SAND2009-5152P

Renewable and Carbon-Neutral Energy Research at Sandia National Laboratories

At Sandia, researchers have been working for decades to solve the technical issues that will allow all nations to make use of the full potential of their renewable, nonpolluting, and non-carbon-emitting energy resources.

Solar

The most abundant energy source on Earth is solar energy. The total solar energy absorbed by Earth's atmosphere, oceans, and land masses is approximately 3,850,000 exajoules (an exajoule is one quintillion joules) per year. On average, this is more power in one hour than all of the people of the world used during all of the year 2002.† The amount of solar energy reaching the planet's surface of is so vast that in one year it is about twice as much as will ever be obtained from all of the Earth's nonrenewable energy resources of coal, oil, natural gas, and mined uranium combined.‡

Power Tower

Sandia has been experimenting with concentrating solar power (CSP) since before the 1973 energy crisis. One of our early solutions was to use an array of sun-following mirrors (heliostats) to concentrate the sun's energy on a central structure. We participated in constructing a facility in southern California to evaluate two versions of this technology. Solar One operated successfully from 1982–86, validating the CSP concept and evaluating energy capture/conversion efficiencies of its direct steam system.

The facility was later reconfigured as Solar Two to use molten salt to capture and store the sun's heat. Sandia had the technical lead in developing molten-salt technology required for Solar Two. The concentrated sunlight heats the molten salt as it flows through the power tower receiver. The 1472 °F salt is then piped away, stored, and used when needed to generate steam to drive a turbine/generator that produces electricity. This thermal-storage capability allows a solar plant to operate smoothly through intermittent clouds, and it can also continue generating electricity long into the night. The recently completed Andasol 1, near Granada, Spain, uses the latest generation of the solar power tower technology developed here to heat 28,000 metric tons of salt—enough to generate its full capacity of 50 MW of electricity for 7½ hours. In August 2009, Sandia will complete an upgrade to our National Solar Thermal Test Facility (NSTTF) heliostat control system.

Dish-Stirling

Sandia, in partnership with Stirling Energy Systems (SES) of Phoenix, Arizona, has made a significant step toward commercializing the dish-Stirling power production system, which SES has christened SunCatcher. SES owns the dishes and the manufacturing knowledge, while SNL provides technical expertise in solar systems—together, we make a formidable team. The partnership's goal is to create a large-scale, grid-connected power plant that will supply the peak power market.

This generation of the dish-Stirling technology has held the world record for solar-to-grid conversion efficiency (31.25% net efficiency) since January 2008 (topping an efficiency mark set in 1984). The most impor-

† "Solar Energy: A New Day Dawning?" [http://www.nature.com/nature/journal/v443/n7107/full/443019a.html], retrieved 7 August 2008; and "Powering the Planet: Chemical challenges in solar energy utilization" [http://web.mit.edu/mitpep/pdf/DGN_Powering_Planet.pdf], retrieved 7-Aug-2008.

‡ "Exergy [available energy] Flow Charts" [http://gcep.stanford.edu/research/exergycharts.html].

tant technical advancement was improved optics. The parabolic dish combines a low-iron glass with a silver backing—focusing as much as 94% of the incident sunlight to the Stirling engine, where prior efforts reflected ~91%. The 4 cylinder, 380 cc Stirling engine has a nearly flat efficiency curve—it operates at almost maximum efficiency even when the sun is obscured by clouds or low in the sky. Its full-year sunrise-to-sunset efficiency is ~25%, roughly double that of parabolic trough solar systems. In November 2008, *Popular Mechanics* gave the system one of their 10 Innovation Breakthrough Awards. SES has signed agreements with two major southern California power companies for large-scale deployments—32,000 units across both sites with the option to expand to 70,000 units. The initial SunCatchers will be installed in August 2009.

