers as well. A Department of Energy report on the status of target physics for inertial confinement fusion said that "The role of light-ion technology in the Laboratory Microfusion Facility decision is very unclear at this time because there are no target physics data. In addition to its driver technology, Sandia must also develop a target database to be in contention. The weapons laboratories have offered that as soon as light ions can show sufficient intensity for target experiments, they will be willing to provide necessary help in developing the target designs. Therefore, the proper focus of the light-ion-beam program should be to achieve beam intensities in the 100 terawatts/cm² range as soon as possible."³⁶

Close to this time, in the fall of 1988, a technical review committee commissioned by Sandia scrutinized its light-ion fusion program. While lauding some significant areas of progress, the Davidson Committee, as it was called, noted poor beam focusing and slow progress in improving focusing on PBFA II as an area of major concern.³⁷ The committee said the decision to implement an energy upgrade of PBFA II (needed in studies for the Laboratory Microfusion Facility) should be deferred until significant progress had been made in beam focusing and a detailed assessment had been made of targets that the upgrade might drive. The committee said, "Making continued progress in diode physics at the energy levels available without the upgrade is of paramount importance and no PBFA II machine time should be diverted until this is accomplished." The committee continued, "The central priority for Sandia must be to establish the credibility that light ions can indeed be produced in pulsed power diodes and focused on the target at levels exceeding 5 terawatts/cm²." It concluded by challenging Sandia to meet that beam

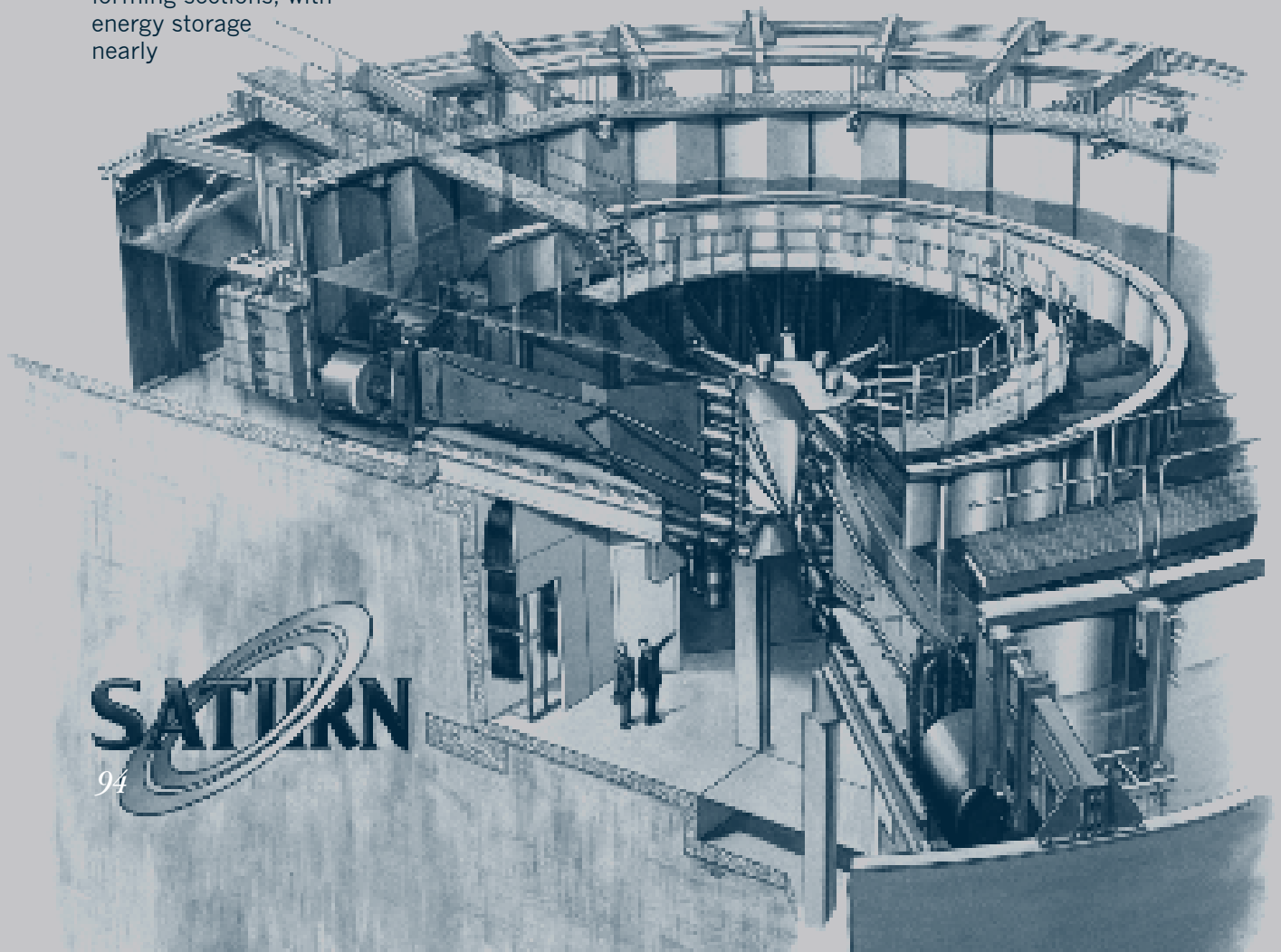
Saturn

With PBFA II within six months of completion, the Pulsed Power Center decided to convert PBFA I from a test bed for the new fusion accelerator into the world's largest, large-area x-ray simulator. To clearly distinguish both machines by name, a contest was held to choose a new name for PBFA I. The *Sandia Lab News* of June 7, 1985, noted that Mark Hedemann contributed the winning name: Saturn, suggesting the multiple concentric rings in the diode of the converted machine, rings reminiscent of the planet Saturn.

The certification requirements for the W88 warhead were the primary reason for converting PBFA I into Saturn, an accelerator designed to produce a source of Bremsstrahlung to test the electronic components of the warhead. Saturn would also be used for radiation effects research and for other weapons component hardening testing as part of Sandia's Simulation Technology Laboratory project (which also included Hermes III). An option to drive z-pinch implosions was included as part of the conversion, scheduled to be completed in 1987. The \$7 million project included upgrades in the energy-storage and pulse-forming sections, with energy storage nearly

doubling and nested tri-axial diodes providing a uniform radiation profile to enhance the efficiency of x rays arriving at the target in the exposure area.

On October 9, 1987, the *Lab News* reported that Saturn had been successfully fired on September 18, completing an effort that had involved more than 300 Sandians and contractors. Saturn became part of the Simulation Technology Department, headed by Jim Powell. At the time, Powell said, "The team took a tech base—pulsed power—and put it into an application—Saturn—without a hitch." Had Saturn been built from scratch, Powell estimated the cost to have been \$40 million, so it was a real bargain. The accelerator was seen at that time as a complement to underground effects shots at the Nevada Test Site. Other uses foreseen for Saturn were designing and developing future weapons systems, evaluating weapons in the stockpile, and assessing the survivability of Strategic Defense Initiative space systems to nuclear countermeasures.



The conceptual and preliminary design for the conversion was developed by Jim Lee, Doug Bloomquist, and Regan Stinnett assisted by Pulse Sciences, Inc. (a company that became part of Titan, Inc. in March 1987, with which Gerry Yonas was then affiliated). Bloomquist was also the project scientist for Saturn. Bloomquist, Lee, Stinnett, Hedemann, and Art Sharpe did the research and physics technical base on Saturn. Lee and Hedemann did the diode and testing application research and design. Bloomquist, Sharpe, and Stinnett performed the accelerator pulsed power and power flow research and design. Sharpe headed the assembly team for Saturn. Chuck McClenahan and Hedemann developed its key element, the multiple-ring diode, using Sandia's SPEED accelerator and Proto II. Larry Choate was manager of Simulations Applications and also a member of the project team. Ken Hanks of Plant Engineering was the Saturn project manager, using the same successful techniques as with PBFA II under Gerry Barr. John Boyes was project leader for mechanical design.

In 1988, a team headed by Rick Spielman developed a gas-puff z-pinch system on Saturn and used it to produce soft x rays. In this configuration of Saturn, a high-velocity cylindrical ring of gas several centimeters long—a puff of gas such as neon or xenon—was injected into the center of the machine. A current of some 10 million amps was passed through the gas. The large current, flowing along the axis (the z direction) of the gas puff, causes a strong magnetic pressure. The pressure rapidly drove the gas inward, toward the axis of the cylinder, creating a high-temperature plasma that emits x rays. The plasma was in fact heated to about 10 million degrees Celsius, near the temperature at the center of the Sun. The radiation was used to test the vulnerability of military hardware to such radiation, and to investigate the physics of x-ray lasers. Using imploding plasmas as the x-ray source, Saturn produced more than 500 kilojoules of x-ray energy in a single burst lasting billionths of a second, a record when it was first achieved. Saturn was able to operate both in the Bremsstrahlung mode and in the

gas puff z-pinch mode. The team involved Spielman, Keith Matzen, Warren Hsing, John Porter, David Hanson, Bruce Hammel, Sam Lopez, Larry Ruggles, and John McGurn, and the Saturn Operations crew. (See *Sandia Lab News*, April 21, 1989.)

Saturn is an accelerator measuring 29.2 m in diameter, with 36 modules converging on a central diode consisting of multiple concentric rings. At the bottom of the diode is a disk-shaped plate supporting a heavy-metal foil where energy from its 36 capacitors is converted into x-ray radiation. The x rays enter an exposure bay beneath the diode and permeate the items being tested.

The diode is novel in that it has three cathodes and four anodes. Saturn's power flow is divided so that 18 of its 36 capacitor banks feed the outer cathode ring, 12 feed the middle ring, and 6 the inner ring. The rings thus receive 50, 33, and 17 percent respectively of the power flow. This division of current produces a uniform radiation profile a short distance behind the converter, where accelerated electrons strike a tantalum target to produce Bremsstrahlung radiation.

The Bremsstrahlung photons are similar to the x-ray photons released in a nuclear explosion. Saturn is designed to produce an x-ray dose rate of up to 5 trillion rads per second for 15 to 20 billionths of a second. It provides a peak dose of 100,000 rads, four times greater than possible with Proto II (in 1987, Sandia's second most powerful x-ray simulator). Saturn was designed to carry out up to three radiation shots a day.

Power transmission flow is from the Marx generators to the diode inside the insulator stack at the center of Saturn. The generators are submerged in oil; the intermediate store capacitors, gas switches, pulse-forming lines, rod transmission lines, and disk feeds are all submerged in water. The insulator stack contains conical triplate magnetically insulated transmission lines, the diodes and the exposure bay; it is about 2.4 m tall and 1.9 m in diameter.

Hermes III

High-Energy Radiation Megavolt Electron Source (Hermes) III began operation in early 1988 as part of the Simulation Technology Laboratory complex in Area IV.^{a,b} The enormous accelerator measures 21 m wide, 15 m long, and is 5 m high. It is still in operation and remains the world's most powerful gamma-ray simulator, producing 13 terawatts of power in a 19-million electron volt, 28-nanosecond electron beam. It produces intense Bremsstrahlung doses and dose rates over large areas to study nuclear radiation effects induced by gamma rays. Hermes III uses technology developed by Pulse Sciences, Inc. and Sandia in the joint Defense Special Weapons Agency/Department of Energy Linear Induction Accelerator program, and can provide eight shots per day, four days per week. The accelerator has both indoor and outdoor test cells, and is used primarily for simulating the effects of prompt radiation from a nuclear burst on electronics and complete military systems.

When Hermes III produced its first "big bang," the *Sandia Lab News* characterized its mission as "to generate a lightening-like bolt of electrons that produces a flood of radiation when it strikes a heavy metal plate" (March 25, 1988). Such a capability was needed to test the vulnerability of weapons systems, in particular their electronics, to radiation. Hermes III was designed to simulate a weapon's exposure to a gamma-ray environment more accurately than

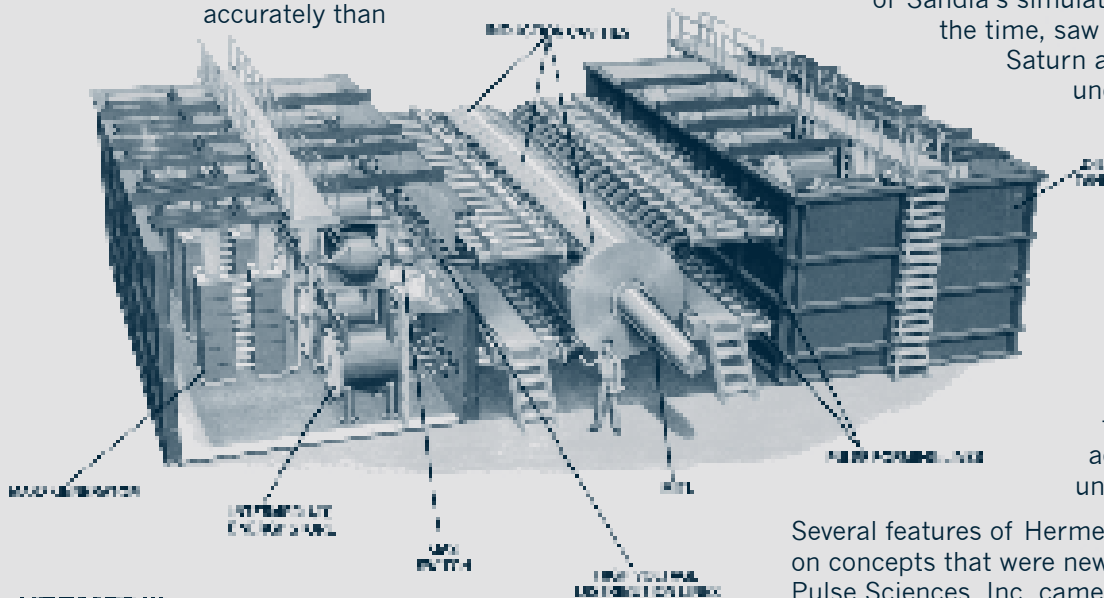
anything else available in 1988. Diodes were developed to efficiently extract the Hermes III beam and propagate it in long (10-m), gas-filled drift cells to an outdoor exposure area where large military hardware (such as tanks) could be tested for their vulnerability to gamma rays. Such beam propagation was record-setting at the time.^c

The burst of gamma rays had to be short, 20 billionths of a second, and intense. When it began full operation, Hermes III produced 10 times as many rads per second as its predecessor, Hermes II; or 5000 billion rads a second. (A rad is a measure of absorbed radiation energy.)

At that time, Juan Ramirez was supervisor of the Pulsed Power Development department, leading the research and development base for the machine during the three years it took to make Hermes III a reality. Ramirez also oversaw construction of its pulse-forming section. Ken Prestwich, project scientist for Hermes III, explained to the *Sandia Lab News* as Hermes III began operating in 1988 that dose rate had a lot to do with the failure rate of devices being tested. "The higher the dose rate—and the more photons deposited in a test object—the greater the chance of component failure. Using Hermes III to zap subsystems and components should give us a much better understanding of how much radiation they can take." Jim Powell, head

of Sandia's simulation program at the time, saw Hermes III and Saturn as complements to underground testing being done at the Nevada Test Site. Hermes III enabled laboratory testing of large components and subsystems at higher dose rates than could then be achieved outside the underground tests.

Several features of Hermes III were based on concepts that were new for the time. Pulse Sciences, Inc. came up with the



HERMES III
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idea of combining induction cavities and a magnetically insulated transmission line voltage adder, and its effectiveness was confirmed in high-energy linear induction accelerator (HELIA) experiments. The decision to try to engineer this new concept into Hermes III was Ken Prestwich's. It was acknowledged to be an enormous challenge; Pulse Sciences, led by Lee Schlitt, provided an initial design of the complex cavities and the adder, and Ed Burgess's Pulsed Power Engineering group successfully implemented the whole simulator. The result was that the outputs of the 20 induction cavities in Hermes III are fed into a magnetically insulated transmission line and an electromagnetic wave is repeatedly voltage amplified in 20 stages along the length of the magnetically insulated transmission line. At the end of this line, an electron beam is generated in an indented-anode diode. High-energy electrons striking the anode generate the gamma rays that are used for simulations.

The indented-anode diode invented by Tom Sanford was another unique feature of Hermes III.^d It used a new diode geometry that prevents a high-current electron beam from pinching or collapsing to a point on the axis of the diode because of the self-magnetic field of the beam. A pinched beam cannot provide a uniform radiation dose over a substantial volume. The indented anode was invented at Sandia specifically for Hermes III to prevent beam pinching and provide a uniform radiation pattern. John Halbleib and Jim Poukey helped develop the diode.

The energy-storage section of Hermes III consists of ten 2.4-megavolt, 156-kilojoule Marx generators, each of which charges two water dielectric intermediate storage capacitors. Laser-triggered gas switches release energy from the 20 intermediate storage capacitors to charge 80 water dielectric pulse-forming lines. The pulse-forming lines produce high-power (1.0 megavolt, 200 kiloamp) pulses, four of which are combined in each induction cavity to produce a 1.1-megavolt, 730-kiloamp pulse that feeds the magnetically insulated transmission line.

The project team included dozens of people from 10 Sandia departments and contractors from Pulse-Sciences-Titan, EG&G, Kirk-Mayer,

Ktech, and C&D. Larry Seamons from Sandia's project management center oversaw Hermes III. Powell, Wendland Beezhold, and Larry Posey defined the requirements for the accelerator. Ramirez, Prestwich, Sanford, and Ron Pate were responsible for the technical base of the accelerator.

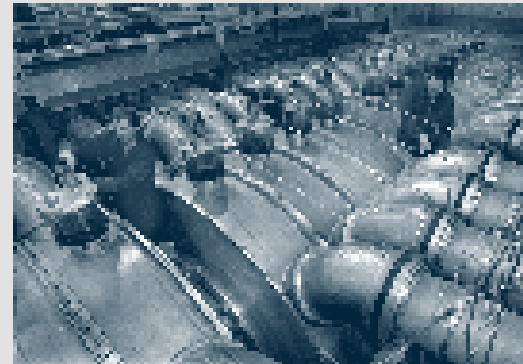
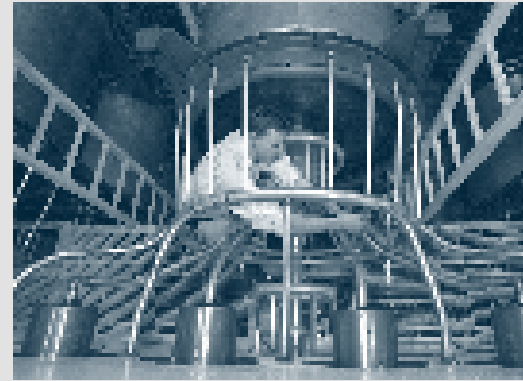
Ken Mikkelsen, Pete Micono, and Mike Eaton developed the data acquisition system for Hermes III. Its control and monitor systems were designed and implemented under Dave Davis. David Johnson and John Corley led the assembly and test team.

a K.R. Prestwich, J.R. Lee, J.J. Ramirez, T.W.L. Sanford, F.J. Agee, G.B. Frazier, A.R. Miller, "Overview of High-Intensity X-Ray and Gamma-Ray Sources," Proceedings of the Sixth IEEE Particle Accelerator Conference, March 16-19, 1997, Washington, DC.

b J.J. Ramirez, K.R. Prestwich, E.L. Burgess, J.P. Furaus, R.A. Hamil, D.L. Johnson, T.W.L. Sanford, L.O. Seamons, L.X. Schneider, G.A. Zawadzka, "The Hermes III Program," Sixth IEEE Pulsed Power Conference, Arlington, VA, 1987.

c See T.W.L. Sanford, "High-Power Electron Beam Transport in Long Gas Cells from 10^{-3} to 10^3 Torr Nitrogen," *Physics of Plasmas* **2**:2539 (1995), given as an invited paper at the 1994 American Physical Society meeting.

d For a comprehensive summary of Hermes III electron-beam diodes, see T.W.L. Sanford, "Dynamics of Electron Flows and Radiation Fields Produced by Electron-Beam Diodes on the Hermes III Accelerator," *Physics of Fluids* **B3**: 2387 (1991), given as an invited paper at the 1990 American Physical Society meeting.



intensity on target by April 1, 1989.³⁸ At the time, the energy on target was about half a terawatt per square centimeter.

Only months later, the *Sandia Lab News* could write the headline “PBFA Beam Team Beats the Clock: New Record—Five Trillion Watt/cm² Focused Ion Beam.”³⁹ In fact the record was set on March 23, with a week to go before the deadline set by the Davidson Committee. (Please see following sidebar on New Record on PBFA II.) Team members said that it was the most intense ion beam ever created; three and a half times that produced on any other accelerator. In praising the achievement, VanDevender told the newspaper, “Seventeen years of research and technology are finally paying off.” The charged particles used in the record-breaking shot were protons, but Cook, who managed the Fusion Research Department, said the milestone indicated the experiments could be scaled up to higher intensities with lithium-ion beams. Now that the intensity needed to ignite fusion in a pellet was known, the trick was to scale up existing technologies to achieve it or come close.

At the close of the 1980s, the Star Wars effort began to be scaled down, although the concept of directed-energy weapons has never completely died. In 1989, Ken Prestwich received the Erwin Marx Award for his outstanding contributions to pulsed power technology. (Please see following sidebar on the Prestwich and Martin awards.) That year, Tom Martin left his management position and returned to research as a senior scientist. Beginning a new decade and a new vision for the Labs, Al Narath returned from AT&T to Sandia as its president in 1989. As part of that changing vision, Gerry Yonas also returned to Sandia to head up a new Technology Transfer Directorate, whose mission was to help the flow of technical knowledge into the private sector as a way to make the United States more competitive economically.⁴⁰ ♦

New Record: Five Trillion-Watt/cm² Focused Ion Beam — *PBFA beam team beats the clock*

Late in September 1988, an external review committee hurled a challenge at Sandia's ion-beam fusion program: demonstrate major progress in beam focusing on PBFA II by achieving a beam intensity of 5 trillion watts per square centimeter on target.

Furthermore, do this by April 1, 1989.

The beam-intensity milestone was a big one, among others the committee suggested, including recommendations on ion focusing, lithium source development, beam transport, and others. It meant that in only six months' time, Sandia needed a tenfold improvement in beam intensity.

Tom Lockner from the Beam Experiments Department and head of the team recalled that when the review was conducted, Sandia was at half a terawatt per square centimeter. He said that by February, researchers had pushed the power density up quite a bit. By early March they were close. PBFA II was then generating the most powerful ion beams ever produced. But the challenging goal still eluded them.

Finally, on March 23, with only a week left before the deadline, the PBFA II team met and exceeded the 5-terawatts/cm² figure. The team announced the results at the IEEE Conference on Plasma Sciences in May. PBFA II experiments were carried out by a large team, including Lockner, David J. Johnson, Regan Stinnett, Bill Stygar, Tom Mehlhorn, John Maenchen, Mike Desjarlais, Ron Kensek, Ray Leeper, Rebecca Coats, Jeff Quintenz, and others in experimental, theoretical, and

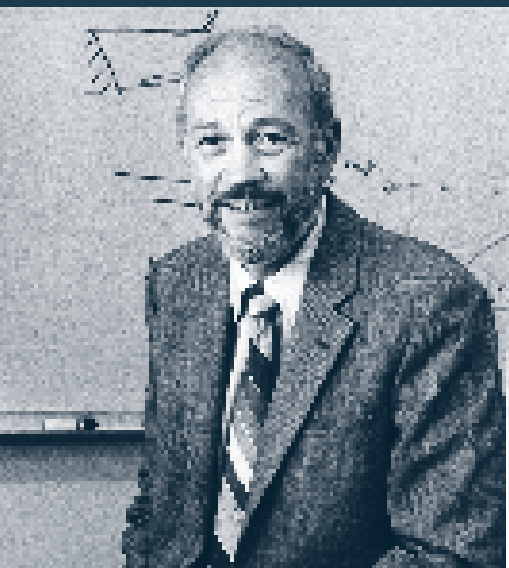
operations groups.^a David J. Johnson was in charge of the proton focusing experiments.

The achievement was made possible by a variety of improved capabilities, among them the ability to get one shot a day on PBFA II at three-fourths of the machine energy (up from a half earlier); excellent performance of the accelerator; good agreement between experiment and theory; computational improvement; getting the right shape and height for the anode to improve the focus of the beam; and finally, improvement in diagnostics that allowed the group to accurately measure what they were getting and to test their ideas and theories.

Sandia scientists found that developing a good source of lithium ions in PBFA II's ion diode—where the machine's pulse of electrical energy was converted into a beam—posed many challenging problems. Three different types of lithium-ion sources were being readied for testing. Sandians also planned to study the physics of how ions deposit energy in a target to produce x rays, an important intermediate step in producing an implosion and fusion reactions in a fuel-filled capsule.

[Condensed from the *Sandia Lab News*, May 19, 1989.]

^a D.J. Johnson, T.R. Lockner, R.J. Leeper, J.E. Maenchen, C.W. Mendel, G.E. Rochau, W.A. Stygar, R.S. Coats, M.P. Desjarlais, R.P. Kensek, T.A. Mehlhorn, W.E. Nelson, S.E. Rosenthal, J.P. Quintenz and R.W. Stinnett. "PBFA II Applied-B Field Ion Diode Proton Beam Characteristics," Proceedings of the 7th IEEE International Pulsed Power Conference, 1989.



