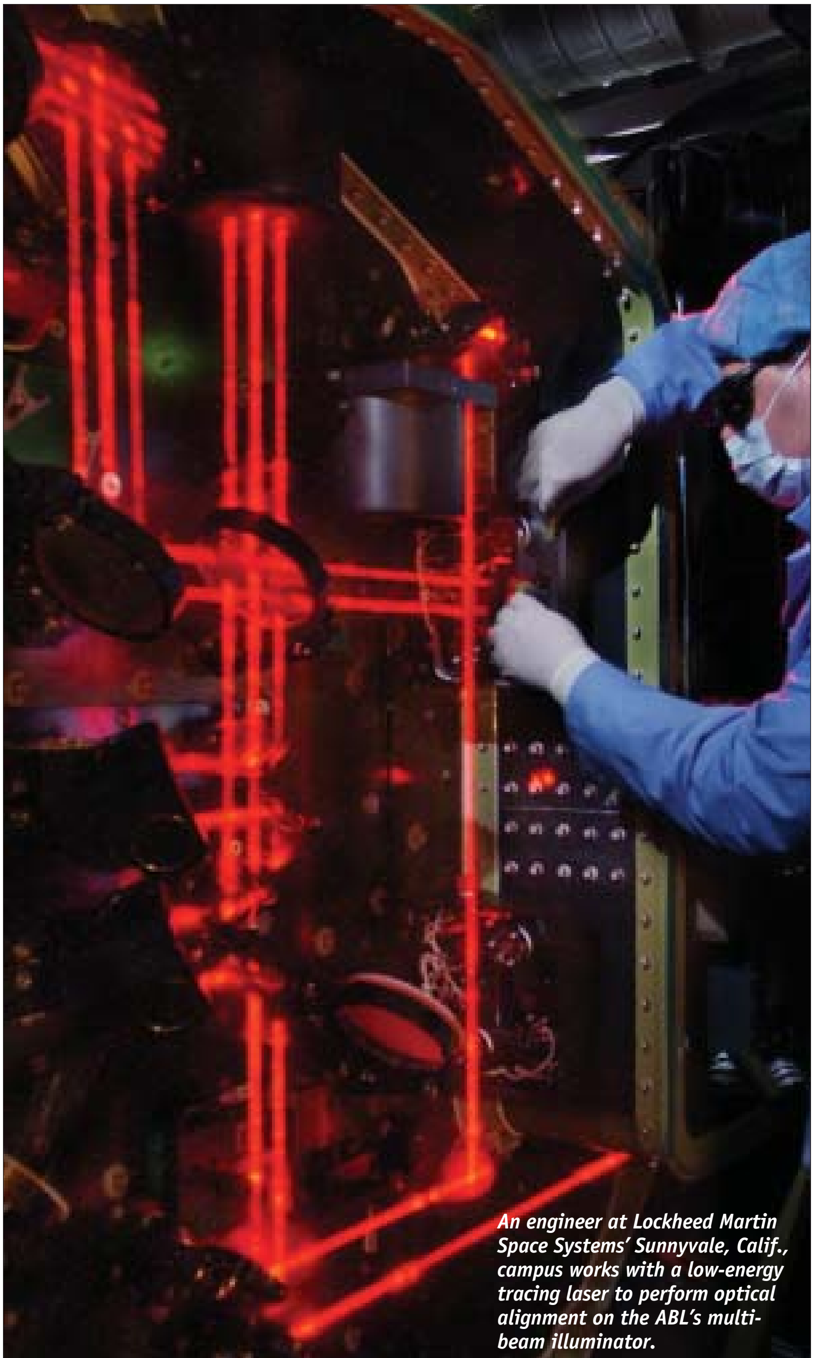
Transforming the battlefield:

The laser's edge



An engineer at Lockheed Martin Space Systems' Sunnyvale, Calif., campus works with a low-energy tracing laser to perform optical alignment on the ABL's multi-beam illuminator.

More than a decade has passed since researchers at Lawrence Livermore Labs set a world record for laser power—more than a quadrillion watts of energy from a device called the Petawatt laser (a petawatt equals one million megawatts). That record shot, on May 23, 1996, exceeded all of the electrical power generating capacity of the U.S. by more than 1,200 times, but was of such short duration—less than a trillionth of a second—that it would have provided only enough power to burn a 100-W lightbulb for 6 seconds.

Today a variety of laser technologies are used for everything from industrial welding to eye surgery to CD and DVD drives. Military lasers guide "smart" weapons to their targets, have led to a new generation of devices for high-quality night vision, can be used for high-speed/high-bandwidth satellite-to-satellite communications, destroy incoming mortar and artillery shells, are the basis of a new "PHASR" (personnel halting and stimulation response) rifle, and are being developed to shoot down ballistic missiles.