Sunshine to Petrol

This team is using concentrated solar energy to chemically "re-energize" carbon dioxide (CO_2) into carbon monoxide. The carbon monoxide could then be used to make hydrogen from water (which provides the other component of syngas) or serve as a building block to synthesize a liquid hydrocarbon fuel, such as methanol or even gasoline, diesel, and jet fuel. "What's exciting about this invention is that it will result in fossil fuels being used at least twice, meaning less CO_2 being put into the atmosphere and a reduction of the rate that fossil fuels are pulled out of the ground," says Rich Diver, one of the project's technical leads.

The prototype device, the Counter Rotating Ring Receiver Reactor Recuperator (CR5, for short), will break a carbon-oxygen bond in the CO_2 to form carbon monoxide and oxygen in two distinct steps. It is a major piece of an approach to converting CO_2 into fuel from sunlight. The Sandia research team calls this approach "Sunshine to Petrol" (S2P). "Liquid Solar Fuel" is the end product—the methanol, gasoline, or other liquid fuel made by splitting water (to obtain hydrogen) and splitting CO_2 (to obtain carbon monoxide) with concentrated solar energy.

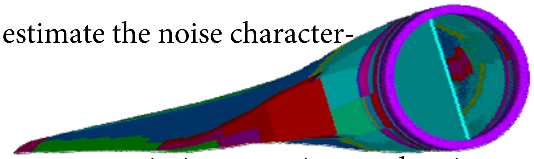
Wind

Innovative Concepts

As wind turbines become larger and heavier, embedding sensors along the blade length to sense local conditions and incorporating small load-control devices (similar to, but smaller than, flaps on an airplane wing) that respond quickly to alleviate fatigue loads offer the potential for significant weight savings. Sandia is focused on three areas: (1) analyzing the blade's aerodynamic performance (2) developing advanced controls, and (3) calculating the maximum potential cost/benefit of energy reductions that can be achieved through reducing fatigue loading. Other concepts for future blades include both active and passive blade controls such as passive bend-twist coupling, microtabs, and continuous deformation of upper and lower blade surfaces to improve energy capture/reduce drag. Finally, as technology allows blades to grow larger (to capture wind energy more efficiently), they may become too long to transport across the nation's roads (currently, truck transporters are exceeding 180 feet). Sandia is investigating the possibility of economically manufacturing segmented turbine blades.

Aerodynamic Tools and Aeroacoustics

Sandia continues to develop and use computational fluid dynamics codes to better understand the highly three-dimensional flow fields under which wind turbine rotors operate. Sandia's high-performance computing tools provide useful information to develop the next generation of wind turbine blades that maximize both structural and aerodynamic efficiency. Additionally, Sandia will continue to develop aeroacoustics emission and propagation prediction codes that provide the capability to estimate the noise characteristics of wind turbine rotors.



Instrumentation and ATLAS II

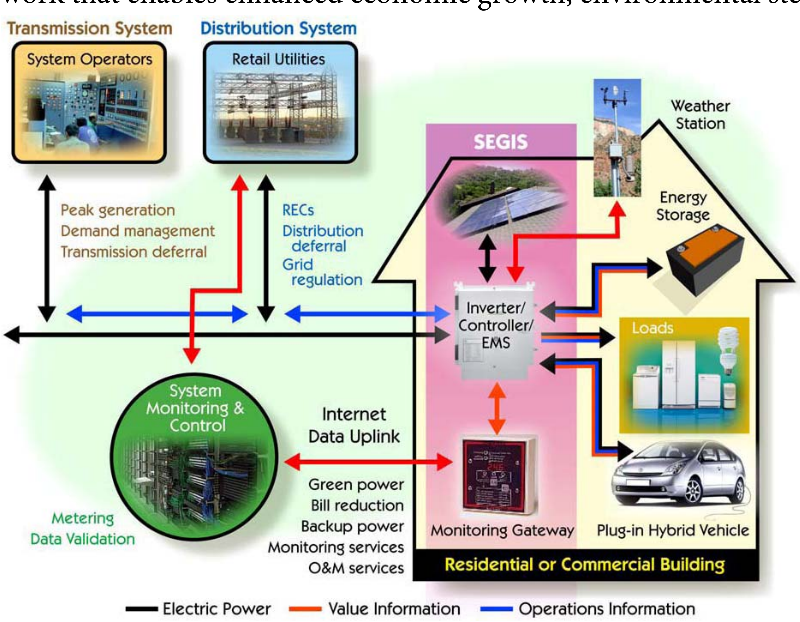
Sandia works in partnership with manufacturers and wind farm operators to optimize operations and maintenance practices. Sandia developed the Accurate Time-Linked data Acquisition System (ATLAS II), which—through a network of embedded strain, pressure, displacement, proximity, control-input, damage-detection, and health-monitoring fiber-optic and piezo-ceramic sensors—provides much of the information necessary to understand how a turbine system is performing. Housed in an environmentally protected aluminum box, ATLAS II simultaneously samples many signals that characterize the inflow, the operational state, and the structural response of a wind turbine. ATLAS II is compact, highly reliable, can operate continuously, uses off-the-shelf components, and has lightning protection on all channels.

