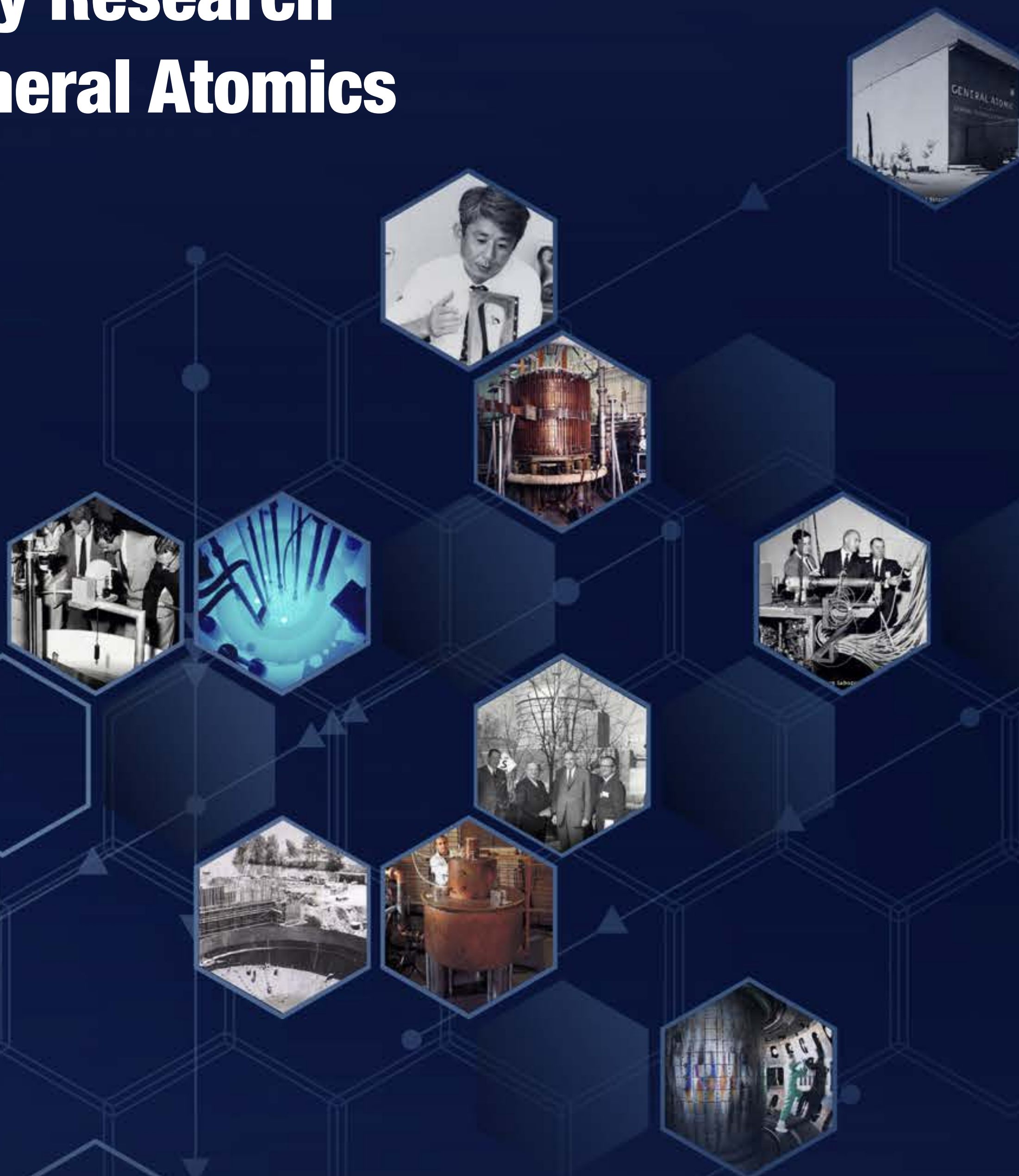
The History of

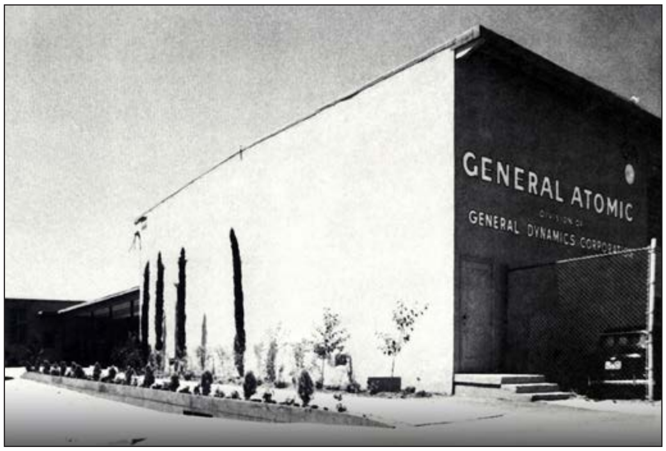
Energy Research at General Atomics



GENERAL ATOMICS

Fission

In May 1953, President Eisenhower pulled back the curtain on the secretive world of atomic energy. In a speech before the United Nations, he proposed that humanity leverage the power of the atom for peaceful uses. He called it "Atoms for Peace." In many ways, Eisenhower's speech helped launch the Atomic Age – and many people were listening.

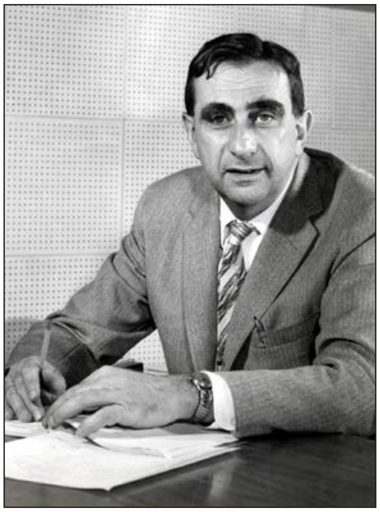


One of them was John Jay Hopkins. Hopkins was the president of General Dynamics, then the largest defense contractor in the U.S., which was already building nuclear submarines for the Navy. He began discussing the possibilities of commercial atomic power with one of his young managers, Frederic de Hoffmann, who was then the assistant vice president for nuclear