20 years of US nuclear stockpile stewardship fuels materials research

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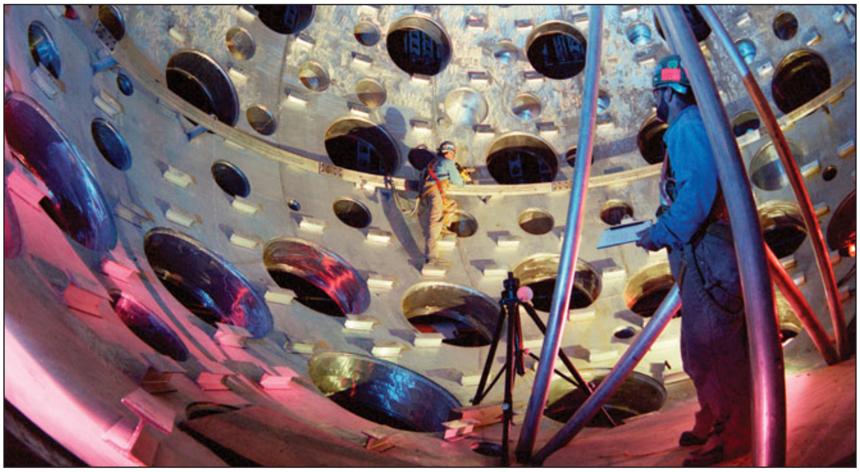
Twenty years ago the US National Nuclear Safety Administration (NNSA) established the Stockpile Stewardship Program (SSP) to keep the country's few thousand nuclear weapons stockpile safe and reliable. With the end of the Cold War, President George H. W. Bush had announced that the United States would stop developing new nuclear weapons and conducting nuclear explosive tests. The program's goal was to use innovative experiments and advanced computer models to study the aging of weapon materials and parts, assess and predict weapon performance, and redesign and replace components as needed.

During its 20-year lifetime, the USD$6 billion program has in particular pushed the borders of materials science and engineering and computational methods. It has led to new, world-class nuclear weapons research and production facilities. And it has driven collaborations between experts spanning disciplines such as materials science, condensed-matter physics, and computer science.

"The nuclear security enterprise is pushing frontiers in computational science, experiments, and theories," said NNSA Chief Scientist Dimitri Kusnezov in a news release. "The labs have developed new techniques for understanding the dynamic behavior of materials. Looking ahead, nuclear security will continue to shape the conversation in areas including next-generation exascale computing, advanced manufacturing, and materials science."

Work supported by the SSP is largely centered at Lawrence Livermore, Los Alamos, and Sandia National Laboratories, and has resulted in cutting-edge materials research that also finds applications in industry and academia, says Raymond Jeanloz, professor of astronomy at the University of California–Berkeley, who studies materials properties at high pressures. "These labs have been at the forefront of developing new materials technologies, systems, and experimental techniques, which end up having vastly broad applications," he says.

In a typical nuclear weapon, chemical explosives are detonated to produce shock waves that induce a symmetrical implosion and compression of fissile plutonium or uranium. This produces a fission chain reaction that releases energy, or, in the case of a hydrogen bomb, ignites a secondary fusion reaction. Nuclear weapons are built of thousands of components containing several classes of materials: fissile uranium and plutonium, metals, organic explosives, plastics, and ceramics.



Target chamber at the National Ignition Facility, the cornerstone of the US Stockpile Stewardship Program. Credit: Lawrence Livermore National Laboratory.

To meet the SSP's challenge, researchers assess every part of the existing nuclear arsenal annually. They use materials science theory, modeling, small-scale experiments, and large integrated experiments to understand the behavior of materials in normal, abnormal, and hostile environments. They analyze weapon components using destructive methods along with statistical sampling and high-resolution electron microscopy, as well as nondestructive techniques such as radiography and ultrasonic imaging.

Without real weapons testing, researchers have to understand the behavior of nuclear materials at the extreme pressures and temperatures found inside imploding weapons. This requires hydrodynamic experiments—hydrodynamics refers to solids that mix and flow like liquids under extreme conditions—on non-nuclear surrogate materials, and subcritical experiments on plutonium and uranium in which the configurations and quantities of explosives ensure that no nuclear chain reaction can occur.

The SSP supports several state-of-the-art research facilities to support such experiments. The program's cornerstone National Ignition Facility (NIF) at Lawrence Livermore National Laboratory has 192 powerful laser beams that can deliver 2 million joules of ultraviolet laser energy. The NIF enables researchers to heat matter to temperatures of 100 million degrees and pressures that exceed 100 billion times Earth's atmosphere. Other key hydrodynamic test facilities include the Dual Axis Radiographic Hydrotest Facility at Los Alamos, the Flash X-Ray

Facility at Livermore, and the Z-machine at Sandia where weapon assemblies containing non-nuclear surrogate materials are imploded while rapid photographic or x-ray images are taken.