The Electric Grid: Transmission, Distribution and Energy Storage

Generating electricity from wind turbines or solar systems is only the beginning of the process. The electricity must travel from its generation source to the customer. America's current (aging) power grid is designed to transmit power from a nearby fossil-fueled power plant to local customers. This grid has only a limited capacity for long-distance power transmission. In addition, it is not designed to store power because fossil fuel is the present energy storage. The electricity must be generated at the instant in which you use it. This problem with renewable energy resources relative to the present electric grid is the lack of dispachability, which is a result of being intermittent *and* the resource may be located in places where little demand for electricity exists.

The Smart Grid

Sandia researchers are participating in the development of many next-generation components for an electrical grid that can accept inputs from distributed power-generation sources to transform America's energy production and distribution system into a more intelligent, resilient, reliable, self-balancing, and interactive network that enables enhanced economic growth, environmental stewardship, operational efficiencies, energy security, and consumer choice.



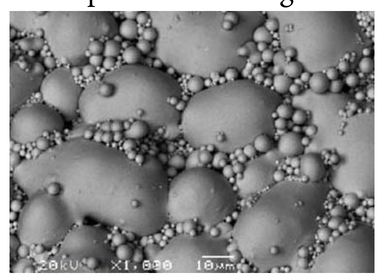
The variable nature of renewable energy sources (e.g., wind and solar) means that time-of-use and peak-demand rate structures will require more sophisticated systems designs that integrate energy management and/or energy storage into the system architecture. The goal is to develop technologies to increase the penetration of renewable energy sources into the utility grid while maintaining or improving its power quality and reliability.

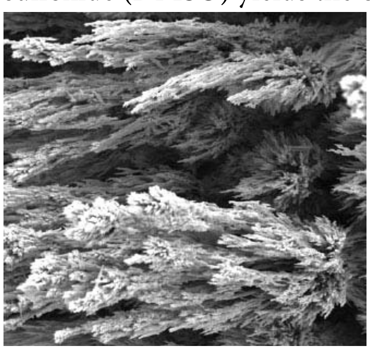
A key element of this effort is the Department of Energy's Solar Energy Grid Integration Systems (SEGIS) program which seeks to seamlessly accommodate two-way power flows as required by wide-scale deployment of photovoltaic (PV) and other distributed resources. The three distributed-energy market segments typically connected to a utility grid are residential (<10 kW, single-phase), small commercial (10–50 kW, typically three-phase), or commercial (>50-kW, three-phase). Highly integrated, innovative, advanced inverters and associated balance-of-system (BOS) elements for residential/commercial energy applications will be the key components developed in the effort. Advanced integrated inverters/controllers may incorporate energy management functions and/or may communicate with stand-alone energy management systems as well with utility energy portals, such as smart metering systems.