planning with the company's Convair division in San Diego. Encouraged by de Hoffmann and Eisenhower's call, Hopkins decided to launch a new division devoted to atomic power, and the General Atomic division of General Dynamics was founded on July 18, 1955.

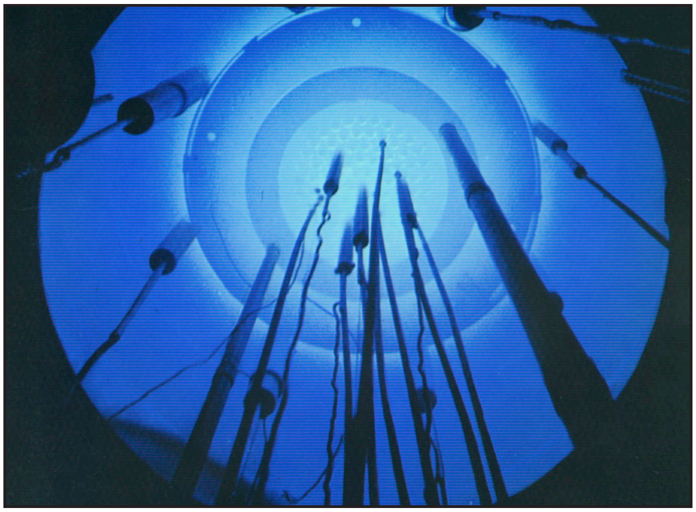
TRIGA

Less than a year after being placed in charge, de Hoffmann decided to bring together a unique collection of around 60 of the world's top nuclear scientists and engineers. Many of them were former colleagues from the Manhattan Project, such as famed physicist Edward Teller; others were leading experts from academia in the U.S. or Europe. The group met in a rented schoolhouse in the Point Loma neighborhood of San Diego during the summer of 1956 for a wide-ranging series of lectures and brainstorming sessions. Their mission was to develop ideas that could commercialize the immense potential of nuclear energy.