Tom Martin wins Erwin Marx Award

Tom Martin, manager of the Pulsed Power Systems Department, was presented with the Erwin Marx Award by the IEEE at its fifth annual Pulsed Power Conference in Arlington, Virginia. The award, the most prestigious in the pulsed power community, is named for the originator of the Marx generator, primary energy source for pulsed power accelerators.

Other recipients include J.C. "Charlie" Martin of Britain's AWRE and Ian Smith, with Pulsed Sciences of San Leandro, California.

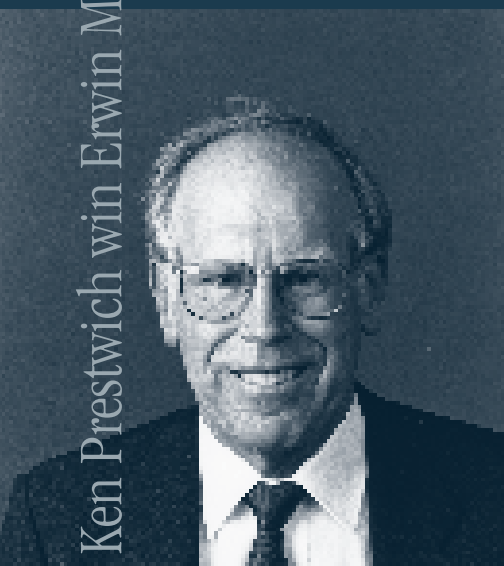
Martin was cited for his "many contributions to the pulsed power community in the field of pulsed power accelerators and the techniques

for generating and transporting terawatt electrical pulses." Martin originated the pulsed power program at Sandia in 1965 by heading up the team that built Hermes II. He and his group designed and built 17 other state-of-the-art accelerators, including Hydra, Ripple, Proto II, HydraMite, SuperMite, PBFA I, and PBFA II.

In accepting the award, Martin said that any development of a major accelerator is a team effort and he mentioned several Sandians who worked on the Labs' pulsed power program since its beginning: Ken Prestwich, Ray Clark, and Dave L. Johnson. He also recognized management support: "They've always wanted one more accelerator constructed," he said.

By 1985, Martin had authored or co-authored 35 technical publications in the open literature and delivered more than 70 invited lectures. In 1983, the Department of Energy recognized him in its awards of excellence for his contributions to the nuclear weapons program.

[From the *Sandia Lab News*, July 5, 1985.]



Ken Prestwich wins Erwin Marx Award

Ken Prestwich, manager of Pulsed Power Applications Department, received the Erwin Marx Award, which recognizes "outstanding contributions to the field of pulsed power technology." The award was presented at the seventh biennial IEEE Pulsed Power Conference in Monterrey, California, the sixth such award by the IEEE.

In accepting the award, Prestwich said he was pleased to be recognized by his colleagues and that it put him among some outstanding people. He continued, "Being at Sandia has given me the opportunity to do the kind of work that leads to an award like this. But everything we do here in pulsed power is a team

effort, and really, it's Sandia's pulsed power team being recognized, not just me."

Prestwich specializes in high-peak-power accelerators and related systems. He has contributed to the development of about 25 systems for purposes such as simulation of nuclear weapon radiation effects, inertial confinement fusion, gas lasers, high-power microwaves, electromagnetic pulses, and research on potential beam weapons. He has made major contributions on several Sandia projects—including Hermes II and III, Nereus, SLIM, Proto I, LILI, Rayo, and RADLAC I and II.

Prestwich is one of Sandia's pulsed power pioneers. He joined Sandia in 1962 and transferred in 1965 to a pulsed power department that subsequently expanded into the Pulsed Power Sciences Center. His work has resulted in 64 publications. The Department of Energy recognized his contributions to the development of pulsed power technology in 1983 by awarding him the Nuclear Weapons Program Award of Excellence.

[From the *Sandia Lab News*, August 11, 1989.]

endnotes

- 1 Dates are in the *Sandia Lab News*, January 23, 1981, in an article about Sandia's technical highlights for 1980. "Pulsed Energy" covered pulsed power work. The dedication of PBFA I was in the *Lab News* of August 8, 1980.
- 2 *Sandia Lab News*, January 23, 1981, reported on the two technologies being considered. About the imploding foil approach it said: "Two recently developed techniques, magnetic insulation and magnetic flashover inhibition, have made it possible to build high-power, low impedance machines which are capable of delivering the high currents (~5 MA) and short pulses (50 ns) necessary to magnetically implode foils at interesting energy levels. With possible applications to inertial confinement fusion, these techniques are especially attractive because of their simplicity and efficiency. Experiments at the 200 kilojoule level will be conducted in the immediate future. These tests will provide the data base necessary to field breakeven experiments on PBFA I and II. (4230)."
- 3 The concept has a long history; see discussion of z pinch in chapter four, giving sources for the history of this technology.
- 4 According to Dillon McDaniel, Sandian and Russian scientists had been separately exploring imploding foils in classified work since 1976; see chapter two. In "Overview," *Particle Beam Fusion Progress Report* for July–December 1981, SAND82-0340, further development of ion sources is mentioned coupled with beam transport systems suitable for application in reactors, showing that the idea of inertial confinement fusion for energy production was alive at Sandia.

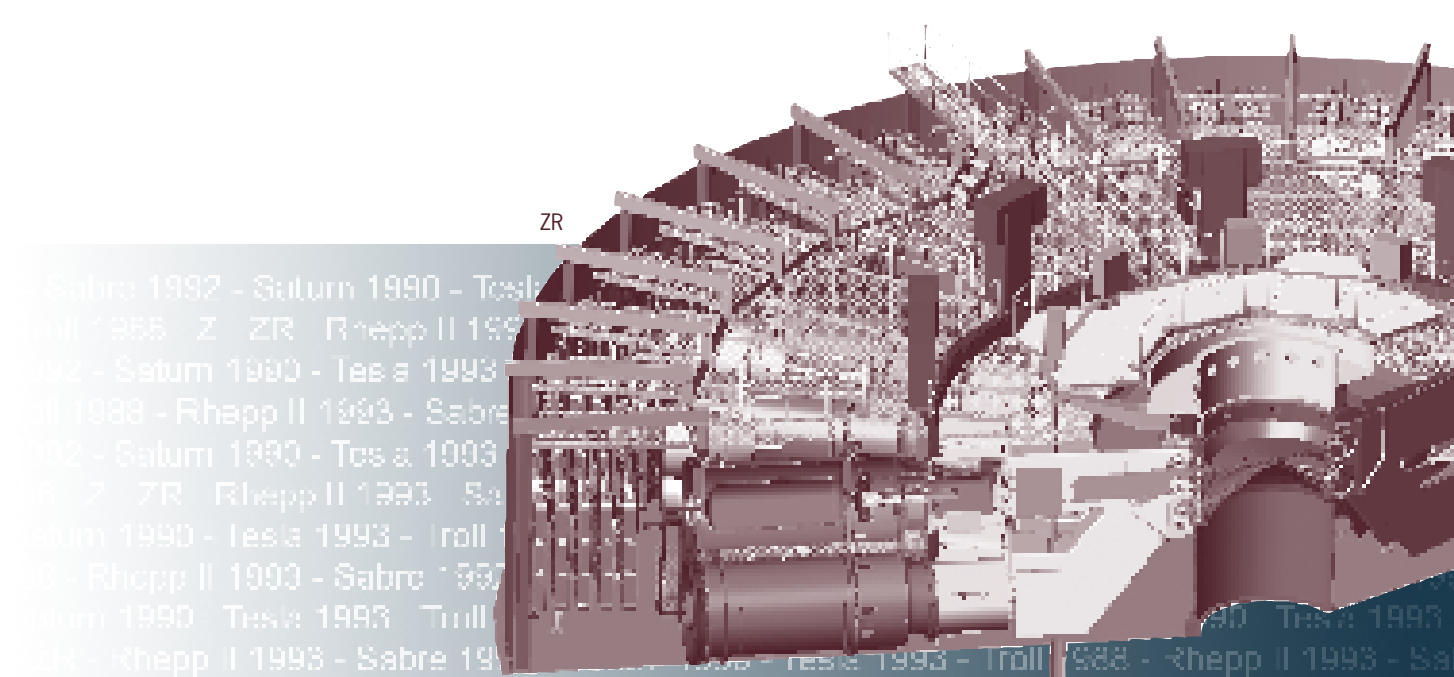
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- 5 See *Sandia Lab News*, “Ground Broken for New PBFA Lab,” April 3, 1981.
- 6 *Science*, 212, May 1, 1981: 517-519. The headline of the article is cited here.
- 7 See “Military in clash over US nuclear fusion research,” *Nature*, 281, October 11, 1979: 414-415.
- 8 Mirror fusion at Livermore was for a time a rival approach to Princeton’s Plasma Physics Lab and its tokamak machine. However, on February 21, 1986, after years of construction and \$372 million, Livermore’s Mirror Fusion Test Facility, a tandem mirror machine, was dedicated and the next day it was mothballed. Budget constraints and the high cost of the magnetic confinement machines forced a hard decision at the Department of Energy over which approach to back. See “Fusion’s \$372 million Mothball,” *Science*, October 9, 1987, an overview of the entire project, which involved several expensive redesigns of the machine. *Science* reports, “They were building a huge machine on fundamentally new and untested principles.”
- 9 See *Science*, 212, May 1, 1981: 517-519, quoted above. The issues raised here are evident in correspondence between Gerold Yonas, head of Pulsed Energy Programs at Sandia, and various Department of Energy officials and key people at Los Alamos and Lawrence Livermore in 1980-1981. See the 1200 Supporting Documentation collection in the Sandia archives, and the 1980s folder in the Van Arsdall archives, where some of this documentation is located.
- 10 “Overview,” *Particle Beam Fusion Progress Report* for July-December 1981, SAND82-0340.
- 11 G.C. Dacey letter of September 11, 1981, to R.E. Batzel, LLNL, and D.M. Kerr, LANL, copy to H.E. Roser at DOE. In the Cook Collection at Sandia archives; copy in Van Arsdall collection, 1980s folder. In the letter, Dacey states that Sandia has no plans or intentions of fabricating fusion targets, intending instead to support those activities at the design laboratories.
- 12 Furman interview of July 1984 with Pace VanDevender; *Particle Beam Fusion Progress Report*, July 1979-December 1979, SAND80-0974, and succeeding progress reports. Information about the imploding foil work is veiled or reference is made to classified reports.
- 13 Details on Sandia partners and international work provided by Ken Prestwich, August 2006. Prestwich attributed some of the international interest in part to “Sandia’s team enthusiasm and optimism for particle beam driven fusion.” (Van Arsdall collection, Prestwich folder)
- 14 See G.W. Barr, J.P. Furaus, and C.G. Shirley, “Particle Accelerator Research and Development at Sandia National Laboratories,” *Project Management Journal* XIX, No. 1, February 1988: 29-47.
- 15 “Dacey on Reorganization: Thinking Long Term and Thinking Short Term,” *Sandia Lab News*, August 6, 1982.
- 16 Letter from Pace VanDevender to Dr. Ronald C. Davidson, Director, Plasma Fusion Center, Massachusetts Institute of Technology, and head of the “Davidson Committee,” November 21, 1983, kindly provided by VanDevender in August 2006. The letter mentions that the decision was “particularly difficult.” (VanDevender folder, Van Arsdall collection). See also J. P. VanDevender, “Light Ion Beam Fusion,” *Proceedings of the Fifth International Topical Conference on High-Power Particle Beams*, San Francisco, California, September 12-14, 1983.
- 17 *Sandia Lab News*, March 2, 1984, “Diodes, Ions Selected: Final Design of PBFA II Set”; Furman interview with VanDevender, July 1984; Van Arsdall interview with VanDevender, 2004; Van Arsdall interview with D. McDaniel, 2005 and 2006.
- 18 Keith Matzen remained with imploding foil work under McDaniel. Matzen had been at Sandia since 1974; years later, beginning in 2005, he would lead the Pulsed Power Program.

- 19 Leeper was a new hire in the mid-1970s when he was involved in the experiment that was said to produce fusion neutrons (see chapter two). His specialty through a long career at Sandia is diagnostics (especially neutron diagnostics), an area crucial to scientific achievements. For the focusing story, see *Sandia Lab News*, "Major Step Toward Particle Beam Fusion," June 8, 1984.
- 20 John Maenchen, who led the experiments, became a supervisor in the Pulsed Power Program in the area of advanced pulsed power technologies. On his team for the experiments were Tom Mehlhorn, chief theorist; Carlos Ruiz, diagnostics (especially neutron diagnostics), chief; and Leeper. Mehlhorn is also currently a manager in the program. (See *Sandia Lab News*, April 12, 1985.) The "Report of the Sandia National Laboratories Light Ion Fusion 1985 Technical Review Committee" by the Davidson Committee in February 1985 praised what Sandia was doing generally, particularly in the fields of beam generation, focusing, and diagnostics. Sandia regularly commissioned technical review committees to guide its progress. Report is in Van Arsdall collection for 1980s, from Sandia archives.
- 21 *Sandia Lab News*, "Focusing 'Scale Up' Works," April 12, 1985.
- 22 *Sandia Lab News*, "Demon Passes All Tests," April 12, 1985.
- 23 *Sandia Lab News*, "Marx Generators Pass Tests," September 27, 1985.
- 24 *Sandia Lab News*, "Good-Bye PBFA I; Hello Saturn," November 22, 1985. In a memo of September 16, 1985, Sandia communications guru Nigel Hey suggested to VanDevender that PBFA II get an easy, user-friendly name too, like Nova, instead of an abbreviation. Handwritten on the memo is VanDevender's reply: "real men don't eat quiche and real fusion machines aren't user friendly; e.g., TFTR, JET, MFTF-B, etc. PBFA II is now internationally known and it is too late to change. Sorry, Pace." Photocopy in Van Arsdall collection for 1980s.
- 25 "Overview," *Particle Beam Fusion Progress Report* for July-December 1985, SAND86-0016.
- 26 "Fusion Possible in the Laboratory?: First PBFA II Shot Successful," *Sandia Lab News*, December 20, 1985. Related to these predictions, see SAND86-0016, *Particle Beam Fusion Progress Report* for July-December 1985. The Technical Overview begins, "Light-ion beams offer an efficient, low-cost, and repetitive driver technology for inertial fusion. . . . (PBFA II) is the only experimental device constructed that has the potential to reach ignition." J.P. VanDevender and Donald L. Cook, "Inertial Confinement Fusion with Light Ion Beams," *Science*, May 16, 1986; also *Sandia Lab News*, "Sandia Fusion Research," special report, April 12, 1985.
- 27 National Academy of Sciences, *Review of the Department of Energy's Inertial Confinement Fusion Program*, Washington, DC: National Academy Press, March 1986. The White House Office of Science and Technology Policy initially requested the review, which the National Research Council performed under the leadership of William Happer of Princeton. Informally this became known as the Happer Review.
- 28 *Sandia Lab News*, "Six Sandia Winners Announced in International R&D Competition," September 26, 1986.
- 29 *Sandia Lab News*, "Powerful X-Ray Source: Saturn Enters Arsenal of Simulation Technologies," October 9, 1987. During the 1970s and particularly the 1980s, statements at the weapons laboratories reflect their emphasis on underground testing to corroborate data from laboratory simulations.
- 30 *Sandia Lab News*, "Hermes III: First Firing of Gamma-Ray Simulator: A Successful 'Big Bang,'" March 25, 1988.

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- 31 *Sandia Lab News*, August 1, 1988, "Labs Accomplishments."
- 32 The Halite-Centurion information was officially declassified shortly after this time. On September 1, 1988, Fusion Power Associates issued a press release with the headline, "DOE [Department of Energy] declassifies previously secret aspects of ICF [inertial confinement fusion] research." It was one of the first times that the concept of indirect drive within a hohlraum was openly mentioned: "ICF targets located in a hollow chamber may be driven by trapped energy, nature unspecified, created in the chamber by one or more energetic beams penetrating the chamber through holes in the chamber walls." Only in the following decade of the 1990s would the indirect drive approach using hohlraums be openly discussed at any length. See also Marshall Sluyter (Department of Energy/Defense Programs) presentation to the Inertial Confinement Fusion Advisory Committee/Defense Programs of September 1988, "Basic concept of ignition and gain validated in Halite/Centurion Program," in the Cook Collection at Sandia Archives, Box 1/Van Arsdall.
- 33 June 14, 1988, "Review of Solid State Laser Technology for ICF," Lawrence Livermore National Laboratory report for Department of Energy/Inertial Fusion Division. Pulsed Power Center Archives, Box 1/Van Arsdall.
- 34 Livermore at this time proposed a \$1 billion follow-on laser to Nova, and Los Alamos proposed an interim krypton fluoride laser fusion research facility. Affecting the funding picture was the approval to build an advanced particle accelerator named the Supercollider in 1987 for high-energy physics research into the basic nature of matter at an estimated final cost of \$6 billion. That same year, the Livermore Mirror Fusion Test Facility was mothballed before it operated. Congress voted to terminate the Supercollider project in October 1993, by then called an \$11 billion project that was one-fifth complete. About \$640 million in an Energy and Water spending bill was allocated to dismantle the project.
- 35 "Status of Target Physics for ICF," report prepared by InterScience for DOE/IF Division on Review of DOE programs, November 14-17, 1988. The report is unclassified, but the review and the meeting were classified. In the Pulsed Power Center Archives, Box 1/Van Arsdall.
- 36 Ibid.
- 37 Not all the numerous reviews of the program are mentioned in this history. Davidson and his committees reviewed Sandia's Pulsed Power Program several times.
- 38 "Report of the Sandia National Laboratories Light Ion Fusion 1988 Technical Review Committee," written by SAIC for Sandia, October 1988. Pulsed Power Center Archives, Box 1/Van Arsdall.
- 39 *Sandia Lab News*, May 19, 1989.
- 40 *Sandia Lab News* articles: January 27, 1989, "Tom Martin Returns to Research"; April 21, 1989, page 1 features a letter by Narath on his return to Sandia; May 19, 1989, "Yonas Returns to Head Tech Transfer Directorate."



CHAPTER FOUR

from the '90s to ZR

As the 1990s dawned, international events were bringing an end to the Cold War, which had shaped US defense policies and the mission of the nuclear weapons complex since the close of World War II. The Berlin Wall fell in 1989, and East and West Germany began to reunite, as Soviet influence over East Germany diminished. In 1991, the United States and Russia signed the Strategic Arms Reduction Treaty, eliminating nearly 50 percent of the nuclear warheads carried by ballistic missiles. That same year, Communism fell across Eastern Europe, and the Soviet Union was replaced by the Commonwealth of Independent States.

The administration of President George H.W. Bush (1989-1993) brought a new head to the Department of Energy. Retired Admiral James D. Watkins demanded military rigor in reporting and operations not only from the Department but from all its laboratories. Intensive government scrutiny of the national laboratories began, particularly in the area of environment and safety, coupled with pressure to consolidate efforts to save money. Watkins was concerned about the national fusion program, and he implemented several programs to learn about the various players

and to set goals and priorities. He saw the magnetic confinement approach as the path to supply much of the nation's electricity and supported inertial confinement primarily for military uses (though recognizing its long-term potential for energy). All of this translated into significant challenges for the Pulsed Power Program at Sandia as the decade of the 1990s began. The new PBFA II accelerator was just beginning full-scale experiments when two important national reviews became the focus of activities in Area IV.

At the end of 1989, in part because of Admiral Watkins' concerns, Congress chartered a National Academy of Sciences panel (known as the Koonin Committee for its chair, physics Professor Steven Koonin of Cal Tech) to review the national inertial confinement fusion program and publish a final report by the fall of 1990. After a preliminary review of the efforts at all the laboratories involved, the committee issued an interim report in which it found that the program as a whole was somewhat distracted by the push toward the Laboratory Microfusion Facility, envisioned as a large-scale fusion facility based either on a laser or an accelerator as the driver and capable of the enormous energy and power needed for sustained fusion. (Please see following sidebar on the proposed Laboratory Microfusion Facility.) Results from the secret Halite-Centurion experiments at the Nevada Test Site (see chapter three) had shown that none of the current lasers or accelerators could achieve ignition, though they could perform experiments to provide valuable information about the conditions necessary for ignition. Given this information, a decision had to be made about the immediate goals of the program.

The Koonin Committee's interim findings were that existing facilities were not being fully used and some critical experiments were not being performed. It recommended a focused national effort to resolve any remaining uncertainties about whether it was possible to achieve ignition in the laboratory using the facilities then available and through cooperation among the laboratories. It said that the highest priority should be given to studies of target physics, because the choice of a driver would be derived from this work. At the Department of Energy, a timely decision in 1990 to review declassification of some details concerning inertial confinement fusion would soon enable discussion with the international community about concepts connected with fusion targets, such as "hohlraum" and direct and indirect drive.¹ (Please see the following sidebar on fusion concepts.)

For years, foreign countries had been routinely discussing details of inertial confinement fusion target technology that US scientists had to keep mum about because it was considered classified weapons information in the United States. US scientists and engineers had long favored declassification of much of their target work on inertial confinement fusion because they felt international cooperation on the difficult scientific problems involved was vital. Thanks to support from Marshall Sluyter, head of the Inertial Confinement Fusion Program at the Department of Energy, a team from Sandia made contact with Russian scientists working on foil

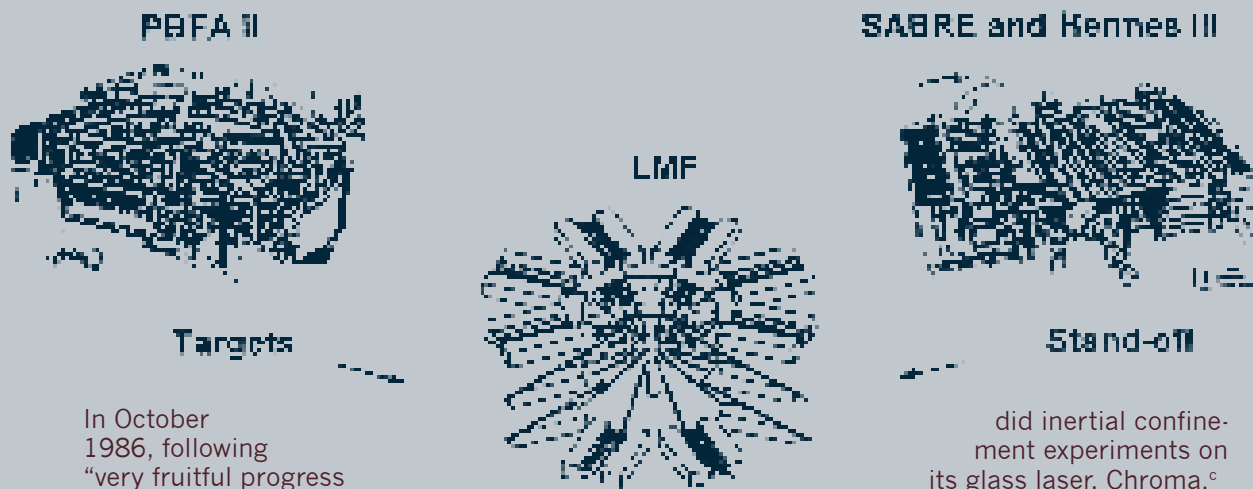
implosions in 1989-90 and then went to Russia to investigate successes they claimed to have made in 1992.² This was the beginning of international collaborations in pulsed power that continue to the present. (Please see the following sidebar on International Collaborations.)

The Koonin Committee report recommended upgrading the lasers Nova at Lawrence Livermore, OMEGA at the University of Rochester, and Nike at the Naval Research Laboratory, and to configure the Los Alamos Aurora krypton fluoride laser to implode a different kind of fusion target. After its initial review of Sandia's Pulsed Power Program, VanDevender later said, "We got a call in December [1989] from Koonin that they [the committee] had decided to kill our program immediately—not even waiting until the fiscal year was out. I negotiated another review in August of 1990. So with death facing us, we went to work."³ Because the results for lithium ions were not yet fully known, the committee deferred a recommendation on the light-ion approach. In doing so, it accepted Sandia's proposal to set and meet five milestones, including producing a high-power lithium-ion beam by the end of July 1990 when the final review would take place.⁴

While the Koonin Committee continued its investigations of the national fusion program, Admiral Watkins also began reforms in the areas of environment, safety, and health (ES&H) at the Department's laboratories. To that end, he sent out independent Tiger Teams to audit compliance with existing ES&H laws and regulations at all the major laboratories.⁵ Watkins said that any facility shut down for safety reasons would have to obtain his signature before resuming operations, thus stressing his concern with the issue. One of the first Tiger Teams came to Sandia in March 1990, and used the PBFA II facility as a training ground for its upcoming official audits. The inspection led to a complete facility shut down on March 13 because of safety concerns, and pulsed power was told to develop a plan of improvement, notably in procedure control. Don Cook, the manager of Pulsed Power Research, drafted a plan for the resumption and continuation of operations on PBFA II in which he listed five underlying reasons for the deficiencies the Tiger Team found: lack of formality of operations; lack of critical self-assessment; lack of time for training, education, and ES&H; conflicting concerns for meeting milestones vs. safety; and lack of job ownership. Al Narath, president of Sandia, held up the findings at PBFA II as lessons for all of Sandia, and the formality of operations that began in the Pulsed Power Program was instigated Labs-wide.⁶

In fact, because of the way in which the nuclear weapons complex had evolved, research into totally new areas had lent itself more to innovative one-of-a-kind experiments than to documented procedures. However, because of the materials involved, the scope of the national laboratories' work, and their now decades-long history of operations affecting the environment, Watkins believed it was time that ES&H concerns be taken seriously. The Department of Energy approved Cook's improvement plan for PBFA II operations, and PBFA II resumed activities on March 29.