The SEGIS program will improve the reliability and increase the value of PV inverter/controllers while developing interfaces for advanced grid integration. The heart of the SEGIS hardware, the inverter/controller, will manage generation and dispatch of solar energy to maximize value, reliability, and safety. The inverter/controllers will interact with building energy-management systems and/or smart loads, with energy storage, and with the electric utility to allow the integration of relatively large amounts of PV energy while maintaining or increasing grid reliability.

Battery Research

Several large-scale battery systems have been installed on the grid and effectively used, but they were not economically feasible so, at the end-of-life of the cells, they were not replaced. Sandia is working with GINER Electrochemical Systems and ADA Technologies to develop nanostructured electrodes and electrolytes for energy-storage devices. Our results from a previous program (in partnership with Los Alamos) to develop room-temperature electrodeposition of highly reactive metals and alloys indicated the promise of using electrolytes with a large working range (voltage) to improve an electrochemical capacitor's energy-storage capability. We are studying ionic liquids for this system to determine what combination of reactive metal salts and dimethyl sulfoxide (DMSO) yields the optimum working range for the experimental electrodes developed in the previous program.





Our industrial partners are working to increase the active area of electrodes—GINER with high-surface-area materials (above, right) and ADA with nanomaterials (left). GINER fabricated and tested high-surface-area nanoporous carbon powder all solid-polymer-electrolyte capacitors. Their evaluation results showed high specific capacitance, high energy density, and high power. ADA sought to use the properties of carbon nanotubes, high-surface-area activated carbons, and environmentally benign ionic liquids to fabricate high-performance electrodes. The activated carbon provides high surface area; the nanotubes help avoid carbon-black aggregation and provide a highly conductive/electrolyte network; and the ionic liquid helps untangle the nanotubes, serves as a plasticizer, and reduces binder content. ADA's activated carbon and nanotube composite electrode exhibited fast charge/discharge kinetics and enhanced capacitance. Adding ionic liquid to the fabrication process further enhanced its capacitance.

Sandia also leads the Electric Energy Storage program for the Department of Energy's Office of Electricity Delivery and Energy Reliability. The program is focused on developing advanced electric energy-storage devices (batteries, flywheels, electrochemical capacitors, etc.), power conditioning systems, and controls—all of which are integrated into utility-scale storage systems. Both in-house and field testing are conducted in collaboration with partner utilities to evaluate performance under a variety of conditions.

Compressed Air

Another way to store the energy from intermittent resources is to transform it from electrons into mechanical energy. During off-peak hours compressors use the power generated by a wind turbine or a dish-Stirling system to pump air into underground caverns, pressurized to as high as 1,200 psi (compared to 15 psi at sea level). During peak demand hours the compressed air can then be used to make electricity generators more efficient. Sandia is a major participant in the Iowa Stored Energy Park, which includes more than 100 municipal utilities in Iowa, Minnesota, and the Dakotas. Together, they account for a nominal 268–13,400 MW per hour of compressed air energy storage with a 50-hour storage capacity. When the wind is blowing, the Iowa facility will harness energy from wind farms; at times of calm it will use compressed air from an underground cavern. The process can achieve savings as high as $5M annually for each participating municipality.

Sandia researchers are now studying core samples from Iowa to make sure the rock cavern is airtight. We are analyzing the geologic, hydrologic, and rock physics using geomechanics to design the Iowa underground air storage cavern, thereby determining how much pressure is needed and whether too much is leaking.

Geothermal

Drill Bits

Our most significant contribution was our research into developing the polycrystalline diamond compact (PDC) drill bit. Sandia researchers conducted the finite-element modeling analyses, diamond bonding research, cutter testing, bit design/ analysis, and laboratory and field testing with industry partners. Sandia's PDC bits now drill over 60% of borehole footage world wide—a $1.5B industry where the bits also *save* the industry billions annually because of the extended life of the each bit.