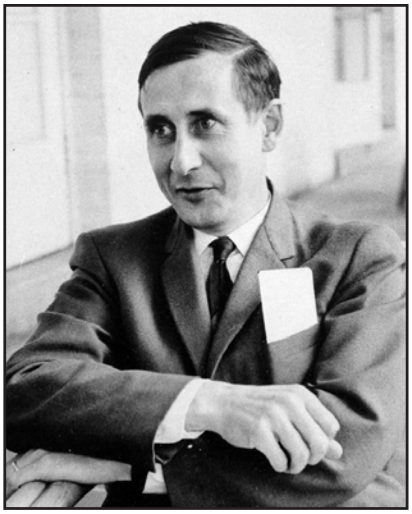
Decades before the word "start-up" would enter the vocabulary to describe high-risk, high-return ventures formed to chase innovative breakthroughs, this meeting would spawn a number of ideas that continue to influence the world of nuclear energy. In addition to Teller, the group included famed physicists Freeman Dyson, Marshall Rosenbluth, and Hans Bethe.



Edward Teller



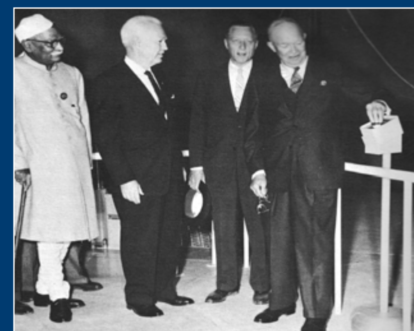
TRIGA



Freeman Dyson

During one of the discussions, Teller suggested developing a safe reactor, by which he meant one that relied on the laws of physics rather than engineering. The group decided to pursue the project. Dyson and physicist Ted Taylor soon conceived the idea of uranium–zirconium hydride fuel, which was chosen because of its large, prompt and negative temperature coefficient, meaning that an increase in core temperature would reduce the power of the reactor.

Unlike other reactors, which depend on engineered safety systems, their design used principles of nuclear physics to keep the core safe and stable no matter what conditions the reactor encountered. If the core temperature rose too high, the fuel itself would shut down the nuclear reaction. The final product, known as Training, Research, Isotopes, General Atomics (TRIGA), was invented by Dyson, Taylor, and Andrew McReynolds. The first prototype was brought online in 1958.



President Eisenhower starts one of the first TRIGAs in India in 1959

After GA displayed the new reactor at the second UN Conference on Peaceful Uses of Atomic Energy later that year, TRIGA was an instant hit and would go on to become the most successful research reactor design in history. More than 65 have been built around world. Most remain in operation, having achieved an unbroken record of safety over more than 60 years.

PEACH BOTTOM

Another idea that emerged from the summer of 1956 was a high-temperature gas-cooled reactor (HTGR). In 1959, GA signed a contract with the Atomic Energy Commission (AEC) and the Philadelphia Electric Company to design and build a demonstration plant in southeastern Pennsylvania. Construction began in 1962, and initial operation was achieved in 1966.

Peach Bottom was a helium-cooled, graphite-moderated, 40-MW reactor operating on a thorium-uranium fuel cycle, which allows for higher efficiencies with reduced waste and proliferation risk. Though it supplied power to the local grid, it was designed and operated as a prototype and technology test bed as part of AEC's Power Reactor Demonstration Program.

The Peach Bottom HTGR operated from 1966 to 1974, and it was successful in demonstrating the feasibility of HTGR technology. Over its lifetime, it operated at 39% efficiency, a higher level than even current light-water reactors can achieve.

Fort St. Vrain fuel assembly

FORT ST. VRAIN

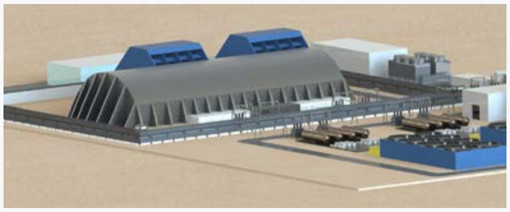
Even before Peach Bottom came online, the AEC and others had begun planning for a full-scale follow-on project. For this, the AEC selected a proposal from Public Service Company of Colorado for a 330-MW HTGR to be built by GA at the Fort St. Vrain site north of Denver.