The military currently is concentrating on two primary types of lasers—chemical, which are capable of the highest useful power generation (100 kW-1 MW) and are small enough to be packed into an aircraft, and solid-state, which currently generate only about 25 kW but are considerably smaller and have significant logistics advantages. Basically, chemical lasers provide the kind of long-range, high-power beam needed for strategic targets, such as ballistic missiles. Solid-state lasers have tactical application on the battlefield against smaller, less resistant targets.

Controversial ABL

Perhaps the best known—and most controversial—laser weapons program is the Airborne Laser (ABL), funded by the Missile Defense Agency and being built by Team ABL: Boeing Missile Defense Systems, responsible for program management, modification of a 747-400 freighter aircraft, systems integration, and the

Laser technology has advanced far faster, and found a greater number of applications, than its earliest developers could have imagined. Its many civilian uses today range from eye surgery to welding to compact discs to DVD players. As new systems such as the Airborne Laser and others are demonstrated, military planners are taking a second look at the myriad ways in which laser weaponry will be transforming the battlefield.

battle management system; Northrop Grumman Space Technologies, building the laser systems; and Lockheed Martin Space Systems, which is responsible for the target acquisition and beam control systems.

"We're having to prove a lot of things for the first time," MDA's ABL program director, Col. John Daniels (USAF), tells *Aerospace America*. "The targets are unique and the test processes and conops [concept of operations] are new ground—not just the technical challenges, but all the things involved with testing a high-energy weapon from an airborne platform.

"I would classify all these as normal development challenges on an extremely complex, complicated system. We have an airplane with a lot of hardware on board, and as we continue to add components—such as the track and beacon illuminator lasers—you encounter normal hardware/software integration issues."

Daniels also says the program suffers from misconceptions about laser technology in general and its ABL applications in particular, from being able to shoot targets through inclement weather, to counteracting a laser beam with a shiny surface on the target missile, to being overwhelmed by multiple launches, even if most are decoys.

"We orbit at a pretty high altitude, above the tops of clouds, above the weather, and we normally shoot up, above the horizon where we are orbiting. Ballistic missiles burn for several seconds at that altitude, above the clouds. The shot altitude may vary a lot between a medium and long-range missile, but we can engage up to a substantial altitude," he notes. "I can't really discuss specific countermeasures or how effective they might be; I can say we have an active program looking at countermeasures and are addressing those we need to address.

In 1966 the Petawatt laser reached more than a petawatt (a quadrillion watts) of peak power, although it lasted less than a trillionth of a second.

"In terms of a salvo launch, we need capability that a speed-of-light weapon will provide. I can't be specific, but we can track multiple missiles with our infrared search-and-track sensors; once we negate one missile, we can slew the turret and negate a second target."

Aircraft and support systems

While the plan is to modify the 747 for airborne refueling, the chemicals used by the laser do have a "shelf life," and the aircraft will need to land to replenish them at some point. How the needed chemicals will be taken to airfields des-

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ignated for that effort—and where those airfields might be—is still being worked out.

Meanwhile, the prototype aircraft and its laser and control systems continue to move forward, starting with "first light" from the laser (on the ground in an aircraft mockup), then on to flight-testing the aircraft itself with a new 6-ton nose, to incorporating the kill laser's support systems.

"The aircraft has been fitted with the full beam control/fire control system, and the beam-and-track illuminator lasers are installed, and all preparations for the high-energy laser are completed," says Boeing vice president and ABL program director Greg Hyslop. "We will measure active track and atmospheric compensation in early 2007, then begin installation of the high-energy laser at Edwards and go through a test buildup of activation and generation of light on the ground, working up to a lethal demonstration against an actual boosting missile in 2008.

"The program has been retiring risk, attacking and solving technology problems as they have arisen through these various phases. But the next couple of years will be the most difficult as we bring more and more functionality into the system. The last two years of a development program are always the hardest."

Enabling technologies and challenges

Hyslop says ABL comprises a number of enabling technologies, from the chemical oxygen-iodine laser (COIL) and demonstrating it was capable of long-duration runs at lethal levels to the resonator that forms and shapes the beam to the proper timing and mixture of chemicals and the efficient generation of photons to point and jitter control (all of which are passively cooled) to the safe operation of a high-energy laser inside an aircraft.

The ABL will reside in the nose of a modified Boeing 747-400.