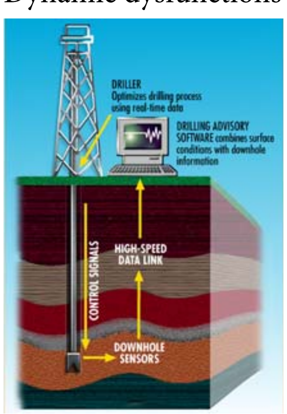
Telemetry, Electronics, and Diagnostics

One of the most difficult elements of drilling is knowing what is happening at the point where the bit is cutting the borehole—hundreds or thousands of feet below the surface. Mud is pumped into the borehole to stabilize the drill string (the pipe that drives the bit). For some time, the industry has used pulses in that mud to act as a conduit for data—at a rate of 2–5 bits per second. Sandia worked to understand the basic physics of wave propagation through the drill pipe and then to develop the engineering and applications codes to devise an acoustic telemetry system that has increased the data transmission rate ten-fold (20–50 bits per second).

By definition, geothermal drilling is a high-temperature endeavor—problematic for the downhole electronics necessary for drilling, data logging, and monitoring geothermal wells. Sandia has become the *de facto* "UL Labs" for testing high-temperature electronic components as well complete downhole tools, seals, batteries, fiber optics, and sensors. Our geothermal scientists work with all major manufacturers to analyze component and equipment failures and provide solutions. We have developed new tools and fabrication methods based on Sandia's capabilities from the weapons programs and supplied prototypes to industry for manufacture. We recently began a joint industry partnership to develop standards and test high-temperature batteries that the oil and gas and geothermal industries need.

Drilling Dynamics Systems Modeling

Dynamic dysfunctions during drilling are among the leading causes of nonproductive time on a drilling site.



The drill bit, drill string, and the local geology interact in a complex way that can induce a variety of vibration-related problems—resulting in a low rate of penetration and/or bit and tool failure. With a unique software/hardware combination, Sandia developed a drilling dynamics simulator to evaluate arbitrarily long drill strings in a laboratory environment. Once validated, our drilling dynamics simulator will

- identify deficiencies in drill-bit designs and help manufacturers improve bit and tool performance before a company is committed to expensive field drilling,
- validate hardware/software for downhole tools that combat vibration,
- improve the industry's capability for predicting vibrations, and
- develop best practices for mitigating vibration.

Biofuels

Sandia participates and leads a wide variety of biofuel projects. We are partners with Lawrence Berkeley and Lawrence Livermore national laboratories and the University of California in the Joint BioEnergy Institute (JBEI), to develop basic science and technology to create environmentally friendly biofuels using plant biomass and microbes. Our research focuses on the efficient conversion into fuels of lignocellulosic biomass, the planet's most abundant organic material. Lignocellulose is a mixture of complex sugars and lignin, a noncarbohydrate polymer that provides plant cell walls with their strength and structure. By extracting simple fermentable sugars from lignocellulose and producing biofuels from them, we can realize the potential of the most energy-efficient and environmentally sustainable fuel crops.

Dairy wastes not only represent a significant regulatory problem and a growing cost burden for producers, but also an opportunity—as an underutilized energy and nutrient resource. Sandia and its partners are pursuing approaches to achieve affordable and *scalable* productive use of New Mexico dairy waste streams to grow algal biomass as feedstock for biofuel and other coproducts. Focusing on algae production using the nutrient-rich liquid effluent will complement the broader use of solid dairy wastes to produce energy in the form of methane, process heat, and/or electrical power using conventional digestor systems. Algae can provide fast-growing feedstock for renewable transportation fuel that can help reduce greenhouse gas emissions, while adding the environmental benefit of recycling nutrients and reducing the contaminant loading of liquid dairy effluent.

Sandia also hosts a large number of smaller research efforts including

- Microalgal Biodiesel Feedstock Improvement by Metabolic Engineering;
- Development of Efficient, Integrated Cellulosic Biorefineries;
- Enhanced Biomass to Bioenergy: Interconversion through Protein and Metabolic Engineering;
- Enhanced Production of Ethanol from 5-Carbon Sugars;
- Breakdown of Lignocellulose Via Mixed-Microbes; and the
- DARPA JP8 Jet-Fuel Biofuels Project.