The Proposed Laboratory Microfusion Facility



In October 1986, following “very fruitful progress in the inertial confinement fusion program,” the Department of Energy’s Defense Programs/Inertial Confinement Fusion Division launched a study to define a baseline facility to produce fusion in the laboratory, at that time usually referred to as microfusion.^a The primary purpose for such a facility was to provide a source of fusion events for weapons physics and weapons effects studies as a supplement to underground testing (or as a replacement for testing if a ban ever went into effect). Developing fusion energy for future electric power plants was considered a supplemental outcome. When the feasibility study began, the cost was estimated to be “greater than \$500 million and less than \$2 billion.”^b

A steering committee was named, made up of representatives from the six US laboratories involved in inertial confinement fusion and Lawrence Berkeley Laboratory, which was doing heavy ion work primarily for energy applications. The laboratories were Sandia and its light-ion accelerator, PBFA II; Los Alamos and the KrF laser, Aurora, supplemented by classified Centurion experiments; Lawrence Livermore and the glass laser, Nova, as well as classified Halite experiments; the Naval Research Laboratory, using a direct-drive approach on its Nike KrF laser; the Laboratory for Laser Energetics at the University of Rochester, which was also using direct drive with the glass laser, OMEGA; and KMS Fusion, Inc., a commercial firm that fabricated targets and

did inertial confinement experiments on its glass laser, Chroma.^c

The initial proposal stipulated that once the needed capability had been defined, a specific Laboratory Microfusion Facility would be designed and potential drivers would be evaluated in terms of cost and performance from among the contenders at the six laboratories.

On March 21, 1988, the Department of Energy officially announced to Congress that it was beginning the study to determine the driver requirements.^d Dr. Marshall Sluiter, head of the Department of Energy/Inertial Confinement Fusion Division, subsequently headed up the study, which involved a detailed review of the candidate machines being developed across the United States. Lasers were considered the front runners because of their technological maturity.

In the fall of 1988, Sandia proposed using PBFA II for target experiments to address the physics of fusion ignition. In parallel, Sandia advocated applying Hermes III technology to drive light ions. By operating in reversed polarity to drive an ion beam, Hermes III could demonstrate a 1/3-scale light-ion driver module for the proposed microfusion facility. Sandia predicted that when results of the PBFA II and Hermes III development efforts were integrated, they would establish the basis for a light-ion-beam system for the Laboratory Microfusion Facility.^e The team behind this work included Ken Prestwich, Juan Ramirez, and Craig Olson.

In 1990, in determining “whether there was sufficient confidence in driver and target technology to proceed with the Laboratory Microfusion Facility, or whether more work with facilities in existence or available soon is required to attain this confidence,” the Department of Energy decided to wait for more results before reaching any final decision.^f At that time, the Department backed an intermediate upgrade for Nova, OMEGA, Nike, a reconfiguration of Aurora for indirect drive, and another evaluation of Sandia’s light-ion approach once more data were available. The University of Rochester, advocating an immediate decision to use a glass laser as the facility’s driver, argued that “It is poor management and poor science to try to keep the inertial confinement fusion program from advancing until the least developed options achieve (or fail to achieve) parity with glass laser technology.”^g At this time, and in cooperation with Rochester, events were under way at Lawrence Livermore that served to alter the course of events considerably.

Plans for the Nova upgrade had begun back in 1988; however, a series of top-secret underground tests code-named Halite-Centurian, coupled with Nova test results, demonstrated the need for a much more powerful laser to reach ignition. In 1990, Lawrence Livermore proposed a \$320 million Nova Upgrade, consisting of an 18-beamline, high-power neodymium-doped glass laser that would be much more compact and efficient.^{h,i} The new Nova would have only one amplifier instead of five. Each beamline would accommodate 16 optically independent laser “beamlets.”^j

In 1991, Livermore established the Beamlet Demonstration Project and began to develop the next-generation technology for inertial confinement fusion lasers. Beamlet technology did not result in the Nova Upgrade but in a prototype beamline for a much bigger and more powerful laser system called the National Ignition Facility, which would be a Department of Energy center to study inertial confinement fusion and high-energy-density science in lieu of underground nuclear testing. The laser for the new facility was designed with 192 beams, to produce 1.8 million joules of energy.

The ambitious and expensive proposal for a National Ignition Facility at Lawrence Livermore began its way through approvals in the Department of Energy in 1991. The facility would be driven by a glass laser and was heralded as being designed to achieve ignition of a fuel pellet by 2000. By 1992, a newly formed Inertial Confinement Fusion Advisory Committee/Defense Programs within the Department of Energy was evaluating plans for the National Ignition Facility in terms of its technology and the roles of other inertial confinement fusion laboratories in the effort.

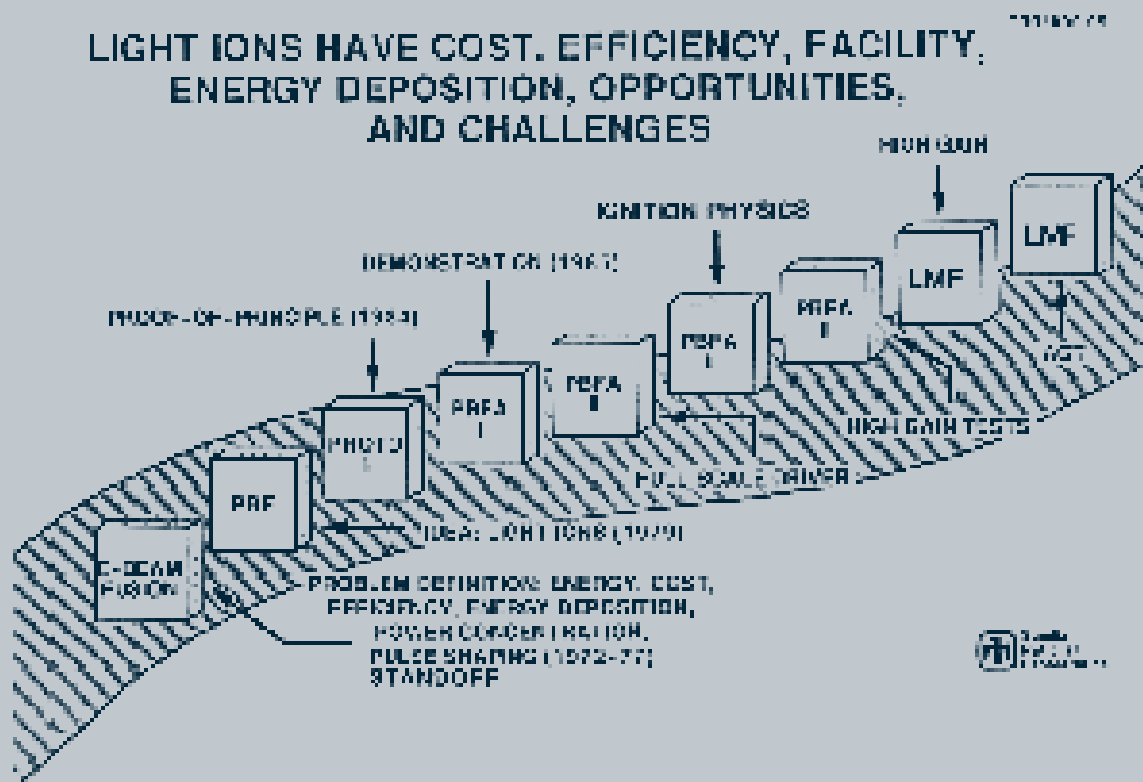
Sluyter, head of Defense Programs, said the National Ignition Facility answered the needs of his programs in a number of areas, although he said Defense Programs ultimately required the capability of a Laboratory Microfusion Facility, particularly if underground testing were permanently banned. He advocated having the National Ignition Facility designed so that it could be scaled up to the Laboratory Microfusion Facility.^k Sandia continued to advocate its concept for the facility using Hermes III and PBFA II.

In 1993 (and subsequently) Sandia defined its responsibilities with regard to the National Ignition Facility, but continued for two years to propose to the Department of Energy plans for new and more powerful machines—Jupiter, and then a module of a potential light-ion Laboratory Microfusion Facility. Sandia’s intent was to develop plans for a facility beyond the National Ignition Facility. Demonstrating ignition at the National Ignition Facility was generally conceded to be a step needed before plans for the ultimate Laboratory Microfusion Facility could be formulated. However, by 1995, the national focus in the Inertial Confinement Fusion Program was on the National Ignition Facility and plans for anything beyond it ceased. After this year, plans for a Laboratory Microfusion Facility became historical documents.

a *Laboratory Microfusion Facility Capability Study, Phase I Executive Summary of the Phase I Summary Report, Department of Energy/DP-0069, June 1989 (Pulsed Power Center Archives, Box 1/Van Arsdaal).*

b *Ibid.*

- c KMS Fusion, Inc., received funding from the Department of Energy/Defense Programs for inertial confinement fusion work from 1974 until 1990. The termination of its contract in 1990 was controversial, because it had been the only private firm in an area dominated by national laboratories and universities. See March 1990, "Government Accounting Office Fact Sheet for the Hon. Jon Kyl, House of Representatives, on Nuclear Science: Department of Energy's Acceptance of Academy of Sciences 1986 Inertial Confinement Fusion Technical Priorities," GAO/RCED-90-115FS; a similar report was delivered to the House Armed Services Committee as GAO/RCED-90-113BR, also in March 1990. KMS's fusion work to 1989 is mentioned in "Toiling on the ICF Vinyards," *Lasers & Optronics*, July 1989, pp. 24-25, and in John Horgan, "Infighting Among Rival Theorists Imperils 'Hot' Fusion Lab Plan," *The Scientist*, June 26, 1989, pp. 1-9.
- d "Review of Solid State Laser Technology for Inertial Confinement Fusion," presentation by Lawrence Livermore National Laboratory to the Department of Energy/Inertial Confinement Fusion Division, June 14, 1988 (Pulsed Power Center Archives, Box 1/Van Arsdaal).
- e October 27, 1988, "Status of Light Ion Beam Driver Development for Inertial Confinement Fusion," report for Department of Energy/Office of Weapons Research Development and Testing/Div. of Inertial Confinement Fusion, by InterScience, Inc. (Pulsed Power Center Archives, Box 1/Van Arsdaal). A note in the report says that work was predicted to be affected adversely in FY 1989 by a nearly 10-percent reduction in funding for inertial confinement fusion research at Sandia.
- f National Academy of Sciences, Committee for a Review of the Department of Energy's Inertial Confinement Fusion Program, Review of the Department of Energy's Inertial Confinement Fusion Program: Interim Report, Washington: National Academy Press, January 1990, p. 2.
- g University of Rochester, "Comments and Recommendations on the Proposed Nova Upgrade," Department of Energy/DP/40200-130, prepared for the National Academy of Sciences review of the inertial confinement fusion program (Pulsed Power Center Archives, Box PP6: 1987-1990).
- h Los Alamos issued an unfavorable review of the full Nova upgrade, saying it found significant probability that it "will fail to achieve ignition, and that the cost estimate is probably overly optimistic." Los Alamos National Laboratory, "Analysis of the Lawrence Livermore National Laboratory Proposed Inertial Confinement Fusion Ignition Facility: issues and proposed experiments," July 25, 1990, prepared for the National Academy of Sciences Inertial Confinement Review Group (Pulsed Power Center Archives, Box I/Van Arsdaal).
- i The University of Rochester backed the proposal; see University of Rochester, "Proposed Nova Upgrade," in reference g above.
- j W. H. Loder milk et al., *The Nova Upgrade Facility*, UCRL-JC-105734 (Livermore: Lawrence Livermore National Laboratory, 1991).
- k Sandia Archives: Cook Collection, Box 1. Folder on ICFA/DP (Inertial Confinement Fusion Advisory Committee/Defense Programs) meetings and the National Ignition Facility.



Fusion Concepts: Direct and Indirect Drive

In inertial confinement fusion, the energy from a particle beam accelerator, z pinch, or laser is used to compress and heat a minuscule fuel capsule containing a mixture of hydrogen isotopes (deuterium and tritium). The compression is intense, squeezing the plasma to a high density and initiating a fusion reaction throughout the fuel.

If the energy directly bombards the capsule, the process is called direct drive. If the energy is first converted to x rays, which then compress and heat the capsule, the process is known as indirect drive.^a

Sandia's inertial confinement fusion research has primarily concerned indirect-drive concepts, involving accelerators to provide energy and fusion targets. Sandia's accelerators have been made increasingly powerful through the years, as this history relates, to satisfy increasing requirements for energy on target. For fusion, the focus of that energy is a fusion target, comprising a container (hohlraum) into which a capsule of fusion fuel is placed (together, as small as a spool of thread). The capsule and hohlraum have to work together to produce a desired outcome, and their configurations and interactions are the subject of intense theory and experiment.

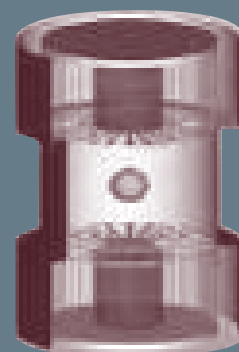
The purpose for the hohlraum (German for hollow space) is to convert the incoming energy into intense x rays. A variety of hohlraums exist, constructed of materials specific to their purpose. Confinement of the x-ray source power within a hohlraum works like an oven to increase the intensity and uniformity of x rays driving the capsule. The x rays envelop the fusion capsule within the hohlraum, causing the outer surface of the capsule to vaporize and rapidly blow outward. This outward movement compresses the deuterium-tritium fuel inside the capsule to an extremely high density and temperature. When the required density and temperature are attained, thermonuclear ignition occurs at the center and spreads throughout the fuel. At Sandia, both ion beams and imploding foils (z pinches) have used hohlraums. Ion beams are remotely created and focus their energy at a distance from the target. With the z-pinch, the electrical connections are made directly into the foil within the hohlraum.

Sandia's research with hohlraums and capsules was largely classified until 1990, but dates back to the 1970s. A number of recent

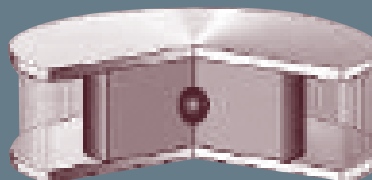
technical publications document Sandia's major efforts in these areas; concepts based, for example, on imploding capsules using double-ended hohlraums and dynamic hohlraums, and also deal with z-pinch-driven compression studies with the addition of a short-pulse laser beam.^b

The reason for classifying much of the technology connected with indirect-drive targets is that it derives directly from the design of nuclear weapons. Much of the work connected with inertial confinement fusion, therefore, is pertinent to understanding nuclear weapons and weapons physics and plays a role in Sandia's mission to certify the reliability of the nation's arsenal of nuclear weapons.

- a Historically, the University of Rochester and its OMEGA laser have concentrated on the key physics issues of direct-drive targets, doing research that is not classified. The Naval Research Laboratory has studied the interactions of laser beams and fusion targets using direct drive with both glass and krypton fluoride gas lasers (thus supporting both Los Alamos and Lawrence Livermore). Sandia, Lawrence Livermore National Laboratory, and Los Alamos National Laboratory have concentrated on the indirect-drive approach.
- b For an overview of Sandia's recent work, see M. Keith Matzen, M.A. Sweeney, R.G. Adams, J.R. Asay, J.E. Bailey, G.R. Bennett, D.E. Bliss, D.D. Bloomquist, T.A. Brunner, R.B. Campbell, G.A. Chandler, C.A. Coverdale, M.E. Cuneo, J.-P. Davis, C. Deeney, M.P. Desjarlais, G.L. Donovan, C.J. Garasi, T.A. Haill, C.A. Hall, D.L. Hanson, M.J. Hurst, B. Jones, M.D. Knudson, R.J. Leeper, R.W. Lemke, M.G. Mazarakis, D.H. McDaniel, T.A. Mehlhorn, T.J. Nash, C.L. Olson, J.L. Porter, P.K. Rambo, S.E. Rosenthal, G.A. Rochau, L.E. Ruggles, C.L. Ruiz, T.W.L. Sanford, J.F. Seamen, D.B. Sinars, S.A. Slutz, I.C. Smith, K.W. Struve, W.A. Stygar, R.A. Vesey, E.A. Weinbrecht, D.F. Wenger, and E.P. Yu, "Pulsed-power driven high energy density physics and inertial confinement fusion research," *Physics of Plasmas* 12, 055503-1 (2005).



Schematic of a double-ended hohlraum with the deuterium-filled capsule at the center.



Schematic of a dynamic hohlraum showing the outer wire array and the fusion capsule embedded in a foam target.

International Collaborations

The global scientific quest to develop new sources of energy intensified in the 1970s because of the negative political ramifications tied to having oil—available abundantly only in limited geographic locations—as the primary source for the world's energy supply. As a result, technical collaboration between political rivals began to be established, such as between the United States and Russia, to explore and develop or improve alternative energy sources, among them nuclear reactors and fusion.



Because of their leadership in technologies related to nuclear weapons, the United States and Russia were also technical leaders in research areas applying to nuclear power and the emerging field of fusion ignition, with its potential as an energy source. A Soviet-American Joint Committee on Atomic Energy was established in 1975 to share technical information. (A related story is the decades-long international effort in magnetic confinement fusion using the tokamak concept for a future power plant. This effort is now centered in the international ITER project located in France.^a)

As early as 1975, French, Russian, and British scientists had visited Sandia to find out about its electron beam fusion work as it applied to energy (see chapter two). Sandia and Russian scientists kept in contact during the decades of the Cold War, discussing the non-military aspects of inertial confinement

fusion. Much of the pulsed power technology was unclassified; the targets were the sensitive area because often they were designed for weapons-related work. Prominent among the Russian fusion scientists who worked with Sandians at that time were Leonid Rudakov and Valentin Smirnov. Rudakov was involved with electron and ion beam fusion; Smirnov with the then-secret imploding foil approach on Angara V, an approach later known as z pinch. Both scientists still collaborate with Sandia's pulsed power directorate. Because particle beam technology was largely unclassified, it was in this area that most collaborations with Russia could occur. The fusion world knew about Russian work with imploding foils through publications and presentations at international meetings. Because of the classified work Sandia was doing with imploding foil targets, Sandia's Dillon McDaniel kept in contact with Smirnov over the years for the purpose of observing the Russians' work.

With the fall of Communism and restructuring of the former Soviet Union beginning in 1989, what had been organized government research programs in Russia splintered, as regular sources of funding for science dried up. Marshall Sluyter, head of inertial confinement fusion programs at the Department of Energy beginning in 1990, said that because of this situation, working with the Russians became a tremendous bargain if it could be done right, and there was great interest in capturing Russian knowledge.^b

McDaniel had heard a talk at the Beams Meeting in 1990 in which Smirnov said his team had reached about 150 electron volts in a z-pinch-driven holraum on Angara V, achieving an internal temperature of 135 electron volts. Because the most Sandia had achieved to that date was 50 electron volts, he and his team were somewhat skeptical of the Russian claims but intrigued by the science involved. (At this time in Sandia's inertial confinement fusion program, the thrust was ion-beam-driven fusion, and z-pinch research was confined to weapons-related work.) With the possibility of direct and more open collaboration with Russian fusion scientists working on z pinch, McDaniel and Sluyter began to plan how to set up a team to work in Russia and explore their approaches to similar scientific problems.

At Sluyter's request, Sandia prepared a white paper for the Department of Energy outlining the benefits of such interactions, indicating four areas of pulsed power technology and applications that appeared to be more advanced in the former Soviet Union than in

^a Sandia contributes to this effort as well; see Leland Johnson, *A History of Exceptional Service in the National Interest*, SAND97-0029, Albuquerque, NM, 1997, pp. 324-25. For ITER (International Thermonuclear Experimental Reactor), see, for example, <http://www.iter.org>. ITER means "journey" or "way" in Latin, and this is often cited as the meaning of the term; i.e., the way to get to fusion energy.

the United States. These areas were production of record high temperatures in low-density foam targets using pulsed power, magnetized fusion targets, repetitively pulsed Tesla generators, and multiple plasma opening switch devices. In its justification, Sandia stated that its staff was uniquely suited to investigate the Soviet advances, validate the results, and apply them to Department of Energy programs in inertial confinement fusion, weapons physics, weapons effects simulations, and development of pulsed power.^c An initial visit to Russia in July 1992 to lay groundwork for the collaborations included Sluyter, McDaniel, Rick Spielman, and James Aubert from Sandia and others from Los Alamos and Livermore. Sluyter later said it took nearly two years from inception of the idea to visiting Russian laboratories and doing the work because of the myriad political complications involved.

Because the work would benefit the Department of Energy laboratories generally, Los Alamos and Lawrence Livermore scientists and engineers were included in the team. Experiments were conducted from May to July 1993 at several locations. McDaniel recalled that seven huge cases of equipment were sent over and back, a complex feat because of the customs regulations. The Sandia team now included all who had gone before and also Dan Jobe (Ktech), Peter Hockday, Jimmy Emmich, and Johann Seamen. Collaborations with Russian institutes and scientists initiated then continue through today. As a result of the work and negotiations with the Russians by Sluyter and McDaniel, a team of about 15 US citizens worked with the Russians on joint experiments at Angara V in 1993-94. They confirmed that a hohlraum temperature exceeding 85 electron volts (about 900,000 °C) had been achieved. Because this was higher than anything achieved at Sandia up to that time, it led to a further set of joint experiments on Saturn in 1994 that included more than 20 visiting Russians.

Other international collaborations continue on fusion research, facilitated by this early effort. An important collaboration for Sandia's z-pinch inertial confinement fusion program is with France and its Delegation Générale pour l'Armement to develop large pulsed x-ray sources.^d



Russian Minister Boris Saltykov (second from left), the Russian Minister of Science and Technology Policy, and Dillon McDaniel (right), Manager of High Energy Plasma Physics Dept. 1273, jointly examine a low-density foam target used in physics experiments on Sandia's Particle Beam Fusion Accelerator II. Behind Saltykov are (at far left) Vladimir Kuznetsov, Consul General, and Valeri Semin, Consul for Science and Education, both at Russia's US Consulate in San Francisco. The Russian science visitors were at Sandia September 22, 1994, hosted by Bert Westwood, Vice President for Research and Exploratory Technology 1000, who briefed them on research initiatives at Sandia. They also received briefings on pulsed power technology, surface sciences, and computer-aided materials processing and met with Executive VP Jim Tegnalia. Clyde Layne, deputy program manager of Sandia's Cooperative Measures Program Office, was with them the whole day, split between Los Alamos National Laboratory and Sandia.

b The following information is from Van Arsdall, interview with Marshall Sluyter, August 7, 2006, and interview with Dillon McDaniel on July 27, 2006.

c D.H. McDaniel, D.L. Cook, J.P. VanDevender, and J.K. Rice, "Potential Soviet Interactions of Benefit to US/DOE Programs in Pulsed Power Sciences," March 4, 1992. Copy provided by McDaniel to Van Arsdall, in McDaniel folder, Van Arsdall collection.

d "Technical Arrangement Between the Department of Energy of the United States of America and the Minister of Defense of the French Republic Concerning Cooperation in the Application of Emerging Technologies," signed in May 2000. Copy provided by McDaniel; in Van Arsdall collection, McDaniel folder.

The shutdown had come at a particularly difficult time, however. Not only was the pulsed power team striving to meet the milestones for the Koonin Committee by July, it was also preparing for a comprehensive review in May by the newly appointed Fusion Policy Advisory Committee. That blue-ribbon committee had been created to advise the Secretary of Energy about the future direction of the national fusion program as a whole.⁷

In August 1990, the Koonin Committee returned to Sandia and was pleased to learn that the Pulsed Power Program had met four of the five milestones the committee had set. Following official release in September of the committee's final report to the National Academy of Sciences, the *Sandia Lab News* reported on October 5: "Sandia Gets High Marks for Fusion Research—Funding Expected to Continue." In the *Lab News* article, Cook praised the teamwork that was involved in meeting the milestones, with 85 Sandians and 50 contractors working long days and long weeks with little vacation. For the milestones, PBFA II had produced a beam of 10 million volts (11 million in one test), generated a diode current of nearly 3 million amperes, achieved a purer lithium beam, and reached more than 70% efficiency in converting electrical to ion power.

The milestone not achieved was in reducing the divergence of the lithium ion beam, i.e., improving the focus, although some improvement in this area was noted. To help tackle the problem, new diagnostics were developed experimentally to better diagnose the conditions inside the diode. In addition, a team in the theory group developed analytic theory and better computer modeling using a new type of three-dimensional code. Together, these efforts had the goal of understanding why the beam spread. Theory was saying that energies high enough to cause ignition were possible with lithium ion beams, but for this to happen the beams had to be precisely focused on target.

For this reason, the Koonin Committee's final report identified reducing the divergence of the ion beam as the highest priority Sandia should set. Other recommendations were to increase the power density of the beam and to begin actual target experiments. It stipulated that detailed milestones be set for the following two years for PBFA II and technical progress be monitored. The committee recommended that the budget remain the same for the next two years, promising that an increase in funding to upgrade PBFA II could become a reality if sufficient progress were made during that time toward the newest milestones. Another review was scheduled for the summer of 1992, but was eventually postponed until March 1993.