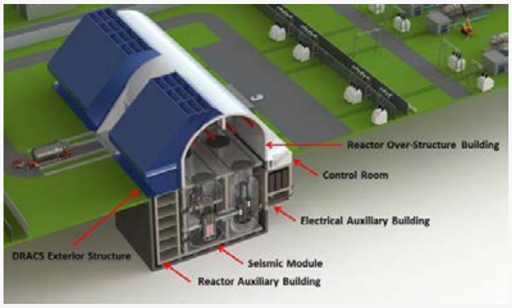
The early success of Peach Bottom helped kick-start development at Fort St. Vrain. Though based in part on technology from the earlier project, Fort St. Vrain incorporated several innovations, among them the first pre-stressed concrete reactor vessel in the U.S. This approach substantially simplified construction, as it meant there was no large steel vessel to transport to the site. Construction began in 1968 and finished in 1972, with commercial operation beginning in 1979.

Like Peach Bottom, Fort St. Vrain used a U-Th fuel cycle, but with a more advanced fuel design. Fort St. Vrain was among the first reactors to employ tri-structural isotropic (TRISO) fuel, in which particles of uranium are sealed inside pyrolytic carbon and silicon carbide for added safety and high-temperature performance.

As a first-of-a-kind project, Fort St. Vrain encountered some substantial issues during startup and initial operation. However, those issues were eventually addressed, and over its decade of operation, the reactor proved to be a successful proof of concept for a large-scale HTGR-based power plant.

EM²



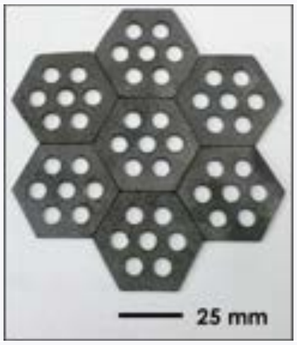


Building on the lessons and technology of TRIGA, Fort St. Vrain, and Peach Bottom, GA has developed an advanced small modular reactor (SMR) concept that addresses four of the most challenging problems facing nuclear energy today: economics, safety, waste, and nonproliferation.

The Energy Multiplier Module (EM²) is a 265-MW helium-cooled fast reactor that is designed as a modular, grid-capable power plant with a 30-year core life. The reactor is sited below grade and uses passive safety methods for heat removal and reactivity control. EM² also employs a closed-cycle gas turbine generator for added efficiency.

SIC-ATF

Silicon carbide (SiC) has been used for a wide variety of industrial purposes for more than 100 years. Its exceptional hardness and ability to survive extremely high temperatures make it ideal for demanding environments. It has been used in nuclear energy applications, such as coating TRISO fuel particles, but its brittleness in pure form limits its use as a structural material. However, it can be significantly toughened through reinforcement with SiC fibers, forming a composite known as a ceramic matrix composite, or CMC.



Leveraging past research with new technologies, GA scientists have developed SiGA™, a high-tech engineered SiC composite material that forms the basis of its Accident Tolerant Fuel program (ATF) for the Department of Energy, which is developing nuclear reactor fuel rods that can survive temperatures far beyond that of current materials. GA is also using this advanced material technology to offer SiGA components for applications beyond ATF.

Fusion

EARLY DAYS

The GA fusion program was also born that first summer in 1956, with a recommendation from the assembled experts that GA pursue energy drawn from controlled fusion reactions. The leaders of the fusion team were veteran Manhattan Project physicist Edward C. Creutz and theoretical physicist Marshall Rosenbluth.

The group quickly secured $10 million in funding from the Texas Atomic Energy Research Foundation. Donald Kerst, one of the developers of the betatron particle accelerator, was hired to manage the program in 1960. Kerst, in turn, hired a young physicist from Japan named Tihiro Ohkawa, who would go on to be a leading light in the field.

Marshall Rosenbluth

The early GA fusion team

DOUBLET REVOLUTION

Dreams of a rapid transition to clean fusion energy soon ran into the reality of funding limitations and substantial physics and engineering challenges. By the mid-1960s, many of the early members of GA's fusion program left for positions in academia, leaving two members of the original group, Ohkawa and Torkil Jensen, to chart a new path forward.