Researchers have studied materials under extreme compression at a very short time scale of picoseconds, so that they can better understand the bonding and structure of materials, and probe their electronic properties. Groundbreaking work has also been done to understand the effects of aging on stored plutonium, says Robert Maxwell, the division leader of materials science at Lawrence Livermore National Laboratory.

Much of this work has implications beyond nuclear weapons research. The highly porous, hierarchical metal foams and carbon aerogels that scientists have developed for NIF targets, for example, are finding use in supercapacitors, Maxwell points out. “Our experience working with plutonium, uranium, and other elements has led to a fundamental understanding of those materials for nuclear power,” he says. “Our work in explosives has carried over into conventional weapons. We look at composites that have side benefits in industrial and other applications.”

Scientists from universities, laboratories, and research centers across the world have used SSP-supported facilities for non-weapons research. The NIF and the Z-machine are at the center of efforts to achieve nuclear fusion as an abundant source of clean energy. Experiments at the NIF help astrophysicists better understand the universe by studying the effects of meteorite impact and by recreating the high energy density matter at the center of planets and stars. “The stewardship program has given birth to a whole new experiment-based astrophysics initiative that hasn’t existed in all of our history,” says Gilbert Collins, a high energy density physicist at Livermore.

Experimental work is tied intricately to computational efforts. Virtual testing requires sophisticated simulations and three-dimensional modeling of weapons materials systems. So the SSP has led to the development of new generations of ultrafast, high-performance computers. The Trinity supercomputer now being built at Los Alamos will be capable of 40×10^{15} operations per second (40 petaflops) with 2 petabytes of memory; it will be the second fastest computer in the world.

The SSP’s next-generation computing systems have allowed materials researchers to use various computational techniques such as quantum molecular calculations, Monte Carlo methods, and first-principles techniques to understand and accurately predict the performance of materials across a wide range of time and length scales as well as temperature and pressure conditions. According to Collins, “many of the discoveries being made through the Stockpile Stewardship Program impact a fundamental understanding of materials or provide new pathways to how we think about material states.”

Prachi Patel

South Africa seeks to strengthen cooperation with Japan for hydrogen economy

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South Africa’s Minister of Science and Technology, Naledi Pandor, closed out the summer of 2015 with a visit to Japan in order to enrich cooperation between the two countries in the field of hydrogen fuel-cell technology. Accompanied by Deputy President Cyril Ramaphosa, Pandor held several engagements with Japanese stakeholders, including a round table meeting with academic institutions and a Symposium on the Hydrogen Economy.

Hydrogen and fuel-cell technology presents a niche area for collaboration between the two countries. While Japan has already started to create a hydrogen economy—boasting the largest share of patents in this field—South Africa has considerable deposits of platinum, which is a key catalytic material used in fuel cells.

As part of the global agenda to integrate energy systems, South Africa has positioned itself as a significant player in developing these technologies. During the Minister’s address to the Symposium on the Hydrogen Economy, she said there was a global movement toward developing sustainable energy systems and reducing greenhouse gas emissions. “For this reason, the use of hydrogen as an energy carrier, combined with fuel-cell technology, has attracted considerable interest from governments, international bodies, and commercial companies worldwide,” said Pandor.

Hydrogen, electrolyzer, and fuel-cell combinations offer a viable and cost-effective method of storing energy on a large scale, especially in instances where the energy is generated during times of low demand. When used as feedstock for fuel cells, hydrogen produces electricity at a high efficiency—with zero emissions—even for applications such as road vehicles and electricity-generation. Globally, a number of companies are developing megawatt-scale proton-exchange membrane electrolyzers to improve energy-storage applications.

In South Africa, the Department of Minerals and Energy projects that 40 GW of new energy generation capacity should be in place by 2030, of which 42% will be derived from renewable energy sources. Of this, 1 GW is expected to be concentrated solar power, which uses thermal storage, and approximately 17 GW will be a combination of wind and other renewable energy options, mostly photovoltaic systems.

“This creates an opportunity for local energy storage that could play a significant role in on-grid and off-grid applications. In this regard, energy is the critical area that needs to be consolidated and strengthened in terms of security of supply and access, as well as for environmental protection,” said Pandor.

She said that South Africa needs to reduce its dependence on imported oil and increase the percentage of alternative energy sources in the energy mix. For broad-based economic development to take place in the country, access to affordable, safe, clean, and reliable energy is crucial. ☐