Sandia had not been the sole subject of the Koonin Committee's report, of course. Lawrence Livermore's proposal to upgrade its Nova laser was sanctioned in the final Committee report as the most promising way to meet what it termed "the national ignition demonstration." The committee endorsed a four-year program at Livermore with a number of milestones, estimating the cost to be \$95 million

The Fusion Policy Advisory Committee and Its Impact on Inertial Confinement Fusion Energy Work

In 1990, a series of interrelated high-level reviews was launched to evaluate US fusion programs. A newly created Secretary of Energy Advisory Board reported directly to the Secretary of Energy, and under this board was a Fusion Policy Advisory Committee. Its charter was to advise the secretary about the future of the nation's fusion research and to make funding recommendations. (These studies were in parallel with the National Academy of Sciences reviewers who were independently weighing scientific progress in inertial confinement fusion.)

The Fusion Policy Advisory Committee examined Sandia's inertial confinement fusion program in the spring of 1990. By this time, defense applications for inertial confinement fusion clearly dominated at Sandia; however, harnessing fusion for energy remained a viable although long-term possibility. Indeed, as from the beginning of Sandia's fusion program, funding was primarily from the Defense Programs side of the Department of Energy, and work aimed at developing fusion for commercial power had to be ancillary to defense uses. On the other hand, the Office of Science within the Department of Energy funded and oversaw a Fusion Energy Sciences organization devoted entirely to research into fusion for commercial power. The thrust here was magnetic confinement fusion, and the inertial confinement approach was a relatively minor player.

By this time, the paramount issue was that no approach to controlled fusion in the laboratory had succeeded after years of effort, with the science and technologies involved spanning both defense and energy programs. A complicating factor was that classification of some areas of inertial confinement fusion, largely concerned with the targets, inhibited full sharing of research results both within the United States and with foreign scientists and engineers.

Because the Fusion Policy Advisory Committee was examining all of fusion in the United States, Sandia and the other defense laboratories were eager to explain how their fusion research, though based in defense applications, applied to energy as well. In several presentations to the Committee, the nuclear weapons laboratories argued that an energy-related program could be built on the defense-related inertial confinement fusion program to resolve technical issues leading to commercial power. They pointed out that the target physics and driver development leading

to high gain used in military applications were equally valid for energy applications. At the time, the Laboratory Microfusion Facility was being planned, and this future facility was envisioned as yielding high gain for both weapons studies and energy. The laboratories argued that after that facility was built, energy research could proceed on an engineering test facility demonstration reactor leading to energy production, while military applications would continue using high yield for weapon physics.^a

The outcome of the Fusion Policy Advisory Committee's findings was that there was a need for fusion energy because of greenhouse warming and depletion of fossil fuels, population expansion, and public concern for the safety of nuclear fission-based power plants. The Committee's report said the United States should set its sights on a demonstration fusion reactor producing electricity by 2025 and plan for a commercial plant by 2040.

The *Fusion Policy Advisory Committee Final Report* appeared in September 1990. On September 27, 1990, the *Albuquerque Tribune* summarized the findings, saying that "the Department of Energy Fusion Policy Advisory Committee calls for new initiatives in civilian fusion energy research to bolster current military fusion projects that have been struggling at New Mexico's two national nuclear weapons labs [Sandia and Los Alamos]. The proposal would eventually shift the military program to a new civilian Department of Energy Inertial Fusion Energy Program, including PBFA and Aurora."

However hopeful this prediction was, the Pulsed Power Program at Sandia remained under Defense Programs as a key component of stockpile stewardship, and fusion for energy would be a very small part of the formal program in the years to come. However, the high-energy-density and plasma physics issues with which Sandia researchers grappled would have bearing on the basic science involved in creating laboratory fusion. (Please see following sidebar on Z-Pinch Inertial Fusion Energy later in this chapter.) In addition, when many details of inertial confinement fusion target development were declassified in the early 1990s, the implications of this approach to fusion energy could be more freely discussed and evaluated.

[Related sources: Documents available at the Office of Energy Sciences website (www.ofes.fusion.doe.gov and www.science.doe.gov).]

The Fusion Policy Advisory Committee and Its Impact on Inertial Confinement Fusion Energy Work

^a March 22, 1990, "Inertial Fusion for Energy Application," Presentations by Defense Programs Inertial Fusion Division to the Fusion Policy Advisory Committee, in the Sandia archives, Pulsed Power Center Archives: Pulsed Power 6: 1987-1990 and Pulsed Power Center archives, Box 1/Van Arsdaal; and in the Van Arsdaal collection.

annually, or a \$25 million more per year budget increase. Citing again the proposed ignition demonstration at Lawrence Livermore and its findings during the review, the committee's assessment of Aurora, the krypton fluoride laser at Los Alamos, was not favorable. In fact, because of dwindling funds for the fusion program, the committee predicted that the \$31 million annually spent on the Aurora program might have to be shifted to cover expenses for the Nova upgrade, thus terminating it (and in fact this is what happened).

At that time, Sandia's fusion budget was \$27.3 million annually. In reporting on the committee's findings and recommendations, one of Sandia's hometown newspapers, the *Albuquerque Tribune*, said "Sandia's work on the \$48 million Particle Beam Fusion Accelerator so dazzled the experts that the lagging accelerator has switched places with Aurora in the last month. Sources close to the panel say that in the early going of the review, the struggling Sandia was the target laboratory for major fusion budget cuts."⁸ Going into the review, few predicted that the Los Alamos laser would be axed and Sandia's accelerator kept alive. Given two years of only level funding before the next review by the committee, VanDevender, who was both the Inertial Confinement Fusion program manager and director of Pulsed Power Sciences, appointed Cook as the program manager in October 1990 to give the program more focused leadership. By the fall of 1991, major target experiments had been carried out on PBFA II, indicating that the accelerator could successfully meet the milestones the committee had set for the following year's review. The series of experiments used hydrogen ions (protons) to heat and implode several types of targets to measure their response. The committee had told Sandia to emphasize work on beam focusing and target physics experiments at increasing power concentration. Explaining the significance of the series to the *Sandia Lab News* in October, Cook said that the quality of the data was superb, and "... the experiments show we're on the right track."⁹

In the wake of these and associated events, while visiting Sandia in September 1992, President Bush told the Labs, "The Cold War is over, and freedom finished first." During a talk to Sandians, Bush outlined some major shifts in funding at the defense laboratories, which included Sandia and Los Alamos in New Mexico. Instead of missile defense, the United States was committing itself to limiting the proliferation of nuclear weapons and to strengthening American industry by emphasizing research and development at the laboratories and then transferring the results to industry. Nuclear deterrence would continue to be essential to national defense, but the number of weapons could be greatly reduced. Bush told Sandia, "We are setting priorities, holding the line on money in other areas of government spending so that we can turn the scientific prowess of American away from creating weapons of mass destruction to creating new industries for mass employment."¹⁰

In October 1992, the United States decided unilaterally to stop nuclear weapons tests, taking the weapons laboratories by surprise, since underground testing was considered the fallback for acquiring data required for accurate studies and predictions.¹¹ (However, many of the weapons effects simulations facilities had

PBFA II Experiments Erase Doubts About Obtaining Data

Pea-size targets imploded by ion beams

October 18, 1991

The first major target experiments have been successfully carried out on Sandia's powerful PBFA II particle beam fusion accelerator.

The series in August and September included the first experiments on PBFA II aimed at heating and imploding inertial confinement fusion ignition-size targets. The types of targets tested included foam targets for diagnosing target heating and spherical targets for diagnosing hydrodynamic response. Hydrogen ion (proton) beams were used. The experiments were recorded with sophisticated diagnostic instrumentation, and this resulted in achieving high-quality data.

During the next year, work will concentrate on improving the focusing and therefore increasing the intensity of the giant accelerator's ion beam. Experiments during this period will use lithium ions.

The goal is to bolster the intensity of the accelerator's ion beam to 10 trillion watts (10 terawatts) per square centimeter and then to do further target experiments with that beam.

A major National Academy of Sciences review in late summer of 1992 will determine whether beam-focusing issues have been resolved and whether PBFA II should be upgraded to higher energies to make it possible to achieve fusion ignition.

The recent series involved two new kinds of targets that are much closer to those of real interest for fusion. They are about 0.6 cm in diameter, near the dimensions required for achieving ignition with a suitably intense lithium ion beam.

One was a cylindrical target filled with an extremely low-density hydrocarbon foam. As the foam is heated by the ion-beam energy to very high temperatures, it gives off x rays. The experiments successfully recorded the spatial distributions and intensities of those x rays.

The second type of target was spherical. It consisted of a shell 6 millimeters in diameter—about the size of a pea—made of 0.1-millimeter-thick plastic.

Inside this capsule was deuterium (heavy hydrogen) gas. These were the first target experiments using deuterium ever conducted on PBFA II. (Tritium, a still heavier isotope of hydrogen and a second necessary ingredient for achieving fusion, has not yet been added to the capsules.)

The intent was to have the proton beam heat the shell directly from all sides, resulting in an implosion of the target and compression of the fuel. The collapse of the target was accurately recorded by x-ray imaging diagnostic instruments. In these first-ever hydrodynamic target experiments on PBFA II, the material was indeed imploded by the ion beam.

The data were of good quality, allowing successful comparisons of theoretical calculations with experimental outcome—one of the goals of the experiments. Don Cook, Manager of the Fusion Research Department, said "There has always been a question whether we would be able to get high-quality target data out of the harsh environment of this accelerator. We proved that we can get the data. We've made major progress."

The new achievements in target experiments are the result of "an exemplary team effort" by Sandia researchers, diagnostics experts, and operations personnel," said Jim Rice, Manager of the Target Research Department.

Rice and Cook gave major credit to Gordon Chandler, principal experimenter for the target experiments, and the target team, Mark Derzon, Paul Rockett, Jose Torres, John Hunter, Jack Pantuso, and supervisor Keith Matzen. In addition, signaled for credit were Rick Olson and Tom Hussey, of the Radiation and Hydrodynamics Theory department; David J. Johnson of the Beam Experiments department for proton beam focusing; Jim Aubert, manager of the Target Fabrication Department, and his staffers Dora Derzon and Patti Sawyer; Jim Bailey, Alan Carlson, and Carlos Ruiz of the Diagnostics Department; Tom Mehlhorn and Ray Dukart of the Diagnostics Theory Department; and all the members of PBFA II operations.

[Condensed from the October 18, 1991, issue of the *Sandia Lab News*.]

been designed with this possibility in mind.) In an effort that became linked to the cessation of underground testing and the need for more capabilities in the laboratory, soon after the Koonin Committee endorsed the Nova upgrade Lawrence Livermore National Laboratory began to promote the concept for a facility designed specifically to demonstrate ignition of fusion in the laboratory. The Nova upgrade would be based on an enormous capability using glass lasers and located at Livermore. It was promoted as an intermediate stage to the Laboratory Microfusion Facility, one based entirely on the laser approach. (Please see following sidebar on the National Ignition Facility.) Concepts for the upgrade to Nova soon became merged with planning for another new facility, which was heralded as a multi-laboratory effort, despite the fact that other laboratories felt it was premature in the light of the current state of technology. In 1992, initial concepts began for an ambitious new laser fusion effort, the National Ignition Facility, which Admiral Watkins approved in January 1993 and whose construction continues to the present. At the time, Sandia's fusion capabilities were seen as supporting this national facility. Realizing that the microfusion facility remained a long-term need, Sandia continued working on its light-ion technology as the basis for it, asserting that pulsed power was cheaper and more efficient than the laser approach.¹²

Soon after the cessation of underground testing, the nuclear weapons complex was given a formal new mission called Science-Based Stockpile Stewardship.¹³ This mission was mandated by the White House through the Department of Energy and Department of Defense beginning in 1993, when the administration of President William J. Clinton began (1993-2001). Science-based stockpile stewardship means that the weapons laboratories use computers, experiments, simulators, and other tools of science to fulfill their responsibility, or stewardship, of the nation's stored arsenal of nuclear weapons, the stockpile. (Please see following sidebar on Science-Based Stockpile Stewardship.) Lawrence Livermore argued that funding for the National Ignition Facility was justified because of its foreseen contributions to this new mission.¹⁴

These interrelated developments helped shape the mission of Sandia's Pulsed Power Sciences Center during the next decade, while Sandia's traditional responsibilities in weapons effects testing and simulation became more critical in the absence of underground nuclear weapons tests. Without these tests, the full spectrum of radiation produced in a nuclear explosion was not available, and the Departments of Energy and Defense needed this capability. Only limited subsets of the radiation could be provided at that time by laboratory simulations on machines such as Saturn and Hermes III. And so, Sandia investigated how pulsed power could be used to provide radiation test capabilities closer to the full nuclear environment, including converting PBFA II for this use and formulating plans for a more powerful simulation facility.

Although the standoff necessary for fusion ignition was then believed impossible on PBFA II, experiments on the accelerator could provide data for fusion studies.

Standoff refers to the separation needed between the ion beam driver and the fusion target. For high yield, and for energy applications, this meant the final light-ion beam had to be transported a distance of typically several meters from the exit of the accelerator to the target, so that the driver could be protected from the fusion blast. Part of the light-ion fusion program was dedicated to studying standoff, and it was led by Craig Olson.¹⁵ A variety of possible transport modes was proposed and studied.

In addition, potential instabilities, such as the two-stream instability and the filamentation instability, were investigated and assessed.¹⁶ The bottom line was that transport and final focusing were thoroughly studied theoretically (and in experiments at the Naval Research Laboratory) both for light and heavy ion fusion and were ready for substantial experiments with high-current, low-emittance, extracted light-ion beams—but such beams never became available.

The more powerful weapons effects simulation facility Sandia envisioned was named Jupiter and was based on PBFA II technology. The more powerful Jupiter driver would implode foil targets to produce the soft x rays needed for weapons physics. Juan Ramirez, who had headed the Hermes III project, led the team to plan Jupiter, a team that would combine talent from VanDevender and Powell's organizations.¹⁷ In addition, the continuing light-ion target studies on PBFA II were now being used in conjunction with results from SABRE and Hermes III to establish the light-ion accelerator basis for the Laboratory Microfusion Facility. Sandia continued developing designs for this facility, calculating that the final fusion plant should be based on lower-cost and more-efficient particle beams.

In March 1993, the Department of Energy's Inertial Confinement Fusion Advisory Committee/Defense Programs conducted a review at Sandia as part of its responsibilities to evaluate the entire US inertial confinement fusion program.¹⁸ The committee was pleased with Sandia's progress toward what it called "a challenging set of milestones" and said the quality of science had improved significantly.¹⁹ The committee recommended that another set of technical milestones be set up for Sandia's program to help it reach its predicted goals. A "Light Ion Technical Contract" was developed that included requirements to define Sandia's role with regard to the proposed National Ignition Facility, and set milestones in the area of beam intensity, targets, standoff, and experimental facilities. The committee also recommended that Sandia's proposal to build Jupiter be delayed until essential target physics experiments had been performed.²⁰ The Laboratory Microfusion Facility concept was still being discussed at this time, and the committee indicated that light ions were seen as a possible approach as drivers for inertial confinement fusion targets. (The National Ignition Facility was considered the primary hope for ignition and the Laboratory Microfusion Facility for high gain; high gain means more energy out of the reaction than was used to produce it.)

Looking back on these crucial reviews, VanDevender later recalled that one of Sandia's principal detractors, Bob McCrory, the leader for direct-drive laser fusion with glass lasers and director of the University of Rochester's Laboratory for Laser



The National Ignition Facility

The National Ignition Facility at Lawrence Livermore National Laboratory is the culmination of decades of work in developing increasingly powerful lasers to ignite inertial confinement fusion in the laboratory. Laser technology has long been central to the national Inertial Confinement Fusion Program at the Department of Energy. As this history indicates, Sandia's pulsed power accelerators were developed in parallel with lasers; sometimes in competition with them, sometimes complementary to them.

Below is a brief outline of the lasers at Los Alamos and Livermore. Over the years, these have been the major laboratories in designing and developing lasers as fusion drivers in a proposed national ignition (or microfusion) facility. Ultimately, in such a facility, fusion events can be used for weapons physics and weapons effects studies and high-yield fusion would then be possible, leading to the development of commercial power plants. The Naval Research Laboratory with its Nike laser, the University of Rochester, Laboratory for Laser Energetics, and its OMEGA laser, and KMS Fusion have also made important contributions to laser and target technologies over the years.

In the late 1960s, Los Alamos began research on the two-beam CO₂ laser Gemini, designed for 2.5 kilojoules. Livermore was developing both the tandem mirror machine and glass lasers.

In the 1970s, Los Alamos built Helios, an eight-beam CO₂ laser, designed for 10 kilojoules. Lawrence Livermore built the 20-beam glass laser Shiva. Later, in 1978, Livermore requested \$220 million for its Nova glass laser, an upgrade to Shiva. Los Alamos began its \$35 million Antares project, a long-wavelength CO₂ laser designed with 72 beams to produce 40 kilojoules (24 beams of which were completed in 1984).

In the early 1980s, Antares, the CO₂ laser at Los Alamos, was in trouble; calculations

showed that long-wavelength lasers would not provide the characteristics needed for the goals of inertial confinement fusion, and Los Alamos built a short-wavelength ultraviolet KrF laser named Aurora as an alternative to Nova. By 1988, Aurora had failed to produce key results, according to John Browne, P-Division Leader.

In 1990, Aurora was cancelled following a recommendation to that effect by a national inertial confinement fusion review committee (the Koonin Committee). That year, Livermore proposed a \$320 million Nova Upgrade: an 18-beamline, high-power neodymium-doped glass laser that would be much more compact and efficient. The new Nova would have only one amplifier instead of five. Each beamline would accommodate 16 optically independent laser "beamlets."

In 1991, the Beamlet Demonstration Project began at Livermore. It resulted not in the Nova Upgrade, but in a prototype beamline (called Beamlet) for a much bigger, more powerful, and more expensive laser system called the National Ignition Facility. In 1994, Beamlet laser was complete. (Beamlet was given to Sandia in 1998 and after reassembly in Albuquerque began a new life as Z Beamlet in 2001.)

Approvals began in the Department of Energy to fund and build the National Ignition Facility. An analytic paper on the "Contributions of the National Ignition Facility to the Department of Energy Strategic Plan" was submitted to the Secretary of Energy in June 1994, drawn up by staff in Defense Programs, and the Office of Energy Research, the Office of Intelligence and National Security, with input from the national laboratories and the University of Rochester. The mission of the facility was "to produce ignition and modest energy gain in inertial confinement fusion targets in support of national security and civilian objectives." It was described as a cornerstone of the Department of Energy's Science based Stockpile Stewardship

Program, a major contributor to the field of high-energy-density physics, and a necessity to evaluate inertial confinement fusion for energy.

Total cost for the National Ignition Facility was estimated to be initially \$340 million, and later \$843 million; the total project cost itself was estimated as \$1074 million. Construction was planned for 1996-2002. After completion, the operating costs and maintenance were estimated to be \$60 million a year. The facility was described as benefiting more than a thousand scientists in basic sciences, inertial confinement fusion energy, nuclear weapons, weapons effects, and inertial confinement fusion. The laser in the new facility was designed with 192 beams, to produce a total of 1.8 million joules of energy.

Groundbreaking for the National Ignition Facility was in 1997 at Livermore. *Science Magazine* reported in July 1997 that the facility was estimated to cost \$1.2 billion, and outlined some of the concerns the scientific and weapons community was voicing about the goals and outcome of the facility. The article was by James Glanz, titled "Harsh Light falls on NIF: This giant fusion laser is meant to simulate aspects of nuclear explosions, but critics question both its relevance to weapons and whether it can meet its technical goals" (Vol. 277, Issue 5324, pp. 304-307, July 18, 1997). While the new facility was being built, Nova was shut down in 1999 to reduce the cost to the national inertial confinement fusion program.

In 2000, the General Accounting Office estimated the National Ignition Facility would cost \$4 billion to complete, including all research and development costs from areas that support the National Ignition Facility. The Department of Energy and Lawrence Livermore estimated \$3 billion and completion by 2008 (GAO/RCED-00-141, August 8, 2000). *Science Magazine* reported that the National Ignition Facility would cost \$3.26 billion and completion was estimated to be in 2008. Charles Seife and David Malakoff wrote: "Will Livermore Laser

Ever Burn Brightly?" (Vol. 289, Issue 5482, pp. 1126-1129, August 18, 2000).

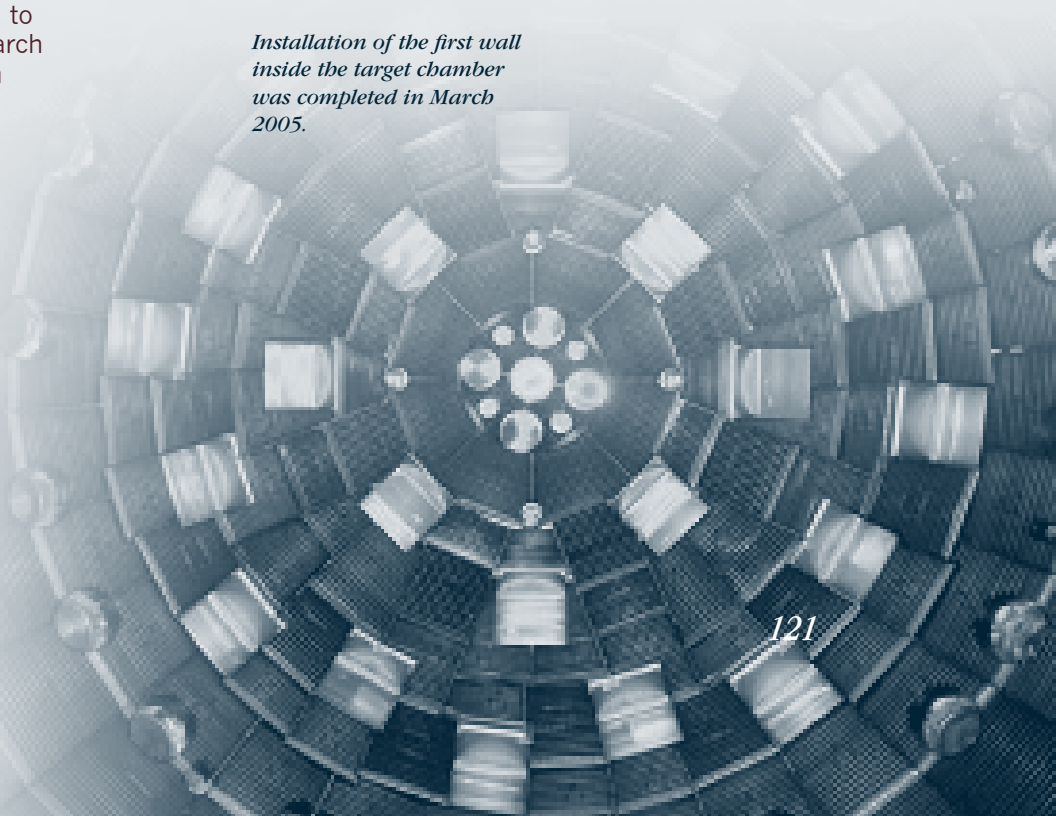
Construction of the building for the 192-beam, 500-terawatt National Ignition Facility was completed in 2000, and construction of the laser beamlines and target bay diagnostics then commenced. At the time, the planned first shot was 2010.

A press release was issued on November 9, 2005, from Lawrence Livermore on the National Ignition Facility: "Statement on congressional funding for the National Ignition Facility" (for that FY): The President's budget requested a total of \$337.4 million for the National Ignition Facility in four categories. In action yesterday, the Energy and Water Appropriations Conference Committee approved the requested \$141.9 million for construction; \$43 million for diagnostics; and \$40.2 million for ignition." (At that time, the facility was said to be more than 80 percent complete. Eight of its 192 laser beams had been placed into operation.)

The National Ignition Facility is scheduled for completion in mid-2009, with the first integrated ignition experiments expected to begin the following year.

[Additional sources include the Los Alamos National Laboratory website, Physics Division Organization, History Page; Lawrence Livermore National Laboratory website on the National Ignition Facility.]

Installation of the first wall inside the target chamber was completed in March 2005.



Science-Based Stockpile Stewardship

In 1993, President Bill Clinton extended the moratorium on nuclear testing and initiated steps toward a Comprehensive Test Ban Treaty. At the same time, he directed the Department of Energy to explore additional methods to maintain confidence in the safety, reliability, and performance of US weapons in the absence of nuclear testing. In 1996, the Comprehensive Test Ban Treaty cemented the moratorium on testing.

The Department of Energy's Stockpile Stewardship Program was established when the National Defense Authorization Act was passed in 1994. The act required the department to establish and maintain a multi-faceted program to increase understanding of the stockpile, to be able to predict any problems as the stockpile aged, to refurbish and re-manufacture weapons and components as necessary, and to maintain the science and engineering facilities required to support the nation's nuclear deterrent. The Department of Defense works with the Department of Energy to set requirements for the stockpile.

Although underground testing never provided all the capabilities needed to understand the total nuclear weapons environment (aboveground testing has added some of this information), it was considered vital to round out weapons physics data and verify computer models. With no underground tests available, data to predict the performance and longevity of nuclear warheads had to be obtained differently. The term science-based stockpile stewardship was in common use for the program at the time, since it involved interrelated capabilities across the nuclear weapons complex at the weapons laboratories, the Nevada Test Site, and production facilities. Complicating the picture currently is the fact that the stockpile is being revamped. Modern manufacturing capabilities and microelectronics are being developed to replace components and reduce life-cycle costs based on developing a scientific understanding of how weapons age and the effects of radiation on them. Today, this work is part of the Stockpile Life Extension Program within what is now called the Stockpile Stewardship Program.