Clean Coal Technologies with CO_2 Sequestration

In CO_2 sequestration work, Sandia is developing hybrid membranes to selectively trap CO_2 from power-plant waste streams/flue gasses, and we are trying to mimic natural CO_2 capture processes as an engineered system (i.e., increase reaction speed and efficiency). Sandia participates in CO_2 sequestration research in the areas of geologic characterization (knowing whether a subsurface pocket will securely hold sequestered CO_2), developing persistent monitoring of sequestration sites using seismic methods, and developing a reservoir-coupled process model (a computational code to help determine the nature/utility of a potential sequestration site).

Combustion Research Facility

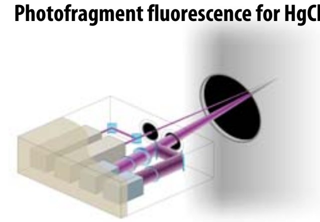
Much of Sandia's research into clean coal technologies takes place at the Combustion Research Facility (CRF) located at Sandia's California site. The CRF is engaged in clean coal research in four specific areas: improving conventional pulverized coal, developing an O_2/CO_2–coal combustion regime, improving gasification-based coal systems, and integrating coal systems with Sandia's hydrogen and carbon-sequestration programs.

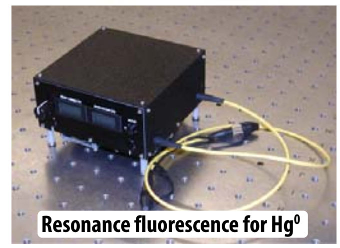
New Coal Combustion Techniques

The DOE Fossil Energy (FE) program and their National Energy Technology Laboratory (NETL) advanced research program are supporting the CRF in improving the coal-fired combustion process with CO_2 captured from the waste stream and reinjected into the boiler. We investigated the effect of O_2 content on coal combustion (and derived the fundamental char combustion kinetics) because oxy-fuel combustion of coal is being actively developed as a technology to facilitate capture and sequestration of the CO_2 formed when coal is burned. In order to effectively capture and sequester the CO_2, it must be of high purity. We achieve this purity by using O_2, instead of air, in the combustion process. This technology promises to improve combustion efficiency and CO_2 sequestration. It can be retrofitted to current power plants, and it is "zero emission." We are utilizing our expertise laser/optical diagnostics and chemical kinetic modeling in this research.

Mercury Control

Photofragment fluorescence for $HgCl_2$





Resonance fluorescence for Hg^0

Pollution-control systems can be effective in removing as much as 90% of the incoming coal's mercury levels in some cases, but in other cases very little mercury is removed. The FE Office manages a program to develop an understanding of mercury emissions, measure the emissions, and devise control technology for these emissions for the U.S. coal-fired electricity generators.

In a FE/NETL project, we are using Sandia's unique talents in laser diagnostics and fiber-optic laser systems to develop an on-line system to detect and then differentiate between elemental mercury and oxidized mercury in boiler flue gas. The two forms of mercury have very different properties and are more effectively trapped by different methods. Our sensor will help power plants detect and differentiate these forms in their flue gas in order to activate the appropriate scrubber techniques.

Water Use

Another area of Sandia research is the use of water in a power plant's cycle. It is not generally understood that power plants use great quantities of water during their generation cycle. In fact, more than 49% of all water withdrawals from underground aquifers in the U.S. are made by electrical power plants. This is a particular problem in Western states—where water is scarce and underground aquifers naturally recharge only very slowly. Our scientists are conducting research into using the waste heat from the power plant to make saline and brackish water usable for cooling purposes. After which, this water could be either reinjected back into the deep aquifer or further purified for other uses.