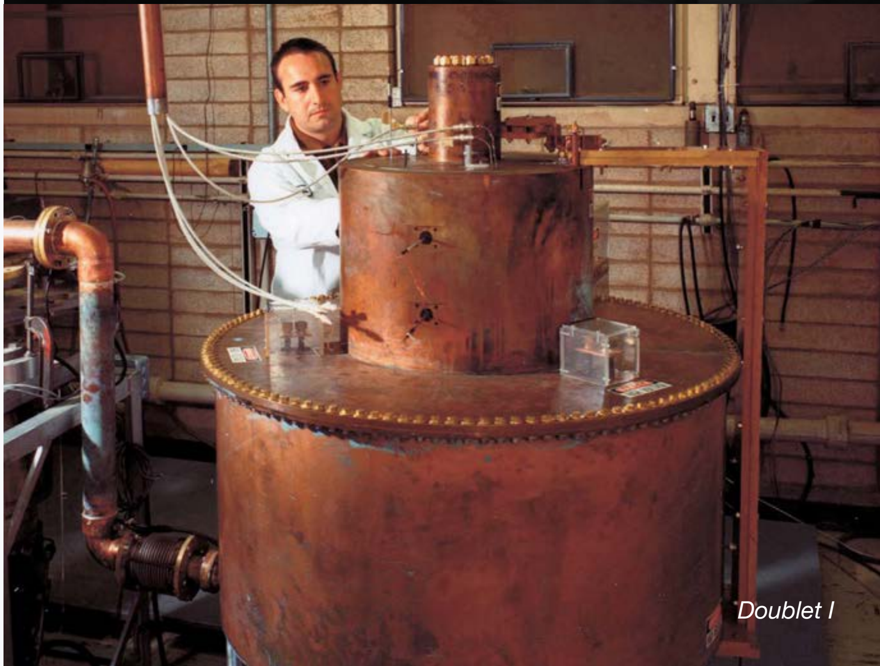
The success of early experiments in studying stable plasmas led to a larger device, the dc Octopole, designed by Ohkawa. The dc Octopole was able to confine a plasma far longer than what was previously thought to be possible.

The path to practical fusion energy, however, would ultimately require a different approach, which emerged in the late 1960s: the tokamak, which was first developed by Russian scientists. In contrast to the internal magnetic fields used in earlier devices, tokamaks combine external magnetic fields with an internal current induced within the plasma itself.

Results from a pilot device built by Ohkawa, named the Doublet I, were promising enough to spur construction of a larger tokamak, the Doublet II. Tokamaks were being studied around the world, but Ohkawa's innovation was using a non-circular plasma cross-section (the "Doublet" name came from its two lobes of plasma).

Built in part with support from the AEC, Doublet II ran from 1972 to 1974. An upgraded device, called Doublet IIA, ran from 1974 to 1979. Among other advances, the Doublet II and IIA devices incorporated numerous innovative diagnostics that enabled plasmas to be studied in ways not possible before. Doublet IIA was among the first devices to benefit from the closer coupling of theory and experiment that was made possible by large-scale simulation methods and computerized data acquisition.

Tihiro Ohkawa



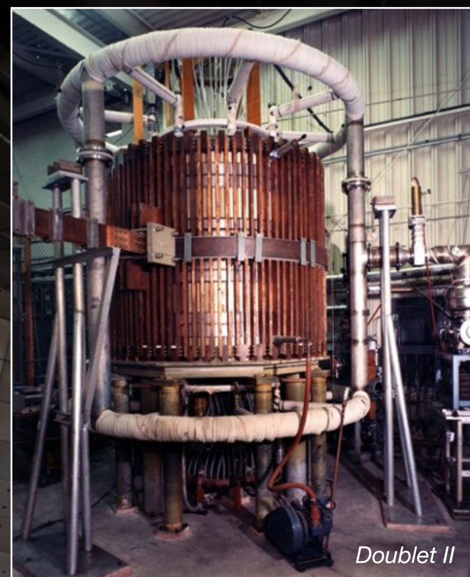
Doublet I

DIII-D TOKAMAK

Even as Doublet II and IIA were breaking new ground, planning was underway for a much larger follow-on device. Doublet III, as it would be called, was almost three times the linear size of Doublet II, and incorporated advanced new plasma control and heating systems that were far more powerful than those of its predecessor devices.

