MISSION IGNIT

An advanced nuclear-fuel capsule offers a new shot at a functional solar core here on Earth.


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NUCLEAR FUSION HAPPENS EFFORTLESSLY, even inevitably, at the temperature and density conditions found at the core of the sun. To make it work on Earth, however, something akin to an artificial solar core—except even hotter and denser than the real one—would have to be replicated here. But that's not the hardest part.

To make fusion into a power source, the artificial solar core would need to be contained rather than allowed to explode (as in a thermonuclear bomb). The sun accomplishes that containment via the gravity of its 2000 trillion trillion metric tons worth of mass. Fusion scientists on Earth have to figure out another way. But that's not the hardest part either.

The hardest part, which humanity has yet to overcome in its quest for clean and abundant power, is doing those things—creating and containing an artificial solar core—without consuming more energy in the process (or losing it along the way) than is generated by the fusion itself. Achieving that—getting more energy out than what was put in—is called ignition. Yet after nearly seven decades of fusion-science research and development, ignition remains a fairly distant hope, perhaps requiring a massive expansion, redesign, and replacement of the world's already-extravagant fusion research facilities.

Or might there be another way?

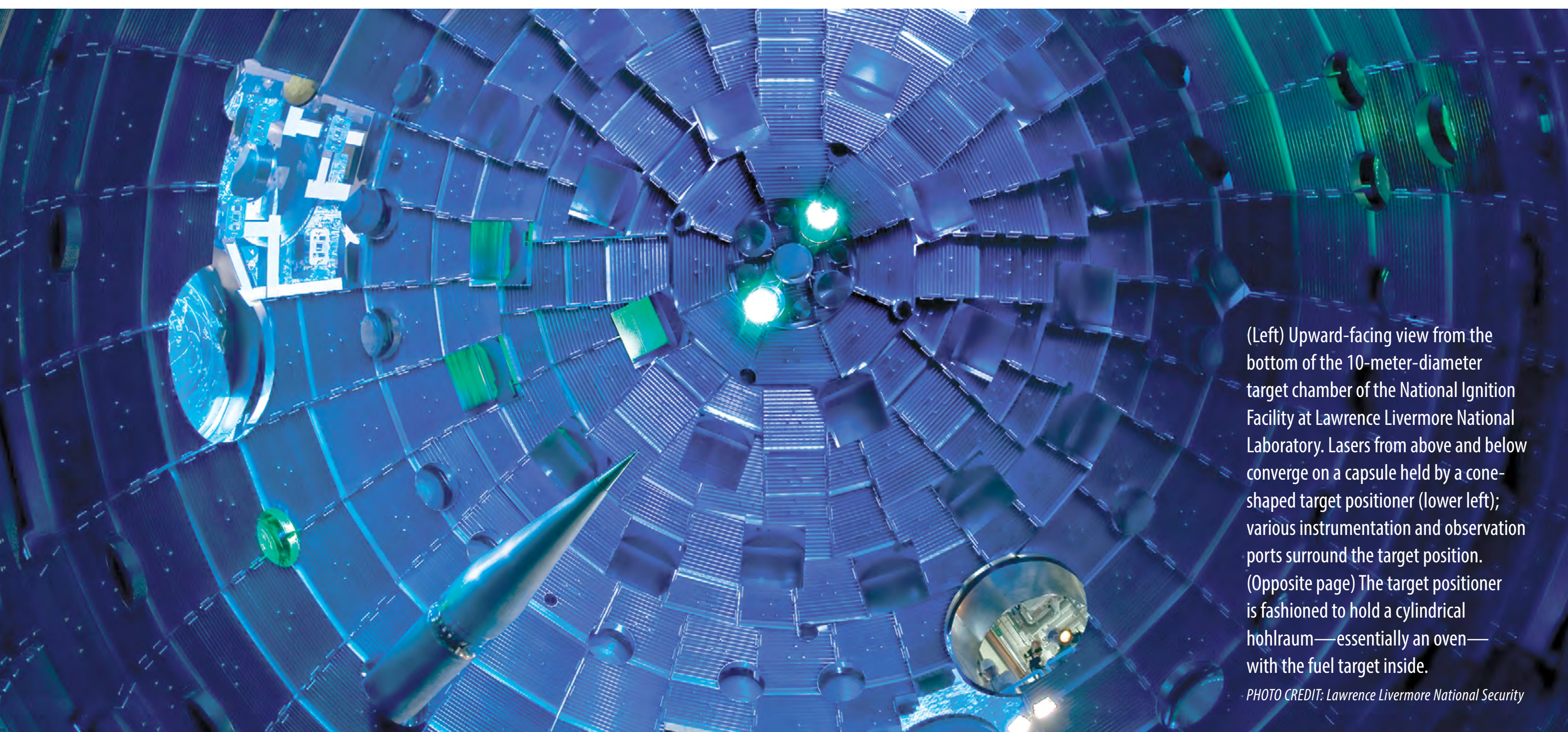
Moment in the sun

History has shown that fusion-based power is much more difficult to achieve than earlier predictions held it to be. Year after year, new design after new design, and dollar after dollar, fusion power—or even self-sustaining fusion for research purposes without all the attributes of a practical power source—has remained unattainable. Earlier in this decade, a campaign intended to cross that threshold once and for all at the National Ignition Facility (NIF)—which is exactly what it sounds like: a national facility designed, built, and operated primarily for the purpose of achieving ignition—came up short. NIF, and the undeniably brilliant concept behind it, apparently fell victim to the same deceptive difficulty that the quest for fusion has encountered time and again.