"To get to the long-duration runs with the high-energy laser, we had to overcome a number of challenges in terms of how the optical system performed and the control systems for those optics. In terms of the chemical systems, each for the high-energy laser is brought on one at a time, and we had to work through a number of problems as we did that. Once they were brought on line, they stayed up and remained tuned," Hyslop says.

"For the beam control system, [the focus] really has been integrating the hardware and software to enable it to perform so you can measure in flight how stable the system is, which tells you how to mitigate jitter in flight. Out of last year's flight tests, we got very good correlation between the sources of vibration and the actions taken with hardware and software; hopefully we have brought it down to a level needed for a lethal demonstration, and if not, what will be needed to do that. So far, the data have shown us what to do to attack any source of vibration."

How it works

The ABL will begin with passive detection of a boosting missile's plume as it breaks above any cloud cover; then a nested set of sensors will provide an ever-narrowing field of view and finer resolution.

"That series of handoffs is the problem. You fire the track illuminator once you have a very tight lock, then measure the return to get a good state vector for the target, walking the track laser up to the nose of the missile, then back down to where the rocket's fuel is located," Hyslop explains. "Doing that from many miles away is difficult. We have good simulation that tells us how the tracker works and good models of boosting missiles we can use. We also have models of aircraft motion.

"Now we have to go out and collect real flight data, tracking a simulated missile signal using a plume generator on a 'Big Crow' aircraft, which has a white missile body painted on the side and a number of heat lamps simulating the plume. The side of the aircraft has sensors to pick up where we illuminate it with our tracking lasers, so we can score how we are doing. That will give us the ability to have a repeatable, measured engagement, where we know what we are putting out and what Big Crow should be seeing; then we can anchor our models based on that."

While one smaller, solid-state laser is tracking the missile, a second is dealing with how atmospheric conditions will affect the high-energy kill beam between the ABL and its target.

"Think of the wavefront of the laser as a sheet of paper; the atmosphere would crumple the paper by the time it hits the missile. You want to measure that, so the beam actually leaves the airplane crumpled and, when it hits the missile body, it is flat and focused again," Hyslop explains. "The beacon illuminator is close to the same wavelength as the high-energy beam, but much lower power. So you illuminate with the beacon, measure the return to get the deformation along that optical path, then a series of deformable mirrors uses that information to defocus the high-energy beam before it leaves the airplane. Once the loops converge, you can fire the high-energy laser.

"To actually go through that engagement sequence requires only a few seconds; the kill time depends on the range to the missile. It is all automated, with no operator intervention—other than the ability to break off if there is a problem. And it can move very quickly (from one target to the next). How many missiles are in the air also is a factor and you may run out of time, which is why you have a multilayer system. A boost effort will take care of a lot of the threat and make it easier for the next layer; being airborne and operating at the speed of light, it can do very well against a salvo."

Skyguard

Northrop Grumman also is pursuing the application of ground-based high-energy chemical lasers through programs such as Skyguard, which was introduced in July 2006 to defend fixed areas, like air bases or cities, against rockets, artillery, and mortars.

"It uses a chemical laser in the megawatt class (the actual power level is classified), based on our Tactical High Energy Laser [THEL] program, which we finished testing at White Sands in 2005, shooting down 46 rockets, mortars, and artillery shells—100%," says Mike McVey, VP of Northrop Grumman Directed Energy Systems. "We improved that technology to create Skyguard, which we are making available both to the U.S. government and internationally."

He says a chemical laser was used because that technology is mature and because a complete Skyguard system could be built and installed within 18 months; by contrast, it will be at least three years before solid-state technology approaches the necessary power output. In addition, solid-state lasers are roughly 15% efficient—it takes nearly a megawatt of power to produce a 100-kW beam. And although chemical lasers are larger to begin with, their power output can be increased with comparatively little increase in system size.

"We could put a Skyguard in Washington, D.C., to protect the entire city from any kind of asymmetric threat, such as a short-range missile fired from a barge, or the airports from shoulder-launched rockets. We are studying that application with DHS," McVey says. "Because cities don't move, the chemical supply isn't a problem. But armies do move. So for a fixed site, chemical is pretty attractive; but the solid state is more attractive if you need mobility."

During THEL testing, which finished in 2005, 46 rockets, mortars, and artillery shells were shot down.

Changing minds

No Skyguard systems had been sold by the end of 2006, but McVey says the battles Israel fought with Hezbollah in southern Lebanon that year changed a lot of minds about whether air and even ground forces alone could defeat hidden or mobile rocket launchers.

"Chemical lasers could and should have been operationalized some time ago. The damage in the Israeli-Lebanon conflict might have been negligible if we had set up a Skyguard. We had the technology to shoot down everything that was fired in that conflict, but neither the U.S. nor Israel did so," he says, noting it was a decision based on what was known and believed at the time.