The design process for Doublet III was led by Ohkawa, scientist John Gilleland, and physicist John Wesley. A successful proposal to AEC led to funding for construction, which began at a new site on the GA campus in late 1974. First plasma was achieved less than four years later, in early 1978. At the time, Doublet III was the largest tokamak in the world.

Funding from the Japan Atomic Energy Research Institute (JAERI) allowed for upgrades to Doublet III's power and heating equipment. Successful research on Doublet III in the early 1980s led to a vision for major modifications that would allow for "D"-shaped plasmas. Led by physicist John Rawls, the initiative resulted in designs for a new vacuum vessel and significant enhancements to its heating, diagnostics, and plasma control systems. The new tokamak, dubbed DIII-D, began operations in 1986.



Doublet II

Doublet III

Signing the agreement with JAERI

Breaking New Ground

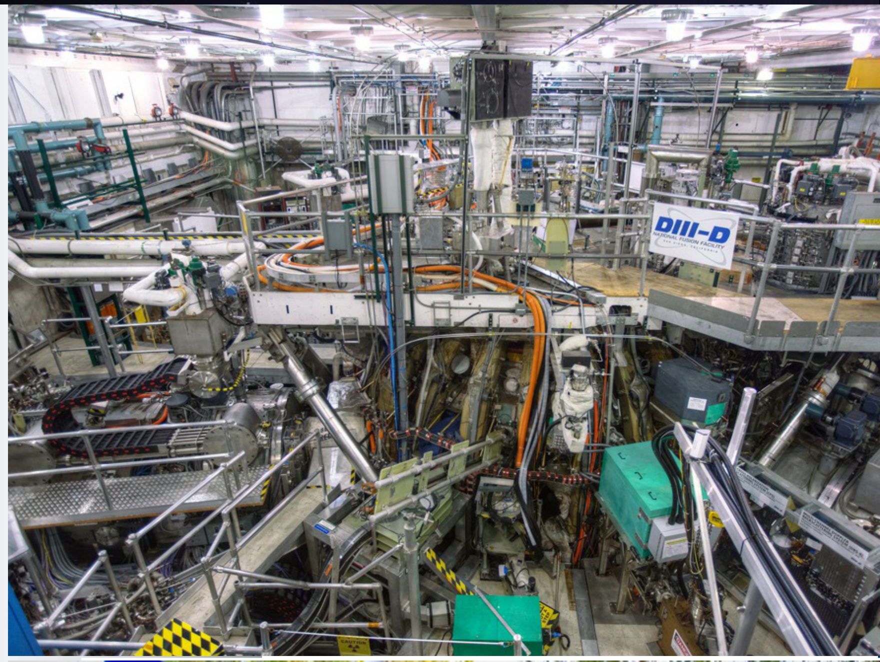
One key goal of the new DIII-D was reaching higher levels of plasma beta ($\boldsymbol{\beta}$), which is the ratio of the plasma pressure to magnetic field pressure. $\boldsymbol{\beta}$ is an important measure of plasma stability and fusion output, since high plasma pressure is key to practical fusion energy.

And indeed, researchers were soon able to achieve record levels of $\boldsymbol{\beta}$ on DIII-D. Aided by advances in computer coding and theory, work on DIII-D began charting a path toward the high-performance operating regimes that would be necessary for the next generation of advanced tokamaks and future fusion reactors.

Over its three decades of operation as a DOE Office of Science user facility, the DIII-D National Fusion Facility has remained at the forefront of fusion science, both through continual upgrades to its capabilities and diagnostic equipment, and the hard work of its staff and collaborators. DIII-D scientists pioneered the use of small 3-D magnetic fields to eliminate plasma instabilities known as Edge Localized Modes, a critical advance for future devices. Work at DIII-D has also demonstrated multiple approaches for high performance, steady-state tokamak operation.

Researchers at DIII-D were responsible for the discovery of Super H-mode, an operating regime that offers the potential for a fourfold increase in fusion performance. Other work has included comprehensive research into plasma turbulence in conditions that will be used in future reactors.