The Stockpile Stewardship Program is directed by Defense Programs within the National Nuclear Security Administration (a semi-autonomous arm of the Department of Energy).

The scientific and engineering tools are state of the art in a number of fields, ranging from banks of extremely fast and highly powerful computers to perform simulations, to basic research fusion/radiation facilities such as the ZR at Sandia and the National Ignition Facility at Lawrence Livermore, to hydrodynamic and radiographic test facilities at the Nevada Test Site, Los Alamos, and Sandia.

Sandia itself has a wide range of responsibilities related to the Stockpile Stewardship Program. Pulsed Power Sciences contributes to these stewardship responsibilities (specifically under the National Nuclear Security Administration's Directed Stockpile Work and the Stockpile Stewardship Program campaigns), providing

- intense x rays to measure material properties at high pressures to certify the survivability and performance of strategic systems
- research on Z toward the long-term national goal of high-yield inertial confinement fusion, which, when available, will enhance US capabilities in radiation effects, weapons physics, and fusion for energy, thus supporting a number of areas in the Stockpile Stewardship Program
- contributions toward weapon science campaigns, which are challenging, multi-year, multi-functional efforts, notable among them: dynamic materials properties studies to develop physics-based, experimentally validated data and models of all stockpile materials for a broad range of dynamic conditions; advanced radiography to provide the technical basis for deploying compact, inexpensive pulsed-power-driven flash radiographic x-ray sources in support of work at Los Alamos and the Nevada Test Site; and using Z and Z-Beamlet to assess the performance of the secondary component in weapons
- support for activities associated with certification of specific weapons for the Stockpile Life Extension Program
- advances in x-ray power output and magnetic pressure and in repetitive, high-average-power accelerator technology for basic science applications
- accurate high-pressure equation-of-state data for a broad range of materials, including deuterium and special nuclear materials.

Energetics, said, “There has been a sea-state change of science at Sandia and Sandia deserves more funding.”²¹ VanDevender said this recognition of Sandia’s success made a profound impression on him. Having shepherded the Pulsed Power Program through this challenging time, VanDevender turned it over to different leadership in April 1993 (later becoming the director of the new National Industrial Alliances Center after a brief stint as director of the Corporate Communications Center for the contract transition to Lockheed Martin).²² (Please see following sidebars on “Sculpture Honors Pulsed Power Researchers” and on the VanDevender Lawrence Award.) Don Cook was then promoted to head up the Pulsed Power Sciences Center; Jeff Quintenz, who had been in the program since 1975, became the center deputy and program manager of Inertial Confinement Fusion Program; and Keith Matzen, at Sandia since 1974 and in pulsed power after 1980, was named manager of Inertial Confinement Fusion/High-Energy-Density Physics. Quintenz, long an advocate for theory to support experimental work in pulsed power (see chapter two), said about this successful review that what had been called an “arcane endeavor” back in the early days of pulsed power had clearly become a science-based research program in large part due to advances in theoretical capabilities.²³

Cook later characterized the time between 1994 and 1996 as key. Sandia faced another review by the advisory committee, and the future of its fusion program hung on being able to show it could produce the energy on target that it had promised. Cook said, “We got stuck at the 1989 level of energy for four years. We just could not improve the power concentration. We tried and tried.”²⁴ The main reason for not being able to improve was not fully recognizing the fundamental physics involved. At this time, the National Ignition Facility was emerging as the Department of Energy’s champion for microfusion, over the protests of other laboratories about its technical merits. The Department of Defense, having immediate x-ray requirements, expressed interest in a less ambitious facility, one more realistic in the near term, to provide the types of radiation it needed for weapons testing. The White House was calling for Science-Based Stockpile Stewardship capabilities at the weapons laboratories. In this very demanding weapons fusion and weapons physics arena, Sandia’s Pulsed Power Program had to prove itself.

Funding cuts for fusion nationwide had been significant since the late 1980s, and by 1994 at Sandia had gone from \$80 million to \$40 million with a loss of about 200 people in pulsed power. The National Ignition Facility was funded in 1994 at an estimated cost of about \$1 billion, and fears were voiced that the entire inertial confinement fusion program was in danger of being committed to this one facility because of its enormous cost. Research dollars had been carefully allocated at Sandia, and in an innovative move to mitigate the situation, Cook and Jim Powell, head of Radiation Effects and Testing, Center 9300, integrated the defense program work of their respective centers in 1995, though remaining in separate organizations.²⁵

A Government Accountability Office Report on *Nuclear Weapons* (GAO-06-261), published in February 2006, states that from fiscal year 2001 through fiscal year 2005, the National Nuclear Security Administration spent more than \$7 billion (in 2005 dollars) on the six scientific campaigns associated with the Stockpile Stewardship Program; i.e., primary, secondary, advanced computing, advanced radiography, dynamic materials properties, and inertial confinement fusion. The intent of the report is to review how well performance and cost are being measured in the Stockpile Stewardship Program, as reflected in a wider evaluation of the “quantification of margins and uncertainties” methodology developed by Los Alamos and Livermore to assess and certify the nuclear stockpile.

[Information primarily from *Sandia National Laboratories Institutional Plan: 2005-2010*, SAND-2005-4400P, where details of Sandia’s responsibilities are outlined; and US Department of Energy, National Nuclear Security Administration paper on Stockpile Stewardship, DOE/NV-1017 (available at <http://www.nv.doe.gov>). See also Physics Today Online: Science Based Stockpile Stewardship, dated 2001: <http://www/physicstoday.org>.]



Don Cook

By 1994, a small research effort in the weapons physics side of pulsed power—using z pinches to create intense x-ray sources on the Saturn machine—was showing such progress that Cook was considering reconfiguring PBFA II so it could operate part-time with z pinches. (Please see following sidebar on Z Pinch.) This z-pinch effort was the imploding foil technology that had been excluded from the main microfusion work when ion beams were chosen, but had been kept alive in the weapons side of pulsed power. Dillon McDaniel and Keith Matzen, who had long worked on imploding foil technology in the Scorpio program, outlined such a project with Rick Spielman and Bill Stygar as the technical leads. They argued that operating as PBFA-Z, the existing PBFA II could efficiently drive z-pinch targets at energy levels no existing facility in the United States could match. It was Powell who made the decision to allocate some of his scarce funds to the z-pinch work on Saturn, at a considerable risk, but it soon paid off. With data in hand, Cook and Powell agreed to make the modifications to PBFA II to scale up the power available for driving z-pinch implosions as PBFA II/Z. Sandia then began to outline the expected benefits of PBFA-Z to several national committees and stressed that inertial confinement fusion work and weapons program work were interrelated and interdependent at Sandia.

In June 1995, Tom Sanford and his team had a breakthrough on the Saturn machine that promised optimistic results on PBFA II, which was being modified at a cost of \$13 million to operate part-time as PBFA-Z.²⁶ (Please see following sidebar on Sandia's 1995 Breakthrough with Z Pinches.) Saturn focused its energy on an innovative target, a configuration of small aluminum wires; they imploded symmetrically, and 40 terawatts (0.5 megajoules) of x-ray output resulted from the implosion—researchers had expected 10 to 15.²⁶ These experiments were based on the reasoning that greatly increasing the number of wires would improve the symmetry of the resulting z pinch, an idea that had not been explored to the fullest. These and other refinements continued to be made in z-pinch technology in subsequent years, building upon the breakthrough and on a significant body of earlier work. Attention then turned from Saturn to PBFA II/Z and its performance as a driver for z pinches; expectations were that the more powerful accelerator could obtain even more impressive results.²⁷

Before the results of the z pinch on Saturn, Sandia was looking toward the future primarily based on the PBFA II ion-beam approach using a new diode concept, the applied-B extraction ion diode. Beyond that was the concept for the super accelerator, Jupiter, envisioned as producing 32 megajoules of energy.²⁸ In mid-1996, PBFA-Z was still seen as a complement to the PBFA-X (the accelerator configured with an extraction diode) and was to be operated primarily for weapons physics programs. PBFA-X was a configuration of the machine to drive an extraction ion diode, designed to enable ion beams to be extracted from the diode and propagated to a target—a feature necessary for fusion and a step on the way to fusion energy. (The applied-B cylindrical, or “barrel” ion diode had focused the ions internally.) PBFA II was to run a six-month set of scaling experiments for z pinches

as PBFA-Z, after which it was to return to light-ion research as PBFA-X.²⁹ Looking back over the evolution of pulsed power to this point, VanDevender some years later attributed the ability to make these switches in technology relatively easily as key to its versatility. “That’s the real story of pulsed power. The versatility of the technology to allow an accelerator to drive all three of those different technologies [electron beams, ion beams, and z pinches].”³⁰

In April 1996, Sandia received a favorable review from an external advisory board, the Welch Committee, of the contributions that the Pulsed Power Program was making to Stockpile Stewardship. In part, the committee found, “The science that is being done in the pulsed power programs at Sandia has reached world-class quality. This is the result of several years of deliberate attention to experimental and theoretical detail, including the development of high-quality diagnostics operating in a hostile environment. The quality of engineering in the program is superb.”³¹

The results on PBFA-Z were even better than anticipated. Between October and early November 1996, the Z accelerator increased its x-ray output from 1 to 1.8 megajoules. The increases came just as the United States signed the international Comprehensive Test Ban Treaty, officially committing the United States to continuing the ban on nuclear testing for the foreseeable future. In a news release from Sandia at the time, the powerful shots on PBFA-Z were billed as capable of providing data for computer simulations used to predict the physics within, and effects of, a nuclear blast. It said the PBFA-Z data could be substituted for some of the data from underground nuclear explosions, now a thing of the past.³²

As positive as the situation concerning z pinches sounds, in many ways it posed a dilemma for the managers in the Pulsed Power Program and for their Department of Energy sponsor.³³ On the one hand, years of effort and innovation had gone into the ion beam inertial confinement fusion work, and several of Sandia’s theorists and experimentalists felt they were capable of overcoming problems that they finally understood. To this point, the thrust of Sandia’s fusion program had been meeting goals set internally and by review committees specifically for ion beam technology. To consider changing course, dropping ion beams, and basing Sandia’s fusion work entirely on z pinches was not only a difficult decision, but a painful one because of how it would affect many who had been committed to the ion-beam program for years. The successes with PBFA-Z were finally so overwhelming that the program managers had to make the final decision to go with z pinches. (Please see following sidebar on Final Results of Sandia’s Ion-Beam Research.)

By early 1997, the Pulsed Power Program was shifting its strategy for proposing to build the more powerful X-1 facility from ions to z pinches. A second review by the Welch Committee in March 1997, specifically to assess the quality and relevance of z-pinch work to stockpile stewardship and populated by potential users of Z, endorsed Sandia’s decision to proceed with the z-pinch approach and saw it as a valuable addition to the weapons program. In June 1997, Quintenz called an all-hands meeting at which he announced that the ion-beam fusion experiments

Sculpture Honors Pulsed Power Researchers, Achievements

--*"Filling the Void"*

Sandia Lab News, March 4, 1994

Science and art have merged in the form of a new metal sculpture honoring the accomplishments of Sandia's pulsed power research community. Titled "Filling the Void," the sculpture was dedicated to Sandia's pulsed power researchers in a brief outdoor ceremony on the bright Monday morning of February 14 just north of the entrance to Building 960.

The idea for the sculpture goes back to 1992 and the day Pace VanDevender received the E.O. Lawrence Award. VanDevender recalled that at the time of the award, he "felt like an athlete who receives an honor in a team sport, because pulsed power is a team effort, and no one person is responsible for its accomplishments."

So VanDevender decided the award really belonged to everyone in pulsed power at Sandia. He put out bids to commission a sculpture with the award money to honor not just all the individuals involved but to recognize what he calls the "superb horizontal and vertical integration" of teams and capabilities at Sandia and elsewhere that helped bring the award to Sandia. Albuquerque artist Walter Hoel and VanDevender worked together to refine the concept for the sculpture, which is made

of 545 interlocking iron rings welded together to form an arch. The outreach of the arch represents searching for new discovery; the interlocking rings and the crucibles from which they rise represent Sandia and the organizations it works with synergistically. VanDevender welded all the metal parts together, and Karen Yank, another Albuquerque artist, applied the surface patina and anti-oxidant coating.

The plaque reads: "Filling the Void" by Walter Hoel and Karen Yank. Presented to the people of Sandia National Laboratories' Pulsed Power Community upon recognition of their work by the Department of Energy's 1991 Lawrence Award for Physics.

A short distance to the northwest, another pulsed power sculpture, "Starburst," made from the power flow section of the old Particle Beam Fusion Accelerator I, likewise glistened in the sunlight.

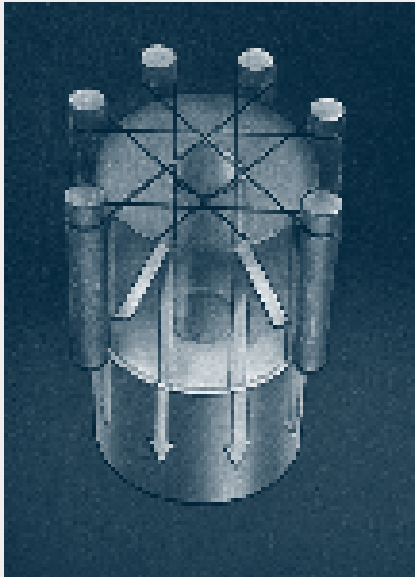


*Pace VanDevender
with sculpture in
Area IV*

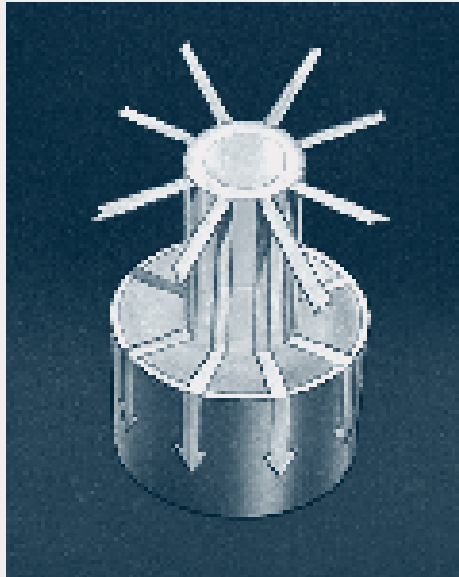
Z Pinch

Pulsed power accelerators take electrical energy from the wall plug and compress it densely in time and space. Like water turned on full at the faucet and tightly compressed at the nozzle of the hose, the power in such accelerators arrives at the center of the machine greatly increased from its origins. Here, at the heart of the accelerator, scientists and engineers devise methods to turn such power into radiation to suit their needs and requirements. Z pinch is one of them.

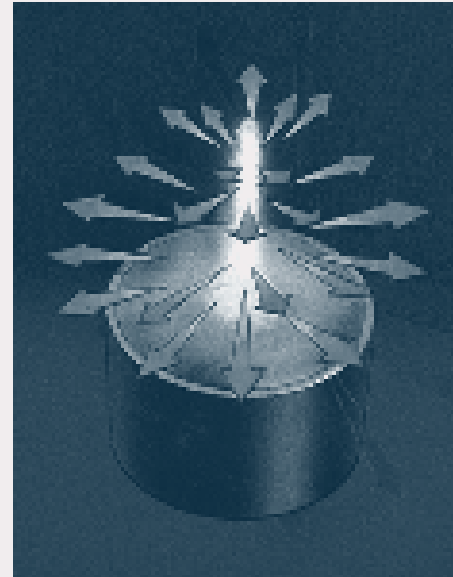
Initiation



Implosion



Stagnation



In a z pinch, enormous amounts of electrical current are converted into soft x rays such as those created by a nuclear weapon detonation. (Such radiation does not penetrate deeply, but is deposited very near the outer surface of materials.) Laboratory sources of these x rays are used in weapons effects and weapons physics studies and in the effort to achieve microfusion in the laboratory.

At Sandia, the z-pinch process is initiated by high currents from a pulsed power accelerator called Z. Released quickly from the accelerator, the currents, some 20 million amperes to date and expected to be 26 million amperes after the refurbishment of Z is completed, flow through a large number of wires (each about the size of a human hair). The combination of the vertically hanging wires forms a hollow cylindrical shape about the size of a spool of thread. Such currents are more than a thousand times larger than lightning bolts, and their force is a million times larger.

The currents in their wires produce intense magnetic fields that rapidly and tightly compress the hollow cylinder of wires to the point that it implodes upon itself toward its axis (called z in mathematics), vaporizing into a

plasma. This squeeze is the z pinch, so named because the enormous force of its compression goes along the z axis. The velocities involved are approximately 500,000 mph.

For decades, scientists and engineers explored various cylindrical assemblies to use with z pinches, such as wire arrays, gas puffs, or metal foils. One problem in the early days was that the power levels needed to create x rays for weapons and fusion work (and to drive z pinches) had not been attained by existing accelerators. Thus, the machines developed by the Department of Energy and Defense Department during the 1970s were in part used to answer this need.

In the world of weapons physics and weapons effects studies, z pinches are used to increase x-ray power output to approximate nuclear detonations. For inertial confinement fusion research, z pinches are used as sources of x rays to heat the hohlraum in which a fusion capsule is placed. The x rays in the hohlraum, as noted earlier, bathe the capsule inside the hohlraum, causing the fusion fuel to be uniformly compressed and heated to the point that it ignites.

Sandia's 1995 Breakthrough with Z Pinches

Sandia's success with z pinches came after years of experimentation and collaborations, including those with Russian scientists in 1992/93 on gas puff loads and hohlraums, and then in particular with Physics International and the Naval Research Laboratory on wire arrays.^a By 1989, Chris Deeney, then at Physics International, and Ken Whitney at the Naval Research Laboratory were working to improve wire arrays, using aluminum and nickel for the wires.

At Sandia, Dillon McDaniel, Keith Matzen, Rick Spielman, and others continued related work on Saturn. From 1991 to 1993, their experiments were indicating that the number of wires was a factor in determining powers and yields because of the fraction of the load mass that was optimally heated. At Physics International, Deeney showed in 1993 that by using mixed elements, yields were enhanced. Diagnostics confirmed that wire numbers above 12 (the number customary before that time) improved performance. In 1994, based on this work, Whitney suggested experimenting with 30 and then 42 aluminum wires with higher mass, larger diameter implosions. In March 1995, using Whitney's suggestion, Deeney, by then working at Sandia, and Spielman, the project lead for z-pinch work, obtained some increased yields and powers when the number of wires was increased from 24 to 40 wires.

Meanwhile, in January 1995, using a new type of camera at Sandia, Tom Sanford observed that with 24 aluminum wires in an array (then the standard), the wires imploded as separate wire array plasmas, not as a plasma shell as had been previously assumed. Sanford thought that if the number of wires were quite significantly increased, perhaps a more uniform plasma shell could be produced with subsequent increase in x-ray power at stagnation because of the more coherent implosion. Experiments to test his theory were delayed until June of that year. In June, Sanford began detailed experiments on Saturn with wire numbers that ranged from 10 to ~200.^b The outcome of the experiments was that Sanford and his team were able to explain and thus solve the plasma instability problems that had long plagued z pinches. George Allshouse and Barry Marder developed theoretical techniques

to understand the implosion of the individual wires and their merger into a plasma shell. It was a breakthrough in z-pinch technology. The *Sandia Lab News* summarized it in this way:

Tom set up a series of experiments, using different radii of wires with spacing adjusted to keep the total wire mass constant, to determine whether the wire size and spacing had any appreciable effect as his team painstakingly measured x-ray output produced by arrays ranging from a very small number to hundreds of wires. The results were clear. A larger number of thinner wires with minimum spacing between them sent the output of Saturn, and then Z, skyrocketing, and eventually caused a change in the world scientific view of the Z-pinch process.^c

Results of the breakthrough were first published in 1995 in the *Bulletin of the American Physical Society* (**40**: 1846) and later in 2006 in *Physical Review Letters* (**77**, 5063) with Sanford as first author.^d

Subsequently, the z-pinch team implemented tungsten arrays with high wire numbers, and by January 1996 Saturn had doubled its output to ~80 terawatts of power because of the additional radiation states available in tungsten. A Sandia news release from April 24, 1996, quotes director Don Cook as saying: "The breakthrough has altered the mindset we've been operating with about Saturn's capabilities. Controlling the symmetry of the implosion was the key." The significantly larger number of wires was the key to creating a plasma implosion with much better symmetry. The pulse was decreased in six months from 20 nanoseconds to about 4 nanoseconds. The results were announced at the BEAMS '96 meeting in Prague by Sanford and Spielman in separate papers.

Spielman, Deeney, Sanford, and John Porter were the main experimentalists who carried the z-pinch work forward into 1996, when experiments begun on Saturn continued on PBFA II, reconfigured into PBFA-Z. Theoretical work investigating the feasibility of z pinches to drive inertial confinement fusion targets was spearheaded by managers Jeff Quintenz, Keith Matzen, and Ray Leeper. Simultaneously, Melissa Douglas did Rayleigh-Taylor instability studies with the ALEGRA computer code. Barry Marder evaluated the dynamic effects of the wire array symmetry using another radiation hydrodynamics code, and

Allshouse designed fusion targets to use with the powerful new x-ray source. Experimental work investigating the feasibility of z pinches to drive inertial confinement fusion targets was spearheaded by Rick Olson, Tom Nash, Mark Derzon, and Ray Leeper. Sandia collaborated with Los Alamos and Livermore on theoretical studies connected with loads and implosions, and with the Naval Research

Laboratory on thorny theoretical analysis to understand and vary the x-ray energy yields from the imploding wire arrays. Sandia's successes begun in 1995/96 with z pinches continued on Z (as PBFA-Z was renamed) until 2006, when Z was shut down for an extensive refurbishment. Z-pinch experiments are slated to begin again in 2008 at x-ray power levels higher than before the refurbishment.

- a For a detailed history of z-pinch research, see M.A. Sweeney, "History of Z-Pinch Research in the U.S.," Dense Z-Pinches: 5th International Conference on Dense Z-Pinches, ed. J. Davis et al., American Institute of Physics, 2002: 9-14.
- b Sanford credits Wendland Beezhold, a manager in the Pulsed Power Program, with funding his experiments, which were outside the main z-pinch work.
- c Sandia Lab News, June 24, 2005, "Tom Sanford shares European physics prize for work on Z: Key observations led to huge increase in Z machine power output." The article explains the work in detail. The prize was the European Physical Society's Hannes Alfen Prize; Malcolm Haines of London's Imperial College and Valentin Smirnov of the Kurchatov Institute in Moscow shared the prize. See M.G. Haines, T.W.L. Sanford and V.P. Smirnov, "Wire Array z-pinch: a powerful x-ray source for ICF," Plasma Physics and Controlled Fusion 47 (2005), B1-B11. Smirnov and his staff had collaborated with Sandia's Dillon McDaniel and his team on z pinch back in 1992/93. Sanford was named a Fellow of the American Physical Society, Division of Plasma Physics, in 2000 for this work.
- d For a technical summary and history of the z-pinch breakthrough including detailed bibliography of relevant papers, see T.W.L. Sanford, "Wire number breakthrough for high-power annular z pinches and some characteristics at high wire number," Laser and Particle Beams (2001), 19: 541-556. Sandia authors include D.D. Bloomquist, D.L. Cook, M.E. Cuneo, C. Deeney, M.K. Matzen, T.A. Mehlhorn, J.L. Porter, J.P. Quintenz, J.J. Ramirez, R.B. Spielman, K.W. Struve, G. Yonas. For an early technical account of the success, see T.W.L. Sanford, G.O. Allshouse, B.M. Marder, T.J. Nash, R.C. Mock, R.B. Spielman, J.F. Seamen, J.S. McGurn, D. Jobe, T.L. Gilliland, M. Vargas, K.W. Struve, W.A. Stygar, M.R. Douglas, and M.K. Matzen (Sandia); J.H. Hammer, J.S. DeGroot, J.L. Eddleman (Lawrence Livermore); D.L. Peterson (Los Alamos); D. Mosher (Naval Research Lab); K.G. Whitney, J.W. Thornhill, P.E. Pulsifer, J.P. Apruzese (Naval Research Lab); Y. Maron, (Weismann Institute), "Improved Symmetry Greatly Increases X-Ray Power from Wire-Array Z-Pinches," Physical Review Letters 77, No. 25, December 16, 1996.



In 2005, Sandia's Tom Sanford (center) shared the European Physical Society's Hannes Alfvén Prize with Malcolm Haines (left), Imperial College, London, and Valentin Smirnov, Kurchatov Institute, Moscow. The award was for Sanford's observation, outlined in this sidebar, and for his follow-up z-pinch research with other Sandians. The prize went to all three scientists for "the remarkable achievements of the multi-filament Z-pinch development in recent years."

would continue only for another few months, then would cease, and that henceforth Sandia's inertial confinement fusion program would be committed to z-pinch technology.³⁴ In July PBFA II was renamed simply the Z machine, reflecting its preferred configuration. (Please see following sidebar on Highlights from Z.) A Sandia news release in August reported that Z was the most powerful generator of x rays in the world, having more than quintupled its output from 40 to 210 trillion watts and achieving a temperature of 1.5 million degrees (fusion was predicted to require 2 to 3 million degrees). The future course of Sandia's fusion work was from then on tied to the z pinch, which had begun years ago as classified imploding foil research.