"Before the recent attacks, the threat seemed to be declining. Second—and this belief exists in the U.S. as well—there is a belief we can solve the problem with air power, we can shoot the shooter; Lebanon proved that wasn't true. [Skyguard] is an expensive system to bring into operation, and you have to make priority calls based on the threats you have. Now it is seen as a problem they need to solve."

McVey compares the adoption of laser weapons to the hurdles that have always faced any new technology, from the long bow to airplanes to radar to UAVs.

"We are just beginning to open our eyes at every level—industrial, medical, military—in terms of lasers. We are at the sunrise point of this technology wave. And when we put these tools in the hands of soldiers, as when we put them in the hands of doctors, they will find new and innovative ways of using them," he says. "And when the power levels get higher, I believe the day will come when laser rifles exist; you never run out of bullets, you can go from nonlethal to lethal. It will change the battlefield as dramatically as did the introduction of gun powder."

Transforming warfare

While the chemical laser may always be the best at producing the highest power beams from a system small enough to be useful, efforts are being made to raise the solid-state laser at least into the 100-kW range. One such is the Army Space and Missile Defense Command's Joint High-Power Solid-State Laser (JHPSSL) program. In early 2006, the Army awarded competitive contracts to Northrop Grumman Space Technology and Textron Systems to develop "military-grade" solid-state technology that would enable high-energy laser systems aboard ships and air and ground vehicles to defend against incoming threats. A decision on which system to pursue is expected in 2008-2009.

Lockheed Martin, while not a producer of laser devices, looks to take its ABL role into other military laser programs as they evolve, "marrying those with systems engineering and beam control to turn them into weapons for the warfighter," according to Doug Graham, vice president of advanced programs.

"The Army has an RFP out now for a beam control technology developer and system integrator to partner up with the JHPSSL device, while the laser is being developed, then roll it all under a system integration contract in 2009."

The company also is providing beam control technology and systems integration in a partnership with General Atomics on a DARPA program to develop a high-energy liquid laser area defense system. Graham says that program hopes to develop a 150-kW laser by 2008-2009.

"They are liquid from the perspective of having fluids in the cavity, but are solid state. They are much more compact and so could be put on a tactical platform, from aircraft to wheeled vehicles. The good news about being compact is fitting on a small platform, but you also are generating a lot of heat that needs to be dealt with. So some designs have a fluid inside the cavity for active cooling of the laser while it is operating," he says, adding the advances being made in laser technology, across the board, support it as an increasingly important part of the ongoing transformation of the military.

"If you look at the progress that has been made, there is good reason to believe solid-state lasers will achieve their objectives in the next two or three years. Once that happens, we will have the initial group of the next generation of weapons systems, where you can't use kinetic weapons. In southern Lebanon and northern Israel, for example, the only viable technology to deal with that kind of threat is a directed-energy weapon. So once this technology is matured and we can show the warfighters it can be packaged in a way to be operationally suitable to them, there will be an enormous market for even the first generation."

Northrop Grumman's McVey concurs. "I really think laser weapons will completely transform the battlefield. On aircraft at low power, to take out radar sites and power lines with great precision, I can hit something the size of a fist at 10 km. So aircraft could use it for air-to-ground or, with greater power, to take out missile sites and protect themselves against air-to-air missiles, which essentially would make the aircraft immune to ground-to-air and air-to-air missiles. The Navy also can use it to deter small boat or jet ski attacks at the small end all the way up to missile defense," he says.

"Solid-state lasers bring you nonlethal to lethal capability and a bottomless magazine—it will keep shooting as long as you have electricity, unlike current ship or aircraft defenses or attack systems requiring missiles, bullets, or

Educating tomorrow's workforce

Roy Hamil, technical director of the Laser Division at AFRL's Directed Energy Directorate, says there is another looming problem that is impacting the national labs, universities, industry, and the military—and ultimately could cost the U.S. any chance of maintaining a technology lead in lasers, among other things.

"Nationwide, our technical workforce is aging, and we have to think very carefully about what we are going to do to abate that problem," he says. "Foreign students [filling U.S. university classrooms] are one thing, but American students don't seem to be going into the technical disciplines in the numbers they used to, back when the space program was so hot in the 1960s. Our problem isn't unique, but it is necessary for us to have people who also satisfy the requirements for security clearances, which is very difficult to do with foreign students or employees."

To address that on a small scale, AFRL has begun a program with the University of New Mexico and New Mexico Tech to use their graduate students in research programs that will help them qualify for PhDs. That program is capable of handling a maximum of only eight students at a time, however, so more such efforts are needed nationwide, involving many government labs, industry, and academia, Hamil adds; but an interest in the hard sciences, which require a lot of work to master for far less monetary reward than other careers, first must be fostered among the very young.