DIII-D and its international team have made numerous other pioneering contributions to the development of fusion energy science, and DIII-D researchers have been honored with seven Excellence in Plasma Physics awards from the American Physical Society. Today, DIII-D continues to deliver cutting-edge fusion science and advance toward practical fusion energy with critical research conducted in collaboration with more than 600 scientists representing over 100 institutions worldwide.




The DIII-D control room

TO ITER AND BEYOND

First conceived in the 1980s, the ITER project has grown to a multinational collaboration of 35 nations, with the goal of achieving a self-sustaining – or “burning” – plasma for the first time. Much of the physics basis for ITER’s design was established at DIII-D, and GA scientists and engineers have contributed significantly to the project. The ITER experiment is currently under construction in Southern France, and first plasma is expected by 2025.

ITER CS module during fabrication

GA is fabricating the world's largest and most powerful pulsed superconducting electromagnet for the ITER project. The Central Solenoid (CS) is the heart of ITER, and the 5-story, 1,000-ton magnet will drive 15 million amperes of electrical current in ITER's fusion plasma for stabilization. Each of the six coil modules that comprise the CS will be seven feet tall, 14 feet wide, and composed of four miles of superconducting cable.

EAST Remote Control Room

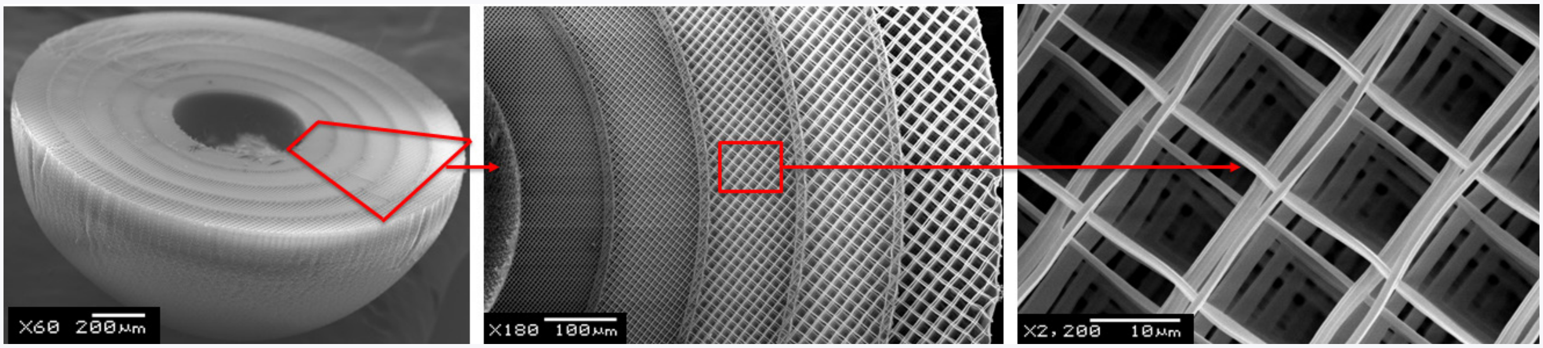
One important feature of ITER will be its planned ability to allow remote participation, so that researchers can take advantage of its unique capabilities from locations around the world. To that end, GA has developed technology and protocols that will allow joint experiments between local and remote researchers on ITER. This technology has already allowed U.S. researchers to carry out experiments on the Experimental Advanced Superconducting Tokamak (EAST) in Hefei, China, from a control room located in San Diego.

Inertial Fusion

Magnetic confinement is not the only approach to achieve fusion. Not long after the invention of the laser in the early 1960s, scientists began recognizing the potential for “laser fusion.” By using lasers with sufficient power, researchers believed they could compress a spherical pellet of frozen hydrogen with enough force to initiate fusion of deuterium and tritium atoms in the target. Because this compression process is initiated and contained by the inertia response of heating the fuel pellet itself, it was dubbed inertial confinement fusion (ICF).

GA’s ICF activities began in the 1990s, when it began supporting research at U.S. laboratories such as Lawrence Livermore National Laboratory, Los Alamos National Laboratory, Sandia National Laboratories, and the Laboratory for Laser Energetics at the University of Rochester.