"It's discouraging, no question," says Los Alamos scientist Mark Schmitt, "but it would be a mistake to assume that means it can't be done." Schmitt and colleague Kim Molvig, both plasma physicists, along with their small team of scientists, are working hard to bring about a new twist on a NIF experiment, designed to avoid the shortcomings of previous tries. They call the concept "Revolver," a name handed down from earlier work at Los Alamos. "With Revolver, we are taking an unconventional tack—one that predicts the generation of a modest energy gain but is more robust against failure. It's an approach that might work."

At the same time, both Schmitt and Molvig are flirting with the increasingly nebulous number known as retirement age. NIF itself, in a way, is similarly flirting with—well, certainly not retirement, but diversifying its research portfolio away from a singular focus on ignition. For both the men and the machine, Revolver offers something worth holding out for: the hope of finally transcending the ignition barrier.

NIF lives at Lawrence Livermore National Laboratory in Livermore, California. A major research facility and a significant investment, NIF looks a lot like Professor X's "Cerebro" machine from the *X-men* comics and movies: a large hollow sphere with metal walls. Instrumentation located around the "equator" of the sphere keeps watch on a millimeter-scale fuel capsule at its center, where 192 ultraviolet lasers originating



(Left) Upward-facing view from the bottom of the 10-meter-diameter target chamber of the National Ignition Facility at Lawrence Livermore National Laboratory. Lasers from above and below converge on a capsule held by a cone-shaped target positioner (lower left); various instrumentation and observation ports surround the target position. (Opposite page) The target positioner is fashioned to hold a cylindrical hohlraum—essentially an oven—with the fuel target inside.

PHOTO CREDIT: Lawrence Livermore National Security near the sphere's "poles" converge. The laser energy—and this is the most energetic laser facility anywhere in the world—heats and implodes the fuel capsule so that the tiny ball of fusion-capable hydrogen isotopes at its center skyrockets to above-solar-core conditions.