Our geoscientists and modelers are applying their experience from the Waste Isolation Pilot Plant nuclear repository to the geology near the San Juan Power Station to determine the potential volumes of water that might be available and the geochemistry of deep saline aquifers at three locations near the plant.

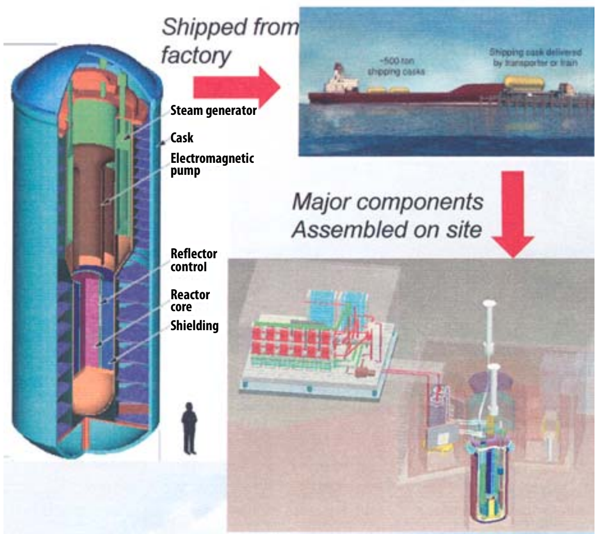
Another project is determining how to efficiently prepare the water for use by the plant. Even though this cooling water need not be "potable," it will require treatment to make it usable. Sandia is developing nanofiltration membranes to desalinate the pumped water to reduce total dissolved solids levels to those appropriate for cooling-tower use and to remove scale-forming contaminants. We are trying to find the solution that minimizes energy consumption in the filtration process to reduce the parasitic losses at the power station.

Nuclear Power

Nuclear power is well established in America and has an exemplary safety record. In addition, the industry has consistently improved its operating efficiency to better than 98%. The 104 nuclear power plants currently operating in 31 states have a combined generating capacity of 100,125 MW of electricity, enough to meet the yearly electricity needs of approximately 62 million Americans. Nuclear power plants account for about 11% of America's total electricity generation capacity, but because they operate at high levels of efficiency and reliability, they produce nearly 20% of the country's annual electricity supply.

Sandia has a long history of working in cooperation with the industry in reducing risks and improving safety at these nuclear power plants. Our large-scale experimental facilities like the sled track where we crashed a defunct F4 Phantom jet fighter into a section of fabricated containment-structure wall to verify the effectiveness of the containment structure. Another facility was used to pressure-test a 1:4-scale model of a prestressed concrete containment vessel that was seven stories high and 35 ft in diameter. During the experimental cycle, Sandia monitored almost 1,500 channels of instrumentation it had installed on the model.

Our current activities include the development of a Right-Sized Reactor (RSR) concept—to develop a small, self-contained reactor design that incorporates intrinsic safeguards, security, and safety. This opens the way for possible exportation of the reactor to developing countries that do not have the infrastructure to support large power sources. This small reactor would produce somewhere in the range of 100–300 MW of thermal power and could supply energy to remote areas and developing countries at lower costs and with a manufacturing turnaround period of two years as opposed to nearly seven years construction time for its larger relatives.



The RSR system is built around a small uranium core, submerged in a tank of liquid sodium. The liquid sodium from the tank is piped through the core to carry the heat away to a heat exchanger also submerged in the tank of sodium. In the Sandia system, the reactor's heat is transferred to a very efficient supercritical CO_2 turbine to produce electricity.

These smaller reactors would be factory built and mass-assembled, with the potential of producing 50 per year. They would all have the same exact design, allowing for rapid licensing and deployment. Mass production will keep costs down, possibly to as low as $250M per unit. Just as Henry Ford revolutionized the automobile industry with mass production of automobiles via an assembly line, the RSR team's concept could revolutionize the nuclear industry.

For further information, please contact Rush Robinett, rdrobin@sandia.gov

SAND2009-xxxxX, July 2009