In 1991, GA became the principal ICF contractor for target fabrication for the U.S. national laboratories, a role that continues to this day. GA’s unique capabilities in micro-manufacturing, coating, and diagnostics have helped drive forward the state of the art in ICF experimentation. Most of the work is related to the National Nuclear Security Administration’s (NNSA’s) science-based stockpile stewardship mission to safeguard the U.S. nuclear deterrent. However, much of this research also supports exploration into high energy density (HED) physics across a range of academic disciplines.



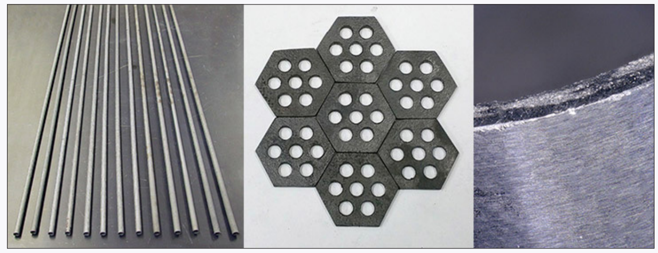
TARGET MANUFACTURING

Along with world-leading diagnostics and associated equipment, GA’s ICF division supplies nearly 15,000 target components every year for a wide range of scientific experiments at U.S. NNSA laboratories. GA’s target fabrication capabilities are supported by highly precise analytical and measurement capabilities that ensure ICF targets meet the most exacting standards of geometry and chemical composition.

Spinoffs

ADVANCED MATERIALS

Very early on, researchers realized that practical fusion power would require plasma-facing materials that could withstand extraordinarily harsh conditions of high temperature and radiation. Research in this area from the 1970s through today has yielded important advances in metallurgy and ceramics, particularly silicon carbide. The latter work helped inform GA research into SiC composites for nuclear fission applications.



RADIOFREQUENCY (RF) AND MICROWAVES

Because fusion tokamaks require precise manipulation of radio and microwaves for heating and control, the Energy Group has a long history of research and innovation in RF technology. Though initially intended for use on DIII-D and other tokamaks, GA's RF components have found applications outside fusion, such as radar and communications.

EMALS

To contain the 150-million-degree plasma inside the tokamak, DIII-D requires carefully controlled magnetic fields and finely tuned pulses of energy. GA scientists developed the technology to make this possible in the 1970s and '80s.

Based on that expertise and technology, the Department of Defense chose GA to develop the Electromagnetic Aircraft Launch System (EMALS) for its next generation of aircraft carriers. This system launches an aircraft from the deck of a carrier using a linear induction motor coupled to the same type of energy storage and power conversion equipment that provide the precise electrical and magnetic control at DIII-D. Because it is much more precise than steam-powered systems, EMALS minimizes physical stress on Navy aircraft, increasing their lifespans and reducing costs. EMALS has been deployed on the *USS Gerald R. Ford* (CVN-78) and will be used on the other ships in her class.

Fusion-derived technology has been applied to a variety of problems of national importance and formed a key element of a new business unit at General Atomics, GA Electromagnetic Systems. Such technology has also been essential to other products such as magnetically levitated trains and railguns for launching hypervelocity projectiles.

HIGH-PERFORMANCE COMPUTING

Beginning with state-of-the-art stability codes in the 1970s, GA has leveraged computer technology to tackle complex fusion physics problems. When DIII-D came online in the 1980s, researchers realized that making the most of its capabilities required ever-increasing computing power. GA was soon at the forefront of the rapidly expanding field of high-performance computing. In addition to groundbreaking work in plasma theory and simulation, these efforts led to several important spinoff initiatives.

In 1980, when the National Science Foundation (NSF) sought to develop a number of supercomputer centers, GA partnered with the University of California San Diego (UCSD) on a successful bid. UCSD hosted the center, while GA was in charge of operations. The center was launched in 1985 with $170 million from NSF, and purchased a Cray system. Though the partnership ended in 2000, the UCSD Supercomputer Center continues its work to this day.

The Future

From its humble beginnings in a San Diego schoolhouse, GA's innovations have advanced the state of the art across the full spectrum of science and technology – from nuclear energy and defense to medicine and high-performance computing. Behind a talented global team of scientists, engineers, and professionals, GA's unique experience and capabilities continue to deliver safe, sustainable, economical, and innovative solutions to meet growing global demands.

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