Pulsed power at Sandia then began to evaluate the role Z would play in the Stockpile Stewardship and Management Program as a companion to its other radiation simulators, Saturn, Hermes III, and other smaller machines. In fusion research, the challenge was to get energy from Z's x rays to heat a hohlraum evenly, making the target within it implode. To do that required near-perfect symmetry when power arrived. The vision was that when Z was scaled up to the power levels on X-1 (a facility envisioned for a time as a successor to Z), a fusion reaction could indeed be ignited in the target. (By now, there was no more talk of the Laboratory Microfusion Facility. The National Ignition Facility finally supplanted those plans because of its cost, although the need for such a facility is still recognized. X-1 was the Laboratory Microfusion Facility in another guise.)

With respect to stockpile stewardship work, absent underground testing and needing capabilities to harden weapons, the nuclear weapons community was calling for increased x-ray capabilities. Viewed from a Department of Energy funding perspective, the situation was complex. High-yield fusion would provide the radiation needed by the weapons community in addition to its potential for energy. Before high-yield fusion, however, a demonstration that fusion could be ignited in the laboratory was needed. The National Ignition Facility was then (and remains) the centerpiece of the Department's inertial confinement fusion program (see sidebar on the National Ignition Facility earlier in this chapter) and its stated goal was demonstration of fusion ignition. However, the costs had steadily escalated beyond estimates and projections.³⁵ A few years earlier, construction had risen from \$842.5 million to \$1.046 billion and program costs were estimated at \$1.2 billion. Sandia's approach to fusion had shown merit and advances, and, with the z-pinch breakthrough, seemed even more viable. But despite years of predictions and expectations, high-gain fusion has remained years away.³⁶

In August 1998, an overview of Sandia's pulsed power work titled "Fusion and the Z-Pinch" appeared in the *Scientific American*, authored by Gerry Yonas, now a Sandia vice president. In it, he advocated building the X-1, saying, "Z may achieve fusion conditions; the National Ignition Facility should achieve ignition; and X-1, building on the lessons of the National Ignition Facility, should achieve high yield." The drawback was that X-1 was estimated to cost more than \$1 billion, clearly impossible in view of the rising costs at the National Ignition Facility.³⁷ (See following sidebar on Yonas 1998 Pulsed Power Award.)

Internal priorities at Sandia came into play at this point. The Labs had developed a proposal to build a Microsystems and Engineering Science Applications (MESA) facility, estimated to cost \$300 million. Of that, \$10 million was being requested for the immediate fiscal year so that the project could get under way and be completed by 2005. MESA figured into Sandia's historic role in the nuclear weapons complex of developing the electronic switches and other non-nuclear components of weapons. With the shift from developing and testing new weapons components and systems to assuring the reliability of an existing stockpile of aging weapons, Sandia intended to use MESA to develop and test microsystems that could be used not only in weapons refurbishment but with high-tech commercial applications as well. Knowing that two top-dollar proposals to the Department of Energy in the same fiscal year was not advisable and unlikely to succeed, Sandia opted to request funds for the MESA project and to postpone requesting funds for X-1. (A facility, ZX, intermediate in energy between Z and X-1, was also considered for a time.)³⁸

A refurbishment of the Z machine had been a fall-back possibility even as the X-1 proposal was being made, and Sandia began in 1999 a plan to modernize Z into a machine called Z-Mod. The primary mission outlined for the program at this point was to support the immediate needs of the Department of Energy's Stockpile Stewardship Program. And too, the international pulsed power community was extremely interested in Sandia's z-pinch technology and recognized the Labs as a leader in the field. France, Russia, and Japan began collaborations with Sandia to improve their own capabilities with z pinches for high-energy-density physics.

Still desirable for nuclear weapons simulations was the capability to emulate the entire spectrum of x rays from nuclear explosions to validate the physical models that formed the foundation of computer simulations. Because new components and microsystems were being developed for the stockpile, the need to test them in the laboratory was urgent. For this, Z and later Z-Mod could provide near-term weapons science and fusion experiments, recognizing that the National Ignition Facility was some years from realizing its goal of fusion. By this time, the Nova laser, a workhorse in weapons simulation work at Lawrence Livermore National Laboratory, had been closed because of the escalating costs of the National Ignition Facility.

Early in 1999, Paul Robinson became president of Sandia, and a major transition occurred in upper management slots. Pulsed Power Sciences returned to the research side of the house, its traditional home, and radiation sciences, including the pulsed power accelerators other than Z, remained in the Nuclear Weapons organization. Yonas became principal scientist and head of a new Advanced Concepts Group. Pace VanDevender assumed duties as Sandia's Chief Information Officer. Don Cook, who had overseen the successful transition to Z, agreed to leave pulsed power to head up the enormous MESA project where the new components for the stockpile would be developed. Jeff Quintenz became director of the program. His deputies, Keith Matzen and Dillon McDaniel, were pulsed power veterans, having contributed to imploding foil (z-pinch) work as it evolved through the years.

Final Results of Sandia's Ion-Beam Research

When the decision was made in 1997 to cease the ion-beam effort and channel Sandia's inertial confinement fusion funds and expertise into z-pinch research, a small core group of researchers was tasked with closing the effort out within a year.^a Reflecting nearly ten years later on what was accomplished, and acknowledging that it was wise to go with the obviously more successful z-pinch approach, Mike Cuneo and Tom Mehlhorn couldn't help wondering whether the tricky ion-beam technology could have finally been perfected.

The results were tempting enough in 1997/98 to make them hopeful. Although it is by now a moot point, the strategy for finishing a series of validating experiments remains in a notebook in Cuneo's office, and the tantalizing 'what ifs' connected to continued funding and more time are not completely forgotten. In the end, most of the people working in the ion-beam program transitioned over to some aspect of z-pinch research, bringing with them valuable experience and knowledge that pertained directly to it.

Closeout on SABRE

From 1979/80 until 1995, Sandia tried out several types of applied-B barrel-type ion diodes to form particle beams on a succession of water-line machines: Proto I, Proto II, PBFA I and PBFA II. In 1989, Juan Ramirez and his group built a 10-megavolt machine called SABRE (Sandia Accelerator and Beam Research Experiment) with \$2 million saved from building Hermes III as a test bed that could be fired many more times than PBFA II and at less cost. After SABRE was completed, new concepts for ion diodes that allowed the beam to be extracted and propagated were tried out while the main thrust of ion-beam research was being carried out using barrel diodes on PBFA II. (With the same technology as Hermes III, SABRE was a companion piece to the older HELIA, which had been the successful prototype for Hermes III, and a Ramirez design as well. HELIA was a high-energy linear induction accelerator also used to try out new diode concepts, notably for proton beams.)

David Hanson, Cuneo, and Peter Menge formed the core of a team that used SABRE beginning in 1992 to develop an extraction diode for possible use on the more powerful PBFA II. Such a diode would theoretically allow the beam to be propagated in a channel, a necessity for the standoff required in a fusion

energy plant. The extraction diode results looked good enough in 1995 that PBFA II was slated to operate in 1996 for six months as PBFA-X (for extraction) and for six months as PBFA-Z, driving z-pinchs for a needed weapons effect project.

As explained by Tom Mehlhorn, the technical situation was the following:

The PBFA II lithium beam intensity was limited by the 24-mrad ion beam divergence resulting from the passive LiF source divergence and the divergence generated by wave-particle interactions between instabilities in the diode electron sheath and the ion beam (electromagnetic divergence). Further, the ion power was limited to about 6 terawatts by a parasitic load. Experiments on PBFA II and the SABRE accelerators have identified the parasitic load as contaminant ions that are desorbed as neutrals in the anode and ionized during the machine pulse. In FY95 we reduced the parasitic load and increased the lithium current density by a factor of 3 to 4 on the SABRE extraction diode through anode cleaning. . . (PBFA-X) generated a record 4 terawatts of lithium power from an extraction ion diode using a laser-produced ion source. The lithium beam divergence was 38 ± 8 mrad in these initial experiments.^b

The discovery of the link between parasitic loads limiting the energy output and contamination on the electrode surfaces within the diode was important. The need for cleaning was one of the reasons for shifting to the extraction diode on PBFA II. The SABRE team was working toward an active (pre-formed) plasma source of lithium ions for the beam, and contaminants—ignored as factors in the past—were determined to be detrimental. For this reason, a pure lithium ion source was the goal. Also, a pre-formed, pure lithium source was crucial to being able to limit the divergence of the beam. (The effect of contaminants in pulsed power technologies generally was a factor that then became integrated into future work on Z.^c)

When PBFA II became Z in 1996 because of the unexpected outstanding results with z pinchs, the extraction diode ion-beam work went back to SABRE, where it continued until the end of 1998. Cuneo credits Jeff Quintenz, then the Inertial Confinement Fusion program manager, with giving the team an additional year to close out the work that had occupied

many Sandians and contractors for decades. One mitigating factor in the decision to go with Z was that the goal of the national inertial confinement program at this time was simply fusion ignition and the z-pinch approach seemed to be the faster way to reach that goal.

In the end, the high-brightness light-ion beams required for fusion energy were never achieved, but whether they could be is another matter. In a paper by Mike Cuneo and his collaborators summarizing the final effort to achieve such beams, the results are as follows:

Experimental and theoretical work over the last six years shows that high-brightness beams meeting the requirements for an inertial confinement fusion energy-injector could be possible, but require the simultaneous integration of at least four conditions: 1) rigorous vacuum cleaning techniques for control of undesired anode, cathode, and ion source plasma formation from electrode contaminants to control impurity ions and impedance collapse; 2) carefully tailored insulating magnetic field geometry for radially uniform beam generation; 3) high magnetic fields and other techniques to control the electron sheath and the onset of high divergence electromagnetic instability that couples strongly to the ion beam; and 4) a pre-formed ("active"), pure, uniform lithium plasma for improved uniformity and low source divergence which is compatible with the above electron-sheath control techniques. *These four conditions have never been simultaneously present in any intense non-protonic ion beam experiment, but we have demonstrated the effectiveness of each condition in experimental tests. A major advance in our understanding is that these conditions are synergistic and tightly linked. We have brought these four key technologies and the underlying physics understanding together on the SABRE accelerator (emphasis added).*^d

Ten years later, Cuneo mused, "Well, we almost brought them together." He likened the operation of an ion diode to that of a Swiss watch, saying: there are many separate parts, cogs, gears, hands, springs, that all have to be present simultaneously, and working exactly in precise relationship to each other to achieve the goal of keeping time. These four conditions necessary for ion diodes to generate high-quality ion beams can be thought of in the same way.

- a Primary SABRE extraction diode team members from 1992-1998 were M.E. Cuneo, D.L. Hanson, A.B. Filuk, R.A. Vesey, D.F. Wenger, W.E. Fowler, D.J. Johnson, R.G. Adams, J.E. Bailey, M.P. Desjarlais, S.A. Slutz, T.D. Pointon, T.A. Mehlhorn, P. R. Menge, C.L. Olson, R. Johnston, B. Clark, T.R. Lockner, R.S. Coates, C.L. Ruiz, W.A. Stygar, J.W. Poukey, J.R. Smith, J.E. Maenchen, R.W. Stinnett, D.R. Welch, D. Nielsen, J. Armijo, M.A. Bernard, G.R. Ziska, J.M. McKenney, and J.R. Chavez.
- b T.A. Mehlhorn, "Intense Ion Beams for Inertial Confinement Fusion," IEEE Transactions on Plasma Science, Vol. 25, No. 6, Dec. 1997: 1336-1356.
- c M.E. Cuneo, P.R. Menge, G.L. Hanson, W.E. Fowler, M.A. Bernard, G.R. Ziska, A.B. Filuk, T.D. Pointon, R.A. Vesey, D.R. Welch, J.E. Bailey, M.P. Desjarlais, T.R. Lockner, T.A. Mehlhorn, S.A. Slutz, and M.A. Stark, "Results of Vacuum Cleaning Techniques on the Performance of LiF Field-Threshold Ion Sources on Extraction Applied-B Ion Diodes at 1-10 TW," IEEE Transactions of Plasma Science, Vol. 25, No. 2, April 1997: 229-251. See also M.E. Cuneo, "The Effect of Electrode Contamination, Cleaning and Conditioning on High-Energy Pulsed-Power Devices," IEEE Transactions on Dielectric and Electrical Insulation, Vol. 6, No. 4, August 1999: 469-485.
- d M.E. Cuneo, R.G. Adams, J.E. Bailey, M.P. Desjarlais, A.B. Filuk, D.L. Hanson, D.J. Johnson, T.A. Mehlhorn, P.R. Menge, C.L. Olson, T.D. Pointon, S.A. Slutz, R.A. Vesey, D.F. Wenger, and D.R. Welch, "Generating High-Brightness Light Ion Beams for Inertial Fusion Energy," [paper IFP/14, Proceedings of the 17th IAEA Conference in Fusion Energy 1998 (2001 edition). Proceedings, C and S Papers series no. 8/C, 4269 pages, ISSN 1562-4153; see references in this paper to other important work in this area.

Highlights from Z

Pulsed Power Fusion Fire

Massive generators in the 33-m-diameter Z facility use a 20-million-ampere surge of electrical current with enough energy to light a hundred homes for a few minutes. The current is driven into a spool-sized array of hundreds of tungsten wires enclosed in a small metal container (a hohlraum) that serves as an oven to maintain uniform temperature. The goal is to create an environment of intense heat that will produce a thermonuclear reaction. For a brief instant, the hohlraum contains the seed of a miniature sun that, with more refinement and research, will ignite the long-sought fusion fire.

[Excerpted from *Pulsed Power Fusion Fire*, Sandia National Laboratories Fact Sheet, SAND98-2020.]

The Z Pinch on Z

A lightning bolt that singes the air and shatters a nearby tree is one of nature's most startling displays of power. Now imagine a bolt that carries 1,000 times more electricity and finishes 20,000 times more quickly.

That's the pulse that drives Sandia's Z accelerator—20 million amperes of current that last 100-billionth of a second. In that short time, the Z accelerator pulse causes a radiation implosion that produces even more impressive amounts of power—290 trillion watts (terawatts), or 80 times the capacity of all the electric plants in the world, for 4 billionths of a second.

In physics terms, Z produces outputs of 2 million joules of x-ray energy and working temperatures of 150 electron volts, or about 1.8 million degrees Celsius. It is the Earth's most powerful and efficient laboratory radiation source. And it is pointing the way for the design and validation of larger fusion facilities.

Sandia, Los Alamos, and Lawrence Livermore laboratories and defense agencies use Z to study the basic properties of matter at high temperature and density, the physics of inertial confinement fusion, and the survivability of hardware in the US nuclear stockpile.

[Excerpted from *The z pinch on Z: The world's most powerful radiation source*, Sandia National Laboratories Fact Sheet, SAND98-2020.]

Understanding the World's Most Powerful Events

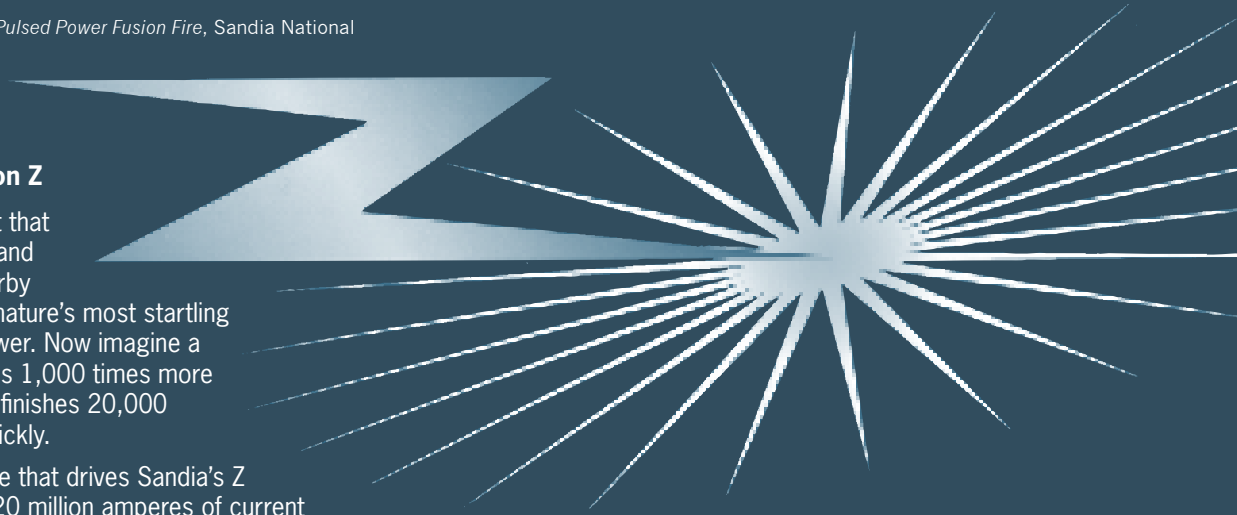
Measuring the implosion that creates millions of degrees of radiation in only billionths of a second in a thimble-sized hohlraum challenges the ingenuity of researchers and the limits of physical devices. As fast and powerful as the implosion is, the instruments that measure it must be an order of magnitude or so faster and able to record an enormous range of outputs.

These measurements are the most critical part of understanding not only Z results, but nuclear events in general. More than ten kinds of instruments measure and record images of the intensity, duration, and spectrum of the x rays emitted from the z-pinch plasma and the walls of the hohlraum heated by the pinch. They obtain information using different and independent techniques so that critical measurements can be compared for accuracy.

[Excerpted from *Instrumentation and Diagnostics: Understanding the world's most powerful events*, Sandia National Laboratories Fact Sheet, SAND98-2020.]

From ICE to Fire—the Future of Pulsed Power High Energy Density Physics

Over the past few years, the Z pulsed power generator has become a premiere facility for high energy density physics research by delivering 20-megamp load currents to create high magnetic fields and pressures. The magnetic pressure can implode a wire-array z pinch, generating x-ray energies approaching 2 megajoules at powers as high



as 200 terawatts for inertial confinement fusion, radiation hydrodynamics, inertial fusion energy, and astrophysics experiments.

Alternatively, the magnetic pressure can directly drive isentropic compression experiments (ICE) to 2.5 Mbar and accelerate flyer plates to more than 20 km/second for equation-of-state experiments. The Z Refurbishment Project will increase the shot capacity and precision, as well as provide a modest increase in the load current to 26 megamps. The increased current should enable more than 50% increases in the x-ray energy and power for inertial confinement fusion and radiation physics experiments, drive isentropic compression experiments in excess of 10 Mbar, and accelerate flyer plates to velocities approaching 40 km/second.

[Excerpted from M. Keith Matzen, *From ICE to Fire—the Future of Pulsed Power High Energy Density Physics*, SAND2002-1164A).

Caught in the grip of a crushing magnetic force: New technique tests, may create, materials

Z increases pressures from zero to a million atmospheres in a few billionths of a second in a new technique called isentropic compression experiments or ICE for short. It is far faster and less expensive than any way available to test materials over a wide range of stress. Project head Clint Hill said the technique would cut costs by an order of magnitude compared with others.

For isentropic compression experiments, scientists remove the cylindrical target array of fine wires in Z, and in their place, insert a target of four plates, each a bit bigger than a postage stamp, several millimeters thick and arranged at right angles to each other like a tiny fort. The massive incoming current creates a rapidly increasing magnetic compression through each plate that acts as a kind of ram against materials secured there. Hill said that the pressure wave Z generates travels through material at 4500 to 9000 m per second, five to 10 times faster than a bullet from a conventional firearm. Such pressure pulses would be important assets in shock physics.

[Excerpted from “Caught in the grip of a crushing magnetic force: New technique tests, may create, materials,” Sandia National Laboratories News Release, August 30, 2000.]

Magnetic field shocklessly shoots pellets 20 times faster than rifle bullet

The machine that generates a magnetic field to accelerate pellets faster than anything in the world except a nuclear explosion has been dubbed the fastest gun in the West, but lead Sandia scientist on the project, Marcus Knud-

son, calls it the fastest gun in the world. Z propels dime-sized pellets called flyer plates only a few hundred millimeters to gain information on the effect of high-velocity impacts. The plates are accelerated in the vacuum chamber at the core of Z. It is the fastest, most accurate, and cheapest method to determine how materials will react under high pressures and temperatures, characteristics that can then be expressed in formulas called equations of state. Such equations tell researchers how materials will react if basic conditions like pressure and temperature are changed by specific amounts.

[Excerpted from “Magnetic field shocklessly shoots pellets 20 times faster than rifle bullet,” Sandia National Laboratories News Release, February 21, 2001.]

Pace VanDevender Receives E.O. Lawrence Award

—One of the Department of Energy's top scientific awards

Sandia Lab News, May 15, 1992

Pace VanDevender, Director of Pulsed Power Sciences, has been selected to receive the Ernest Orlando Lawrence Memorial Award, which recognizes outstanding contributions in science and engineering fields related to atomic energy.

VanDevender is being recognized in the physics category for his "outstanding contributions to the generation of pulsed power." The Department of Energy announcement read, "He has demonstrated new concepts and designs for magnetically insulated transmission lines, dielectric and magnetic pulse forming switches, and magnetically inhibited flashover, and has played a central role in the design of new accelerators generating high-intensity, short pulsed beams."

"This was a total surprise," VanDevender said. "I was really humbled by the news because I respect the people who've been given the award in the past. I was also excited on behalf of Sandia because people don't win these kinds of awards in isolation. I'm fully aware that I'm one person in the midst of 'big science.' So I hope that every Sandian and every member of Pulsed Power Sciences can take pleasure in this award and see that it is a recognition of the quality of the science that is done at Sandia."

VanDevender considered the award particularly timely. "Since we are under the gun for a series of six milestones to be reviewed by the federal advisory committee on inertial fusion this fall, the award takes on a special meaning. I think the award is a statement of support from the Department of Energy that the quality of science we do at Sandia in the inertial fusion program is likely to make us successful, because I don't think they give this award with the expectation that the program will fail. And of course having the visibility of our program at this time is worth much more than the \$10,000 award."

Pace Vandevender; Starburst, May 15, 1992, Lab News. PBFA I/Saturn Pace VanDevender (1200) at Area 4's Starburst sculpture - actually the power flow section of Particle Beam Fusion Accelerator I, removed when the accelerator was converted into the Saturn X-ray simulator.

Gerold Yonas Receives Peter Haas Pulsed Power Award

In 1991, Gerold Yonas received the Peter Haas Pulsed Power Award through the IEEE Nuclear and Plasma Science Society. Begun in 1987, the award is given every other year to recognize individuals whose efforts over an extended period resulted in important pulsed power programs and the growth of important areas of activity including research, education, applications and information exchange. The award is presented at the IEEE International Pulsed Power Conference.

"Still-living Gerry Yonas accepts renamed pulsed power prize"

In June 1998, in Israel, Sandia VP Gerry Yonas had the opportunity not only to receive an award for decades of work in the field of pulsed power, but to have the new biannual prize itself named for him.

When Yonas turned down the honor because he "wasn't dead yet," the following question arose before the 18 learned members of the advisory committee of the International Conference on High-Power Particle Beams: Which was it Yonas had turned down—the award, or the naming of the prize after him?

As things worked out, the one Sandia member of the committee, Don Cook, said "We had a hard decision. We either could change Gerry's status to be no longer among the living, or rename the prize."

This conundrum was solved when the council decided to recognize Yonas as one of the living, rename the prize, and award it to him. The newly named 1998 Beams Prize Award was given to Yonas in recognition of his leadership in the area of pulsed power, high-power particle beams, and intense sources of radiation, and his nurturing and encouragement of the pulsed power community for more than 20 years.

Yonas initiated the conference in Albuquerque in 1975. It has since been held around the world.

[Condensed from the *Sandia Lab News* article of August 28, 1998.]