"Children today are trained from the earliest ages by cartoons on TV that depict the engineer or scientist as someone who isn't quite normal or able to fend for himself. There is always a hero who takes whatever idea is generated by the scientist and saves the day. Children, I think, adopt that mindset. They don't want to be the guy sitting in the corner; they want to be the hero. You can't have that image painted from the earliest days and then expect them to transition to going into a technical field in later life," he says.

"The level of math and science education in elementary and secondary schools is improving, but there is still a lot of room for improvement. Today those classes are electives rather than mandatory, as they once were. So you end up with a populace that not only doesn't go into technical fields, but has problems making decisions in our technical society. People need to be talking about this problem, because it could have profound implications in the future—not just in lasers, but in a general sense."

bombs. Solid-state lasers also are pennies per kill, compared to hundreds of thousands up to millions of dollars per missile. Lasers also have one-fourth the life-cycle cost: You don't have to maintain it—it's not mechanical, so it doesn't break down, and it doesn't need depot resupply. So both on the ground for the Army, in the air for the Air Force or at sea for the Navy, it will be much better than the systems they have today."

Air Force research

The Air Force Research Lab's Directed Energy Directorate at Kirtland AFB is looking at four areas of laser research: chemical, such as the directorate-invented COIL used on the ABL; solid state, including the growing area of fiber lasers; low-energy applications, such as medical; and effects experiments, looking at the lethality of lasers on a variety of targets and materials.

"COIL uses chemicals to transfer energy from excited oxygen to iodine, then lases the iodine. Recently we've looked at how large and efficient such a system can be in a military sense and found it has troubles on the logistics trail from the amount of chemicals used, which are not normally found in the military inventory, so we also are looking at an electrically pumped oxy-iodine laser," says Roy Hamil, AFRL Laser Division technical director. "That has been lased within the last couple of years, and there is some promise there, although that is still in its infancy. In the gas laser area, we also are interested in the alkaline metals—cesium and rubidium—which have the potential for 80% electrical efficiency.

"In solid state, fiber lasers are beginning to show great promise. Several companies have shown near-diffraction-limited output on the order of 3 kW with 20-25% efficiency out of a single fiber. We're looking at coherently phasing a number of fibers together to get into the 100-kW regime. At the lab, we are building a test bed with 16 arms of 200 W each to demonstrate phasing together."

Competition from abroad

As the military continues evolving toward a lighter, faster, modular force operating in a network-centric, integrated battlespace, lasers are being seen as potentially crucial to all phases of communications—ground, air, and space. But while many see lasercom as a mandatory development for future U.S. military dominance, some fear the country is falling behind international competitors in pursuing it—despite its technological maturity.

"There is no science involved in lasercom anymore—it is purely engineering," asserts Dave Begley, director of technology and business development at Ball Aerospace & Technologies in Boulder, Colo. "We can put a system together, fly it, and make it work, with proper funding. We have demonstrated all the key elements—high bandwidth, GEO backbone, user access to that backbone, and user terminals.

"It is a constant push and pull with Congress, showing the technology is really ready for primetime. There are still steps we need to go through to make certain we have all the technology bases covered, but there are no technology roadblocks. What we need is a demonstration of the technology with operational performance capability, so after you demonstrate it, you can use those same assets for an operational scenario. We need to do that with U.S. industry-generated and -produced hardware.

"Experiments done by national labs provide the kick, the proof of principle; but a government-funded, industry-based demonstration of the technology with residual operational value is the real key to going forward."

The French and Japanese have conducted space-based tests the U.S. has yet to emulate, Begley adds, despite lab tests showing the base and performance technologies could exceed what those countries did—if industry gets the funding needed to launch its systems into orbit.

"Once we've done that, we'll be able to provide communications services to the users, the LEO and airborne platforms, that will surpass anything anybody has ever imagined and really break the bandwidth constraint for the warfighter and decision-makers," he insists. "In terms of lasercom, we can send 40 times the content of the *Encyclopedia Britannica* in 1 sec. So we have the capability—we just have to get it into space.

"The labs do a great job of technology advancement, but there is a problem in efficiently and effectively transferring that knowledge to the industry base to leverage and provide services to the government. The labs' charter is to push technology, to be the pointy end of the spear, but it takes industry to bring that technology to an operational system."

A technician at Northrop Grumman Space Technology checks diagnostic instruments used to monitor IR laser beams fired by a laboratory demonstrator for the JHPSSL program.