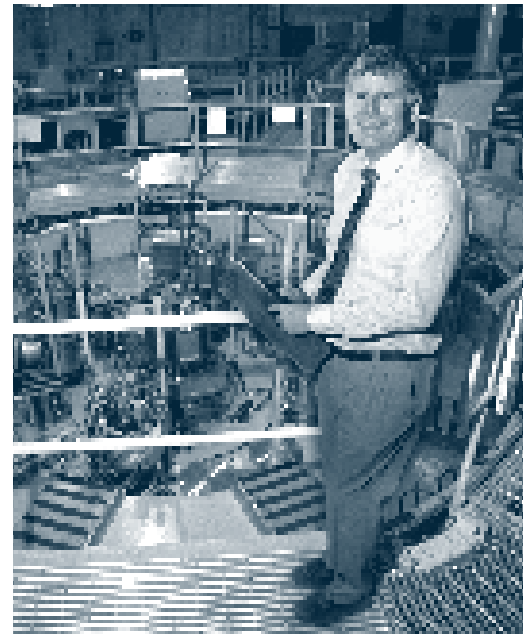


Quintenz found himself reporting to two men who were also new to their positions: Al Romig, Vice President for Research, the line organization for Pulsed Power Sciences, and Tom Hunter, who headed Nuclear Weapons Programs. At their suggestion, Quintenz and his management team drafted a plan for Pulsed Power Sciences that would guide it into the future and exercise the expertise in designing big pulsed power machines that had not been used since creating Hermes III years ago. Called “Pulsed Power Path Forward: A Strategy for Leadership,” the plan outlined the need for a modernization of Z that would double the radiation produced by the z pinch, increase the reliability and shot rate of Z, and reduce the cost of operations. To achieve these benefits would involve improvements in several areas of pulsed power technology in which Sandia traditionally excelled. The plan stressed how the modernization could significantly contribute to the needs of the Stockpile Stewardship Program and to international collaborations in pulsed power technology. In the end, for political reasons, the modernization or upgrade to Z was called the Z Refurbishment Project, and both Hunter and Romig endorsed it.³⁹

Little more than a year later, the Pulsed Power Sciences Center was reviewed by the Garwin Committee. Its findings, released in June 2000, gave the Labs’ Pulsed Power Program high marks on every count and strongly endorsed the upgrade of Z, calling pulsed power at Sandia an important national asset and encouraging collaboration with Russia, France, and other countries to leverage work being done abroad.⁴⁰ The committee backed Sandia’s continued long-range vision of fusion ignition, and beyond that to obtain more energy from the reaction than had gone into it—the long-standing Holy Grail in fusion physics. High-yield fusion in the laboratory would provide an enhanced capability in radiation effects, weapons science, and inertial fusion energy.⁴¹

But for the time being, the committee felt the Z refurbishment was a prudent step toward that vision, promising to shed important light on the feasibility of inertial confinement fusion in the lab, and at the same time serving as a more powerful contributor to the Stockpile Stewardship Program. Other aspects of the Pulsed Power Program receiving kudos and encouragement were for materials physics studies and radiography. At this time, the national fusion program recommended substituting the term ‘high-energy-density physics’ both for inertial confinement fusion and weapons science work. Such physics is characterized as studying extreme states of matter, such as plasmas, revealing “a universe of colossal agitation and tempestuous change.”⁴²

At the same time as these developments, using inertial confinement fusion for peaceful production of electricity had always been of interest to Sandia’s Pulsed Power Sciences. Sandia’s concept was to use repetitive pulsed power to drive a fusion reactor. As director, Don Cook supported light-ion-fusion power-plant studies and, following him, Jeff Quintenz supported similar studies using z-pinch drivers. Z-pinch inertial fusion energy complements and extends the *single-shot* z-pinch fusion program on Z to a *repetitive*, high-yield power plant scenario that can be



Jeff Quintenz

used for the production of electricity, and also, for example, transmutation of nuclear waste, hydrogen production, and desalination of water, with no production of CO_2 and no long-lived radioactive nuclear waste. Z-pinch then became the newest of the three major approaches to inertial fusion energy (the others are heavy ion and laser fusion).

Before 1998, no one believed there was a way to make a repetitive z-pinch machine for inertial fusion energy. But about 1998, several concepts for repetitive z pinches were beginning to be proposed and assessed. Sandia's Craig Olson gave the first talk on the final results of the light-ion fusion program and the start of the Z program approach to fusion energy at the first joint magnetic fusion energy/inertial fusion energy meeting in the fall of 1998. Subsequently, researchers from Sandia (including Steve Slutz, Mark Derzon, Gary Rochau, Greg Rochau, and Olson), Lawrence Livermore (Jim Hammer and Dmitri Ryutov), and the Naval Research Laboratory (Gerry Cooperstein and his team) contributed to several initial z-pinch power plant concepts.

The concept of a recyclable transmission line, as conceived and developed by the same Sandia team, quickly became the mainline concept. (Please see following sidebar on Z-Pinch Inertial Fusion Energy.) Under Olson's leadership, Z-pinch inertial fusion energy began to play a major role nationally.⁴³ Initial research from 1999-2003 was supported by special corporate research funding (Laboratory Directed Research and Development) up to \$300,000 annually. The Z-pinch Inertial Fusion Energy Program grew into a 19-member collaborative team supported by a Congressional Initiative for \$4 million in both fiscal years 2004 and 2005 and again by Sandia's corporate research funding (\$2.6 million) in fiscal year 2006. This research addressed critical issues and led to the concept for z-pinch inertial fusion energy being accepted by the broader fusion community.⁴⁴ However, the funding future for fiscal year 2007 and beyond for z-pinch inertial fusion energy, for heavy ion fusion, and laser fusion is uncertain. For the last decade, there has been no home for inertial fusion energy within the Department of Energy.

Sandia began the time-consuming process of developing a plan to upgrade the Z Machine for the Department of Energy/National Nuclear Security Administration. The project was soon officially named ZR, for refurbishment of Z; Z remained the name of the accelerator. In June of the following year, 2001, a review that Sandia had requested supported the ZR project and recommended that funding be included in the High Energy Density Program budget because of its importance to Stockpile Stewardship. The estimate to refurbish Z was approximately \$60 million in 2001. (Please see following sidebar on Refurbishment of Z: ZR.)

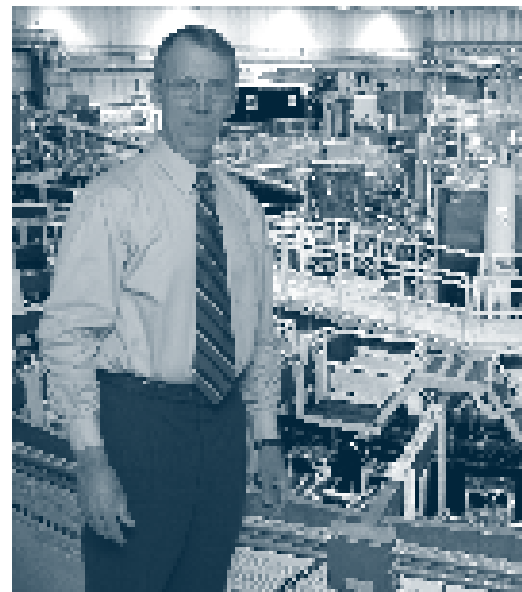
Experiments continued on Z, and in mid-2001, in its first use as a diagnostic tool for the accelerator, the giant Z-Beamlet laser documented what was happening inside the hohlraum, the outer part of the target that generates the x rays, which surround and heat the fusion capsule. (In August 1998, the Beamlet laser had

been transferred to Sandia from Lawrence Livermore National Laboratory to use as an x-ray backlighter for hydrodynamic experiments. It was reassembled at Sandia and modernized in a \$13 million project.) (Please see following sidebar on Z-Beamlet.) An x-ray radiograph produced by Z-Beamlet showed that Z spherically compressed a simulated fusion pellet during a shot with the newly developed double-z pinch or double-ended hohlraum.⁴⁵ Fusion was thought to require a factor of 30 compression, beyond the utmost capability of Z; however, the diagnostic photo revealed that the technology was definitely on the right track. A number of papers were published, many in *Physical Review Letters*, describing Z-beamlet work in detail, initiated by John Porter and his department.⁴⁶

Sandia announced a significant step toward the compression needed for fusion in the spring of 2003 at a meeting of the American Physical Society. In March, Z had created a hot, dense plasma that produced thermonuclear neutrons. Theoretical predictions agreed with experimental results: a yield of 10 billion neutrons. Neutron pulses had been observed late the previous summer, and the March experiments demonstrated that neutron production had been in the capsule (hohlraum).⁴⁷ Compressing plasmas, an action that produces neutrons, is a crucial part of realizing fusion ignition. Again, a stream of papers described the results.⁴⁸

The following year, the National Nuclear Security Administration authorized \$61.7 million to refurbish Z. Of overriding immediate importance was Z's ability to provide data for supercomputer simulations of nuclear weapons explosions and tests of materials under extreme conditions. Ultimately, the refurbishment of Z should enable more insight into z pinches and the possibility for high-yield fusion. Scheduled to last two years, the overhaul involves installing 36 new and more powerful Marx generators of exactly the same size as the 21-year-old originals in PBFA II. From the outset, the refurbished Z has been designed for the high currents suited to z pinches, not for the high voltages that lithium-ion beams needed and for which PBFA II had originally been designed. The trigger switches, too, have been designed to be upgraded and converted to a system in which each switch could be individually controlled, improving the ability of researchers to shape the pulse of electrical current in each of the 36 transmission lines emanating from the Marxes.

The refurbished facility offers improvements on every front. The high currents used to vaporize tiny tungsten wires are to be increased from 18 million to 26 million amps. The peak emissions of x rays should rise from 230 to 350 terawatts, and the x-ray energy output from 1.6 to 2.7 megajoules. The number of possible shots per year could be expected to double, from 200 to approximately 400. The refurbished machine is expected to support the weapons program and materials work at Sandia, Los Alamos, and Livermore. Furthermore, it is expected to contribute to the national inertial confinement fusion program, complementing the National Ignition Facility. ♦



Keith Matzen became director in 2005.

Z-Pinch Inertial Fusion Energy

The day after Sandia announced its observation of fusion neutrons during an experiment on Z, the *New York Times* linked the success to the possibility of at last being able to harness fusion for energy, one goal of the US fusion program since its earliest days. Titled “New Fusion Method Offers Hope of

New Energy Source” and featuring a color photo of Z in action, the April 8, 2003, article contrasted the inertial confinement and magnetic confinement conceptual techniques for producing commercial power:

The Sandia experiments, by comparison [with magnetic confinement] could lead to something more like an internal combustion engine, in which power is generated through a series of explosions. “Squirt in a little bit of fuel, explode it,”

Dr. Jeff Quintenz said. “Squirt in a little bit of fuel, explode it.” . . . But designing a machine that could detonate controlled thermonuclear explosions in quick succession—and survive them—is an engineering challenge that scientists have only begun to think about.

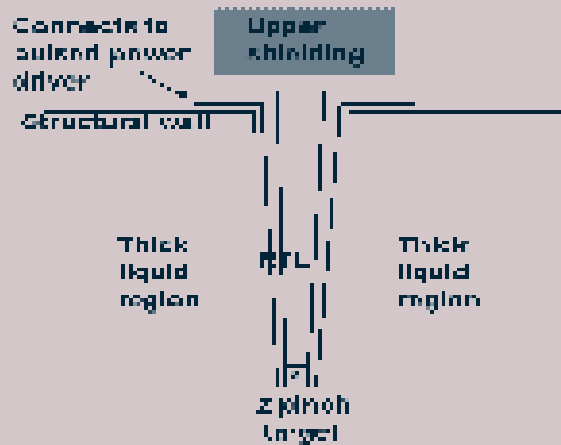
In actuality, by 2003 Sandia had been working on the challenges related to inertial fusion energy for some time, and continues to do so. One important area is developing the capacity to fire a high-current pulsed power machine repetitively to allow for repetitive explosion. The norm for such machines has always been one shot a day. Another area is the target; at that time, as now, they are precisely designed and experimental. Once an optimum target has been developed, then the challenge will be to pulse the machine several times a minute, like a gas-fired engine, with each pulse creating a fusion event within the target. The target chamber will have to be designed to capture the energy from the shots and transmit it to a power-producing system. The trick is to be able to quickly replace the targets and to devise a suitable standoff scheme that will allow repetitive operation.

The recyclable transmission line is central to a standoff scheme that emerged in 1998/99, and quickly became the mainline concept for z-pinch inertial fusion energy. The concept is to make the final transmission line out of a solid coolant material (e.g., Flibe—a binary

salt) or a material that is easily separable from the coolant (e.g., carbon steel). As shown in the figure below, the recyclable transmission line would enter the fusion power-plant chamber through a single hole at the top of the chamber (~1 m radius), and extend into the chamber a distance of two or more meters. The line would bend at the top of the chamber, and upper shielding would be placed above it. In operation, the recyclable transmission line/

target assembly would be inserted, the shot fired, portions of the line would be vaporized and finally be mixed with the coolant to be recycled. The upper remnant of the line would be removed, and the cycle would be repeated. The present strategy for z-pinch inertial fusion energy is to use high-yield targets (~3 gigajoules per shot) and low repetition rate per chamber. Initial experiments at the 10-megamp level on Saturn led by Steve Slutz were successfully used to study the electrical current initiation in the recyclable transmission line, the line’s low-mass limit, and the line’s electrical conductivity.

The concept for z-pinch inertial fusion energy requires a repetitive pulsed power driver. The idea for a linear transformer driver, as developed under the leadership of Michael Mazarakis, emerged as the mainline choice for z-pinch inertial fusion energy in 2002. This technology is different from the Marx generator/water line technology used on Z/ZR, because in it, Marx generators and pulse-forming lines are eliminated altogether. This concept calls for a series of compact, low-inductance capacitors to be charged directly in parallel, in



The Recyclable Transmission Line concept for Z-Pinch Inertial Fusion Energy

a cylindrical formation, at a moderate voltage (~100 kilovolts). A series of switches next to the capacitors, and in the same cylindrical formation, switches the charged capacitors directly to apply voltage to a single, inductively isolated gap. By proper selection of compact, low-inductance capacitors, pulse lengths on the order of 100 nanoseconds can be achieved directly—and this is the typical pulse length desired to drive a z-pinch fusion target. To reach higher voltages, a series of modules is stacked into an inductive voltage-adder configuration. In addition, linear transformer drivers are well-suited for repetitive operation. The concept was pioneered at the High Current Electronics Institute (HCEI) in Tomsk, Russia, and a single 0.5-megamp linear transformer driver cavity has operated repetitively at Sandia with 10.25 seconds between shots. This is the rate needed for a z-pinch inertial fusion energy power plant. (Five 1.0-megamp cavities have been operated in a voltage-adder configuration at Tomsk.)

The proposed technology for z-pinch inertial fusion energy uses a thick liquid wall chamber. The coolant (typically Flibe) is used to absorb the neutron energy, breed tritium, and shield the structural wall from neutrons. Initial work at Sandia on this area was by Mark Derzon, Greg Rochau, and Gary Rochau. Further neutronics studies (from the University of Wisconsin and Lawrence Livermore National Laboratory) indicate that wall lifetimes of about 40 years are now possible. Thick liquid walls essentially eliminate the ‘first wall problem’ (common to all magnetic fusion schemes and to dry-wall inertial fusion energy schemes). Such walls lead to a faster development path for fusion energy, since no new neutron test facilities are required. Extensive work on z-pinch inertial fusion power plants continued at Sandia during FY 2004-FY 2006. Moreover, recyclable transmission lines, linear transformer drivers, and thick liquid walls are also applicable to a single-shot inertial confinement fusion high-yield fusion facility,

A September 13, 1999, news release from Sandia about the first Snowmass Fusion Summer Study said that scientists at the conference “placed z pinches on the list for recommended scientific exploration as an energy source.” This was a real breakthrough

for Z, whose primary mission had always been regarded as weapons work.

Since 1999, the pieces of the puzzle needed to use z pinch for inertial fusion energy have been coming together at Sandia, and enabled the 2003 *New York Times* hopeful predictions. Work on recyclable transmission lines, repetitive rate operation, and target and chamber designs has moved to the point that Olson can be cautiously optimistic. Though admitting it has been an uphill battle to get z-pinch technology accepted in the fusion arena, Olson said z-pinch inertial fusion energy at Sandia was funded for \$4 million in FY 2004 by Congressional initiative. In addition, in its review of the national Inertial Fusion Energy Program in the spring of 2004, the Fusion Energy Science Advisory Committee formally recognized the synergy between weapons-related inertial confinement fusion research and energy applications, particularly where basic physics issues span both areas. The report concludes: “In sum, the Inertial Fusion Energy Panel is of the unanimous opinion that the inertial fusion energy program is technically excellent and that it contributes in ways that are noteworthy to the ongoing missions of the Department of Energy.”

Sandia's Z-Pinch Inertial Fusion Energy team encompasses staff in the research (1000) and energy (6000) areas of the Laboratory, and involves researchers at Lawrence Livermore National Laboratory; Los Alamos National Laboratory; Naval Research Laboratory; Argonne National Laboratory; University of California, Berkeley; University of Wisconsin; University of California, Los Angeles; University of California, Davis; Georgia Tech; University of Alabama; Texas A&M; Hobart and William Smith College; General Atomics; Voss Scientific; SAIC; the Institute of High Current Electronics-Tomsk, Russia; and the Kurchatov Institute, Moscow, Russia.

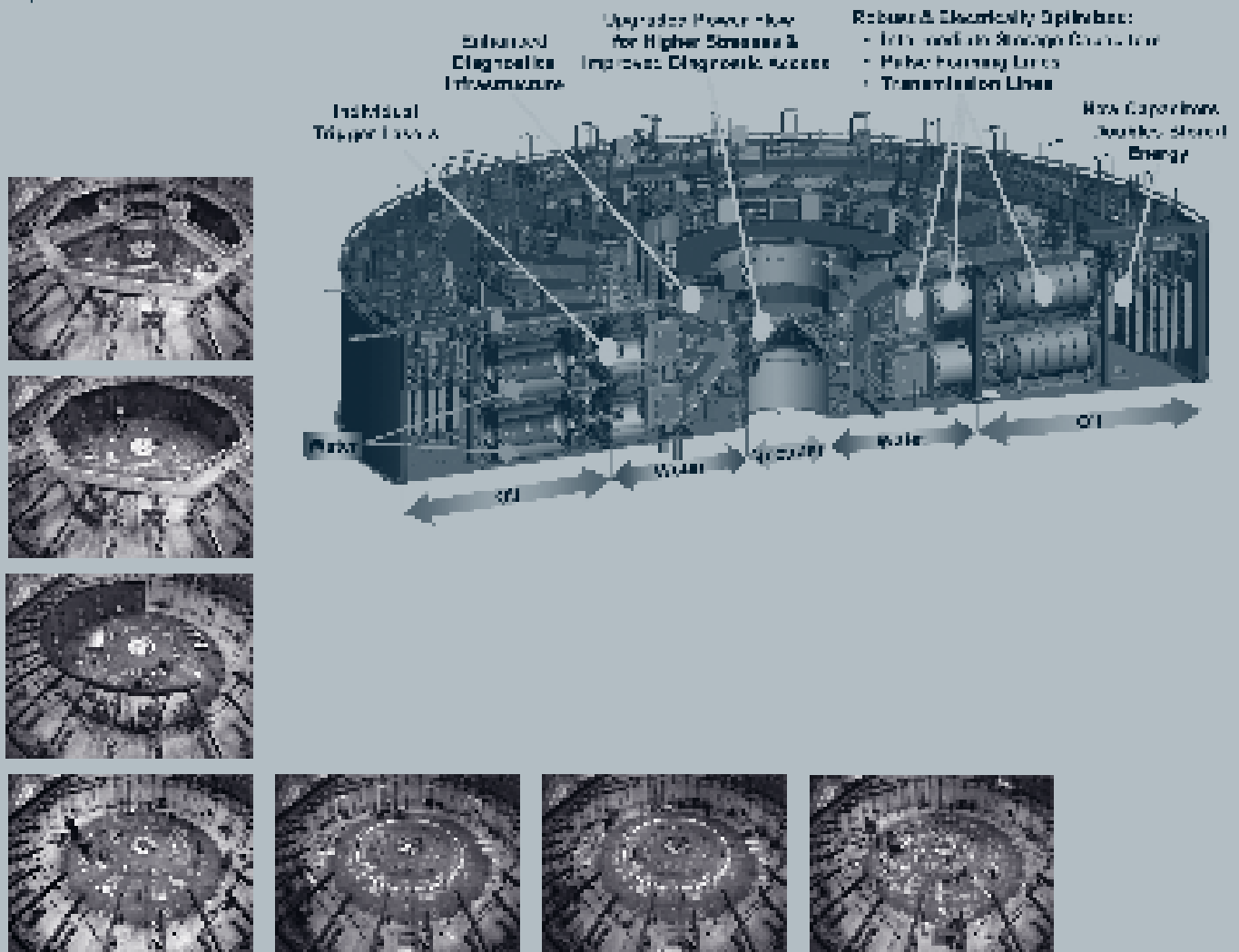
[Sources: Interview with Craig Olson, May 2004 and January 2007; Craig Olson, “Inertial Fusion Energy,” presentation to the Advanced Concepts Group at Sandia, May 7, 2004; “A Review of the Inertial Fusion Energy Program,” final report to the Fusion Energy Science Advisory Committee, March 29, 2004; Robert Conn, “Reflections on Fusion's History and Implications for Fusion's Future,” paper based on invited talk at the Snowmass meeting, July 11-23, 1999 (copies in the Van Arsdall collection, Sandia archives.)]

Refurbishment of Z: ZR

Several important reasons factored into the need to refurbish Z. By 1999, only three years after PBFA II was permanently converted into Z, increased demand for Z shots had exceeded the capacity of the machine by a factor of 2. More users were asking for shots and they needed Z to be a stable, precision platform for a large number and variety of reliable, reproducible experiments. Most of the hardware in Z dated to 1985 when PBFA II was originally constructed as a high-voltage machine to drive ion beams rather than z pinches, which require high current rather than high voltage. Moreover, Z was not designed to handle daily operation at greater than 18 megamperes. Z had been heavily relied upon since 1997 as a workhorse for weapons physics and weapons effects programs, for basic research, and for research into critical material properties and equations of state.

Congress appropriated \$10 million in October 2002 to begin the refurbishment of Z, known as the ZR Project. With concurrence of the National Nuclear Security Administration, Sandia's Nuclear Weapons Program allocated an additional \$50 million to ZR in 2003-2007 for engineering and hardware procurement within the Readiness in Technical Base and Facilities program. Sandia's Pulsed Power Technologies and Inertial Confinement Fusion program budgets applied about \$30 million in other project costs to the ZR Project for component and subsystem development and for hardware installation.

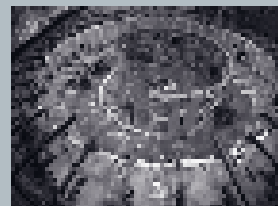
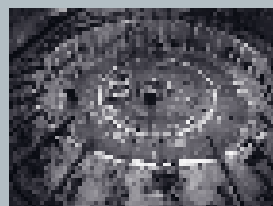
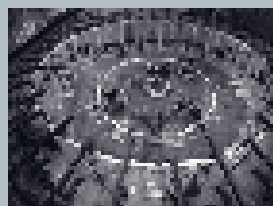
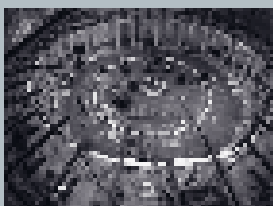
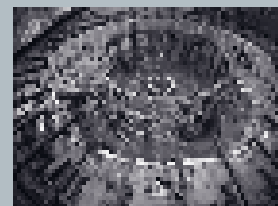
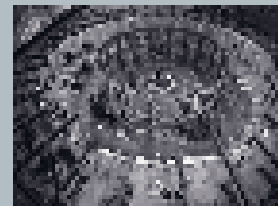
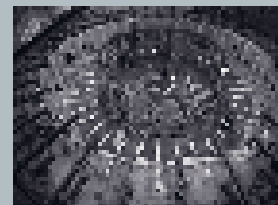
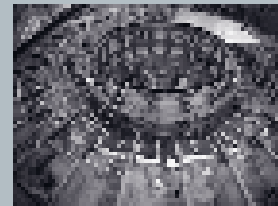
ZR Architecture



The redesign and upgrade of the major sections of the 22-year-old Z will enable significant improvements in its reliability, overall robustness and maintenance, potentially allowing 25 to 40% more shots using approximately the same number of personnel. The redesigned pulsed power drive system improves the efficiency of energy transfer and the additional energy storage capacity enables higher delivered load current. By incorporating individual control of key timing components, a range of pulse widths and shapes can be provided that were not possible on Z. Improved precision of the delivered pulse will be particularly useful to scientists working to validate the nuclear stockpile. Modern capacitor technology will allow the refurbished Z to double the amount of energy stored in the same volume, providing 40% increase in current.

The overall goal of the project is to achieve—routinely and often—more current to the load with high precision and flexibility. The project goals are to

1. Enable the facility and diagnostics infrastructure to support a higher number of experiments per year.
2. Provide enhanced precision, improved timing jitter, and advanced pulse shaping capability needed for full parameter space assessment for materials of interest to the Stockpile Stewardship Program.
3. Provide a useful increase in current; i.e., 26 megamps into a standard z-pinch load (compared to 18 megamps on Z).



Z-Beamlet

Uniform compression of a fusion capsule is an essential step in creating controlled nuclear fusion. Using Sandia's Z accelerator, the x rays from a z pinch compress the capsule, and the Z-Beamlet images the compression so it can be studied and modeled. Z-Beamlet is a \$30 million laser that was originally at Lawrence Livermore National Laboratory. Built in 1994,

Z-Beamlet creates a bright x-ray source behind the fusion capsule when Z is fired; the x rays penetrate the capsule and make direct images of objects inside it. Such a diagnostic tool is called an x ray backlighter.

In a burst of energy only a fraction of a billionth of a second long, Z Beamlet takes an x-ray snapshot of the

it was used as a prototype for the National Ignition Facility. Measuring 30 m long, it is one of largest pulsed lasers in the world.

In the fall of 1998, Livermore's Beamlet was disassembled and shipped to Sandia to be reassembled and configured specifically to take x-ray pictures of plasmas created by Z. In the transition, it was renamed Z-Beamlet.

BB-sized fusion capsule inside the central chamber of the firing Z machine.

In a special x-ray camera, developed at Sandia specifically for the Z experiments, curved crystals are used to focus the Z-Beamlet x-rays into a detailed image of the fusion experiment. This new camera system produces significantly more detailed images than the original 'point projection' camera that merely records an x-ray shadow of the target.

Z-Beamlet is housed inside a former warehouse adjacent to the Z facility. This warehouse was converted into a state-of-the-art clean room required by a laser before Beamlet arrived from California. Its beam travels 68.5 m from the warehouse and turns downward 90 degrees into Z, where it is focused to a small spot about the diameter of a human hair. Because the laser pulse delivers all its energy in about 1 nanosecond, it is extremely powerful.

It then strikes a metal plate and the plate releases x rays. The entire laser system is run and monitored by an elaborate computer control system, an enhancement incorporated into Z-Beamlet when it came to Sandia.

The entire project to reassemble the recycled Livermore laser cost \$12.875 million, took three years to complete, and required the talent and dedication of scores of individuals from Lawrence Livermore and Sandia. Sandia's John Porter was the project director.

In the summer of 2001, Z-Beamlet was first used to image the compression of a fusion capsule inside the Z accelerator and confirmed that Z spherically compressed it. The addition of the Z-Beamlet laser to the Z complex represented a revolutionary combination of technologies: the efficiency of Z and the precision of Z-Beamlet.

The next step for Z-Beamlet is to modify the laser to increase its peak power a thousand-fold from terawatts to petawatts. To increase the power of the laser pulse without damaging laser components, a short pulse is stretched out in time before passing through the laser and amplified to high energy. Then, before it strikes the pellet, it is compressed back into an extremely short, high-power pulse. This process, called Chirped Pulse Amplification, required extensive modification of Z-Beamlet and a means of compressing the final pulse,

which advanced the state of the art in the design of such compressors. One crucial component of a petawatt laser is a laser source that is capable of producing the very short pulses required at the beginning of the system.

Z-Beamlet has developed such a short pulse system over several years and has operated the laser at the one-tenth petawatt level, using a small scale compressor, while performing experiments to develop in imaging techniques

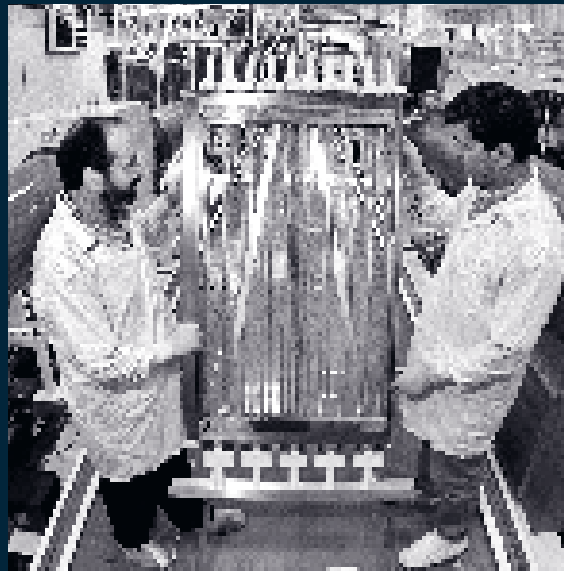
necessary to allow the short pulse petawatt laser to be used on Z experiments. Petawatt development is timed to take advantage of the pause in routine operation while Z is being upgraded. During the pause, the necessary final large-scale modifications will be made to boost the short pulse from the tenth petawatt level to the full petawatt capability and add the full-scale compressor necessary for higher power operation.

With the petawatt capability, Z-Beamlet

experiments will be conducted in the following areas:

Radiography. When a petawatt laser is a reality, it should provide x rays up to the megavolt range (instead of the <10 kilovolt range currently available). More penetrating x rays will permit images to be made of denser materials undergoing much more fleeting transformations. These images could contribute valuable knowledge to the study of weapons effects and fusion processes. Protons generated from the petawatt laser-driven backlighting of targets could be used to create a new kind of image of materials, structures, and events.

Fast Ignitor Fusion Research. Although lasers can be used to compress a target, at Sandia this function is performed by the Z accelerator. However, the perfectly uniform compression of the target that is required in fusion experiments is difficult to attain. Instead, a short, well-timed pulse from Z-Beamlet would act as a spark plug to initiate a fusion burn in a less



than perfectly compressed target, reducing the required uniformity to achievable levels. This approach to fusion experiments may ultimately make it possible to produce more energy from experiments than is put into them, yielding valuable insights into fusion processes. However, its success depends on having a petawatt laser.

Pure Physics. The extremely high power levels to which target materials could be exposed may produce reactions that are unexpected and generate responses that are of great inter-

est to scientists. Although the exact nature of the discoveries that might be produced is impossible to predict, the transmutation of materials and the production of exotic atomic particles might be studied.

[Sources include Sandia National Laboratories press releases and *Sandia Lab News* stories about Z-Beamlet (for example, articles of August 24, 2001, January 11, 2002, March 22, 2002; the Z-Beamlet website (<http://www.z-beamlet.sandia.gov/>); the 2005 technical paper by M. Keith Matzen et al. on "Pulsed-power-driven high energy density physics and inertial confinement fusion research" fully referenced in the sidebar on Fusion Concepts in this chapter; and input from I.C. Smith, P.K. Rambo, B.W. Atherton, and M.A. Sweeney of Sandia in 2007.]



endnotes

- 1 US Department of Energy/Office of Security, *Restricted Data Declassification Decisions 1946 to the Present*, Section IX on Inertial Confinement Fusion; Official Use Only, RDD-8. In 1990, the hohlraum (indirect drive) approach and much capsule data were declassified except for certain areas, and in 1993, many calculations were declassified, again, with certain exceptions. See the World Energy Council report, "Prospects on the Use of Inertial Nuclear Fusion," by G. Velarde, J.M. Martinez-Val, and S. Eliezer, *Proceedings of the World Energy Congress*, Houston, 1998, outlining the history of US classification of inertial confinement fusion from a European perspective. In fact, a major textbook on inertial confinement fusion was written in 1989/90 and the indirect drive approach was entirely omitted because of US scientists' constraints. Newer sources cover the topic completely: see J.D. Lindl, *Inertial Confinement Fusion: The Quest for Ignition and Energy Gain Using Indirect Drive*, Springer-Verlag, 1998, and S. Atzeni and J. Meyer-Ter-Vehn, *The Physics of Inertial Fusion*, Clarendon-Press, Oxford, 2004.
- 2 In 2006, Sluyter recalled that his support of the collaboration was motivated by his desire to get Sandia's Pulsed Power Program out of the rut it was in at the time and get some fresh ideas from the outside.
- 3 VanDevender review of October 2, 2006, draft of this history and in an earlier interview with VanArsdall.

- 4 *Sandia Lab News*, March 23, 1990. The article refers to the review as being “last December” but it was in November 1989, as a number of presentations to the committee prove; copies are in Pulsed Power Center Archives, PP6, and in Box 1/Van Arsdall. See also the Committee for a Review of the Department of Energy’s Inertial Confinement Fusion Program, “Review of the Department of Energy’s Inertial Confinement Fusion Program; Interim Report,” National Academy of Sciences, January 1990; in the Pulsed Power Center Archives at Sandia National Laboratories archives, Box 1/Van Arsdall.
- 5 “Watkins mandated sweeping reforms to remedy years of inattention [in the areas of environment, safety and health], forming an Office of Environmental Management and boosting the budget until the Department of Energy had the largest environmental restoration and waste management program in the world.” Leland Johnson, *Sandia National Laboratories: A History of Exceptional Service in the National Interest*, SAND97-1029, p. 309.
- 6 *Sandia Lab News*, March 23, 1990, “Don’t Just Fix the Symptoms: Tiger Team Training at PBFA II Gives Lessons for All Sandia.” The article summarizes all the findings and concerns. The Don Cook collection in the Sandia archives has a number of documents and memos related to this incident; Box 2, Tiger Team.
- 7 Also in March 1990, the US General Accounting Office issued a Briefing Report to the Chairman, Committee on Armed Services, House of Representatives, on “Nuclear Science: Performance of Participants in Department of Energy’s Inertial Confinement Fusion Program.” It was complementary to the National Academy of Sciences review and did not differ from the findings the National Academy of Sciences would make some months later. The issue of decreasing support for continued funding of KMS Fusion, Inc., a private firm that had been part of the inertial confinement fusion effort for more than ten years, is dealt with in this report.
- 8 *Albuquerque Tribune*, September 20, 1990.
- 9 *Sandia Lab News*, October 18, 1991. “Pea-Size Targets Imploded by Ion Beam: PBFA II Experiments Erase Doubts about Obtaining Data.”
- 10 *Sandia Lab News*, September 18, 1992. “Deeply Impressed by Labs’ Work: Bush Announces Weapon Nonproliferation Initiative at Sandia,” and “Weapon Part Sculpted into Plowshare: President Views Labs Technology, Receives Symbolic Gift.” The gift was a “Swords to Plowshares” sculpture that artist Doug Weigel made out of material from a dismantled B61 nuclear weapon.
- 11 The United States instigated a unilateral moratorium on nuclear testing beginning in October 1992 under President Bush. The moratorium continued under President Clinton until 1996, when the United States signed the United Nations-sponsored Comprehensive Test Ban Treaty (CTBT). It is still in effect, with the United States as a signatory; however, the Senate did not ratify the CTBT when it came up in 1999. See the related *Sandia Lab News* article of May 15, 1992, “Watkins Testifies Against Nuclear Testing Moratorium Bill: Tests Maintain Stockpile Safety, Security.”
- 12 For some time after approval of the National Ignition Facility, Sandia continued to plan to scale up its pulsed power technology for the Laboratory Microfusion Facility, a national goal that faded away. An intermediate facility, Jupiter, was also proposed.
- 13 See Leland Johnson, *Sandia National Laboratories*, note 5, pp. 352-357; *Sandia Lab News*, December 16, 1994, “ ‘Science-based stewardship’ new long-term mission of the three nuclear labs, Domenici tells Sandians.”

- 14 Cook Collection at Sandia, Box 1, folder labeled National Ignition Facility.
- 15 Olson also worked with the Heavy Ion Fusion program at Lawrence Berkeley and Lawrence Livermore on final beam transport for heavy ion beams beginning when the heavy ion fusion program began in 1976.
- 16 This research was performed at Sandia and with Paul Ottinger et al. of Naval Research Laboratory, Dale Welch et al. of Mission Research Corporation, and Simon Yu et al. of Lawrence Berkeley National Laboratory. For the light-ion Laboratory Microfusion Facility, and for a light-ion power plant study named LIBRA (developed over several years at the University of Wisconsin), Olson developed an achromatic two-lens system. Extensive work was also done on channel transport and self-pinched transport. Because an "extracted" ion beam never became available for transport studies at Sandia, experiments were performed with the GAMBLE II ion beam at Naval Research Laboratory, where a collaborative self-pinched transport experiment was successfully performed near the end of the light-ion fusion program. Results from all of these studies are included in several large proceedings: (1) *Workshop on Transport for a Common Ion Driver at Sandia*, C. Olson, E. Lee, and B. Langdon, September 20-21, 1994 (SAND95-0116, UC-712); (2) *Ion Beam Uniformity, Standoff Meeting Series at Sandia*, four meetings March/April 1995; (3) Tri-Lab Meeting at Livermore sponsored by Lawrence Livermore, Sandia, and Lawrence Berkeley national laboratories, November 16-17, 1995 (UCRL-MI-123016); (4) Tri-Lab Ion ICF Meeting at Sandia National Laboratories sponsored by Sandia, Lawrence Berkeley, and Lawrence Livermore national laboratories December 17-18, 1996 (SAND98-0845); (5) *Workshop on Pinch Phenomena in Final Transport of Heavy Ion Beams*, Danville, CA, February 13-15, 2001 (HIFAR-513, LBNL-47686).
- 17 See VanDevender/Powell memo, January 18, 1993, in Cook Collection, Box 2, Folder on Jupiter. The memo says that Jupiter is a high priority for Sandia in preparation for an era with reduced reliance on underground testing, but indicates the proposed project has not yet been approved. It indicates that the Department of Energy and the Department of Defense/Defense Nuclear Agency might partner to fund it as well as be potential customers for such a facility.
- 18 The Department of Energy chartered the Inertial Confinement Fusion Advisory Committee/Defense Programs (ICFAC/DP) on April 14, 1992, which reported to the Assistant Secretary for Defense Programs. Duties were to review the programs, meeting two to three times a year, and report on technical and management aspects of the program. Cook Collection, Box 1, has a large folder on the ICFAC/DP from 1992-1996.
- 19 Letter from V. Narayanamurti, chair of the ICFAC, to E.H. Beckner, acting Assistant Secretary for Defense Programs, Department of Energy, April 12, 1993, on the results of the review. In Cook Collection.
- 20 See W. Beezhold, R. Comisso, R. Gullickson, and R. Spielman, *Jupiter Design Options Study Team-Final Report*, May 1995, 3 vols. (SAND94-3163), a feasibility study written at the request of Juan Ramirez to help justify the Jupiter project to the Department of Energy and Department of Defense. The pre-conceptual study was multi-disciplinary, lasted six months and was completed in January 1994, and took almost a year to write. Jupiter was envisioned as an ultimate laboratory x-ray simulator for weapon effects with a primary focus on experiments for x-ray-produced mechanical damage. (See Pulsed Power Center Archives, Box 2/Van Arsdall, and a box labeled "Pulsed Power All 1987-1996.") Jupiter was intended to provide the spectrum of warm x rays needed for materials and structures testing that had only been available from live nuclear tests. Jupiter was not funded, but remained a desired facility for some time after this.

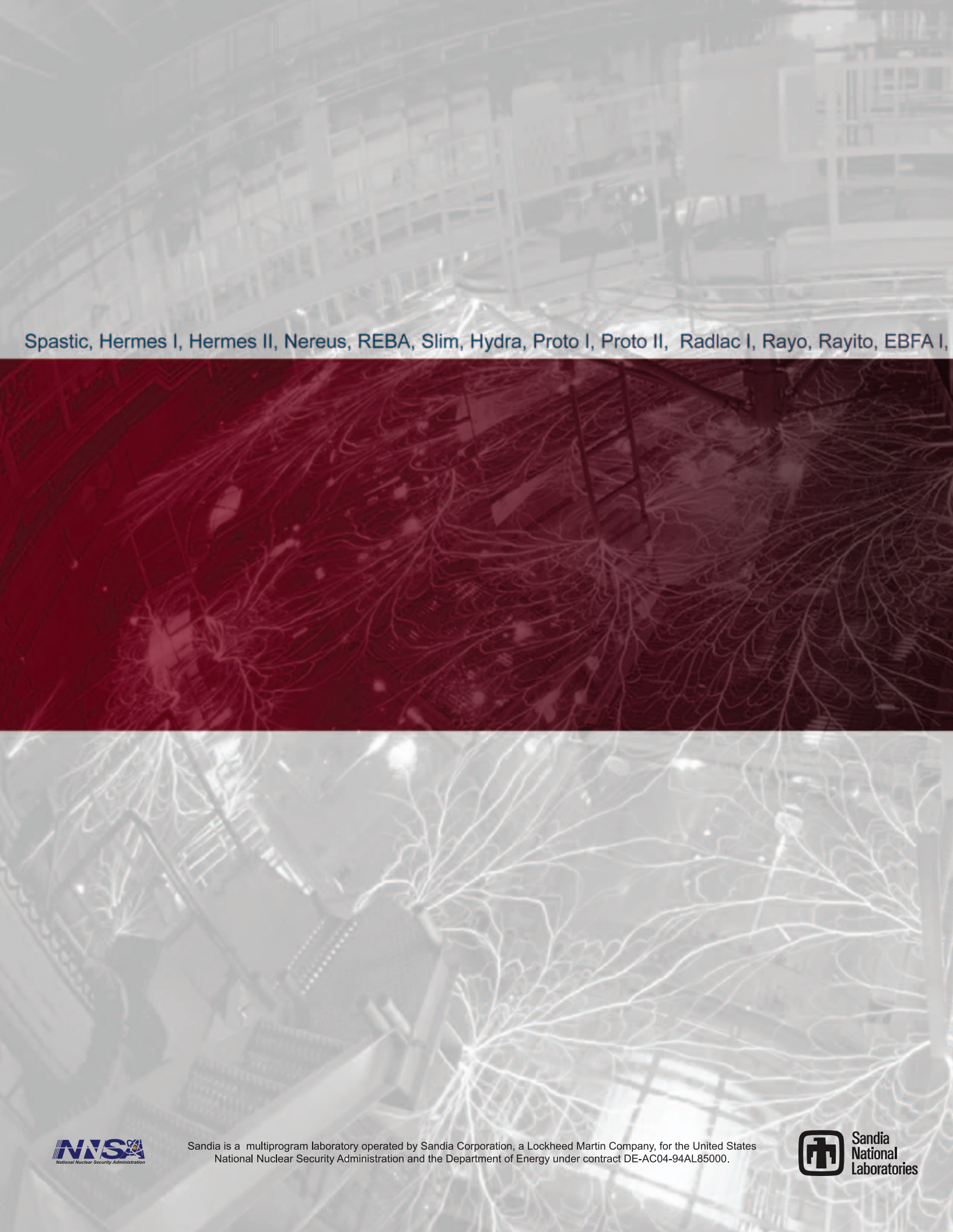
Chapter Four

- 21 Van Arsdall interview with Pace VanDevender, September 23, 2003. VanDevender's move to head the new communications center is detailed in the *Sandia Lab News*, April 30, 1993. At the time, VanDevender said, "I've been the director of Pulsed Power Sciences for a long time. We just had a successful review of the major portion of our pulsed power work. So that organization has never been in better shape—the spirit of teamwork, the closeness to our customers, and the competence of our technical staff and managers has never been better."
- 22 VanDevender became head of Sandia's Communications Center in April 1993 and then head of National Industrial Alliances in March 1994. After later serving as the Chief Information Officer, VanDevender became Vice President for Science, Technology and Partnerships in August 2003.
- 23 Memo from Jeff Quintenz to Anne Van Arsdall, September 5, 2006. Quintenz added: The panel was composed both of experimentalists and theorists with some very high-power plasma physicists (Marshall Rosenbluth, to name one) who were very impressed with the explanation of the instability in the diode, and the fact that we could actually measure the growth of that instability using a spectroscopic technique that Jim Bailey had perfected. So it was again, an evolution from "arcane endeavor" to science that I think was recognized by that panel and helped prolong the program at that time.
- 24 Van Arsdall interview with Don Cook, October 6, 2003.
- 25 For a short time, radiation effects and pulsed power were united in an organization titled Information and Pulsed Power Research and Technology, which Yonas headed. In 1999, pulsed power returned to the primary research organization at Sandia and radiation-effects work went to the weapons side of Sandia.
- 26 G. Yonas, "Fusion and the Z Pinch," *Scientific American*, August 1998, p. 43, and Van Arsdall interview with Tom Sanford, March 2007.
- 27 *Sandia Lab News*, December 6, 1996, "PBFA-Z's energy bursts reach new highs, help predict nuclear blast physics, edge closer to fusion." The Z story is told in many publications, from popular to scientific, from this point forward. See for example M. Paterniti, "A Voyage to the Sun," *Esquire*, November 1999; "Will NIF Put the Squeeze on Sandia's Z Pinch?" *Science* 277, 18 July 1997: 306 ff. Several Sandia news releases were issued on Z in the late 1990s (available from Sandia's Media Relations Department). See also the color portfolio of information, *Pulsed Power: Fusion Fire*, SAND98-2020.
- 28 Memo of Record, June 14, 1996, from Robinson, Hagengruber, Powell, Crawford, Yonas, and Cook on "What We Agreed to at the June 5 Meeting on Pulsed Power." (Pulsed Power Center Archives). *Sandia Lab News* Release, April 24, 1996, "Pulsed Power Accelerator Achieves Record-Breaking X-Ray Outputs," which has a sidebar on X-1 and Jupiter.
- 29 Z-Pinch Modification Correspondence, Cook Collection, Box 2; input from Mike Cuneo to Van Arsdall, September 2006, that the PBFA-X diode work was based on extraction diode work done on SABRE.
- 30 Van Arsdall, interview with Pace VanDevender, September 23, 2003.
- 31 "Sandia External Advisory Committee on Pulsed Power-Based Stockpile Stewardship Final Report," Jasper Welch, chair. SAIC Report, April 2, 1996. In Cook Collection, Box 2, Stockpile Stewardship; also in Box 1, Stockpile Stewardship, 1994.

- 32 *Sandia Lab News* Release of December 2, 1996. "High Output Sandia Accelerator Able to Predict Nuclear Blast Physics." For more information on the long history of z pinches in the United States and in particular at Sandia, see M.A. Sweeney, "History of Z-Pinch Research in the U.S.," *Dense Z Pinches: 5th International Conference on Dense Z-Pinches, American Institute of Physics, 2002*: 9-14 and the 1998 *Scientific American* article by Gerry Yonas cited in text.
- 33 From interviews with Jeff Quintenz, Keith Matzen, Don Cook, Pace VanDevender, Gerry Yonas, Ray Leeper, Tom Mehlhorn, and Marshall Sluyter, the Department of Energy sponsor.
- 34 Quintenz memo to Van Arsdall, September 5, 2006, and Van Arsdall, interviews with Mike Cuneo and Tom Mehlhorn, 2006.
- 35 For detail on the cost of the National Ignition Facility, see the Natural Resources Defense Council 2000 report, "When Peer Review Fails: The Roots of the National Ignition Facility Debacle."
- 36 Numerous presentations from this era also focus on inertial confinement fusion energy.
- 37 Notes to the Lab Leadership Team from Paul Robinson, November 1998. (In Don Cook Collection, Box 1, Galvin Committee.) It is an isolated document but highly interesting. By this time, the idea for a Laboratory Microfusion Facility had been abandoned largely because of the focus on the National Ignition Facility and because Sandia and other weapons laboratories were looking at other possibilities to fill the simulation needs of the military.
- 38 "Sandia Bets on Mega-Microsystems Facility, Holds Off on Pulsed Power," *Physics Today*, October 1999, pp. 65-66. Letter from Tom Hunter to Gil Weigand, Department of Energy/DP, July 23, 1999, about priorities at Sandia regarding MESA and pulsed power, stressing that the decision was to postpone, not abandon, ZX, and citing the importance of pulsed power to Sandia and to weapons science; in the VP 1000 files, Box 6.
- 39 See Memo from Jeff Quintenz to A. Van Arsdall of September 5, 2006, and the 2000 "Pulsed Power Path Forward: A Strategy For Leadership," mentioned in text. The authors were J.R. Asay, K.W. Bieg, D.D. Bloomquist, J.R. Lee, R.J. Leeper, J.E. Maenchen, M.K. Matzen, D.H. McDaniel, J. Polito, J.P. Quintenz, P.S. Raglin, M.S. Sluyter (Department of Energy, retired), G. Smith, and W.J. Tedeschi.
- 40 Pulsed Power Program Peer Review-Executive Summary by SAIC, June 22, 2000, in the VP 1000 Files, Box 6; Richard Garwin, *Pulsed Power Peer Review Committee Report*, SAND2000-2515, October 2000.
- 41 See justifications cited in "Pulsed Power Path Forward: A Strategy for Leadership," J. Quintenz et al. (Copy in Van Arsdall Collection, Quintenz folder.)
- 42 *Frontiers in HED Physics: The X-Games of Contemporary Science*, Committee on High-Energy-Density Plasma Physics; Plasma Science Committee. National Research Council, 2003.
- 43 For example, see Sandia's role in inertial fusion energy at the 1999 Snowmass Fusion Summer Study, the IAEA Cooperative Research Project on Inertial Fusion Energy (IFE) Power Plants, the 2002 Snowmass Fusion Summer Study, the Fusion Energy Sciences Advisory Committee (FESAC) 35-year Plan Panel Report (2003), and the FESAC IFE Panel Report (2003).

Chapter Four

- 44 See for example C. L. Olson, "Z-Pinch Inertial Fusion Energy," in the *Landolt-Boernstein Handbook on Energy Technologies* (ed.-in-chief W. Martienssen), Volume VIII/3, *Fusion Technologies* (ed. K. Heinloth), Springer-Verlag (Berlin-Heidelberg), 495 (2005), which includes an extensive list of references; *Z-Pinch IFE Program: Final Report for FY04*, SAND2005-2742P, Sandia National Laboratories (856 pages) CD (2005); *Z-Pinch IFE Program: Final Report for FY05*, SAND2006-7399P, Sandia National Laboratories (1037 pages) CD (2006); *Z-Pinch IFE Program: Final Report for FY06*, Sandia National Laboratories, SAND2007-0419P (1032 pages) CD (2007).
- 45 Sandia News Release, August 30, 2001, "Z Beamlet image shows Z evenly compresses pellet." *Nature* 413, 338 (2001), "Crushing victory could help in quest for fusion energy."
- 46 Researchers included J.L. Porter, J.H. Hammer, M.E. Cuneo, G.R. Bennett, and R.A. Vesey.
- 47 Sandia News Release, April 7, 2003, "Z produces fusion neutrons, Sandia scientists confirm." See also *Labs Accomplishments for 2003* (printed March 2004), which says "the deuterium fuel in inertial confinement fusion capsule implosions has been heated to temperatures found at the center of the sun (ca. 11 million degrees C). This temperature measurement, coupled with measurements of the emission of 2.45 MeV D-D neutrons, confirms the thermonuclear origin of neutrons from inertial confinement fusion capsule experiments driven by a 20-MA z-pinch dynamic hohlraum. Scaling predicts ideal ignition at about 30 MA. Other experiments on Z demonstrated its reliability to contain hazardous materials, enabling revolutionary dynamic materials studies." Ray Leeper, who had done the initial diagnostics in 1978 when neutrons were thought to have been produced, told Van Arsdall in a 2006 interview that he made absolutely certain about the results in 2003.
- 48 First authors included T.A. Sanford, T.J. Nash, S.A. Slutz, J.E. Bailey, T.A. Mehlhorn, and C.L. Ruiz.



Spastic, Hermes I, Hermes II, Nereus, REBA, Slim, Hydra, Proto I, Proto II, Radlac I, Rayo, Rayito, EBFA I,



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