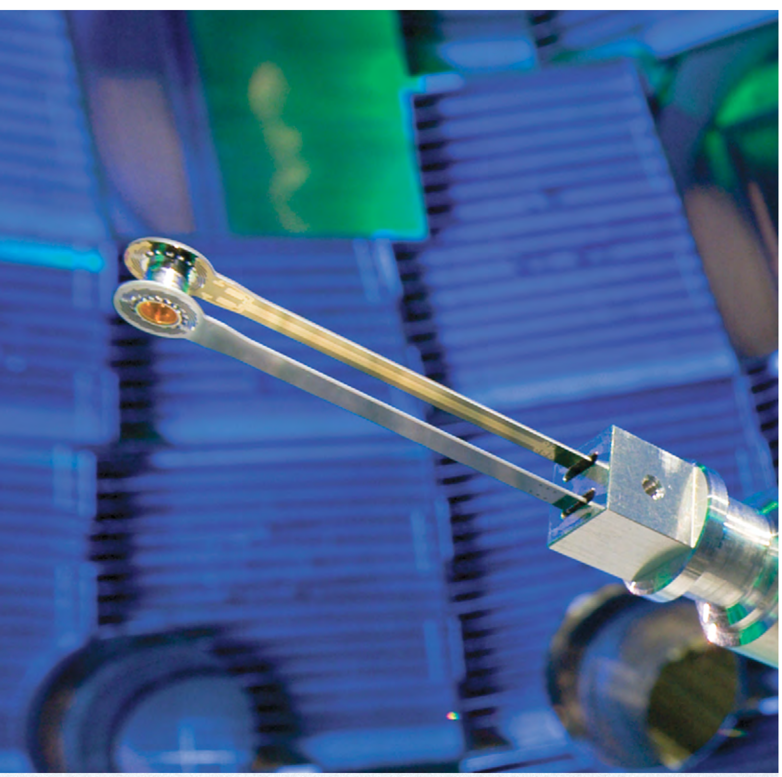
At that point, positively charged hydrogen nuclei are zipping around so rapidly and in such close proximity to each other that they slam into one another despite their mutual positive-positive electrical repulsion. They merge to produce helium nuclei and other particles with enough energy to spawn a tremendous release of heat. That heat is the point of the whole thing—heat to drive a steam turbine and electrical generator, for example. But so far, there's just not enough of it. Too much is escaping, and too few fusions are producing it in the first place.

THIS WAS ALWAYS GOING TO BE A LONG GAME.
BUT IT'S AN INCREDIBLY WORTHWHILE GAME.

Broken symmetry

Oddly, the trouble does not reside in the wildly complicated and ingeniously engineered NIF system itself. The chamber, the ultrapowerful and finely controlled lasers, and the operating procedures are all essentially flawless. By all accounts, the trouble seems to lie within the millimeter-scale pocket of nuclear fuel.

Fusion fuel is a mixture of deuterium and tritium, both rare isotopes of hydrogen. In conventional fuel capsules, the deuterium-tritium (DT) mix is encased in a spherical shell of solid material. The capsule is loaded into a small hollow cylinder known as a hohlraum that acts like an oven: when NIF's lasers enter through small holes at its top and bottom, they bounce around the inside and produce tremendous heat. The hohlraum's interior walls become hot enough to release x-rays, which cook the outer shell of the spherical fuel capsule and cause it to blast away, or "ablate," like a million tiny rocket ships launching from the fuel capsule in every direction. The recoil from the ablation produces an implosion, rapidly compressing and heating the DT fuel to spark fusion.



It might sound straightforward, and it basically works, but the compressed core where fusion occurs is utterly minuscule, and controlling the tiny but massively energetic implosion to get the core just right is both critically important and extraordinarily difficult. The DT mixture, initially arranged as a solid shell surrounding a vapor pocket, acts as both the fuel and, a little farther out, the agent that compresses the fuel. It must squeeze down to produce a 10,000-fold increase in density of the solid-fuel shell and a "hot spot" initiation region that grows with enough stability to achieve ignition. To do that, it needs particularly high temperatures and implosion speeds that produce a sophisticated convergence of shock waves, all of which has proven prohibitively difficult to control. Achieving the symmetry required for this method is what the hohlraum was intended to accomplish, but it introduces other variables and complications, and it has not performed as hoped.

If, with all this in the mix, the resulting compressed core shape isn't sufficiently spherical and uniform—if it becomes stretched or lopsided—then the fusion "burn" will be inadequate. If the core dissipates too quickly or just gets a little too thin somewhere, then the reaction will fizzle as energetic particles stream out through that thin patch. If the implosion isn't clean and ends up mixing vaporized shell material into the DT fuel, the fuel will become too cold and dilute. The core must maintain a uniform profile and spherical symmetry with minimal mixing for a long enough time to generate the required fusion energy. So far, the human race has been unable to make this happen.

What goes wrong? Most likely, it begins with minute imperfections in the fuel capsule and the uniformity of its implosive drive. A tiny bit thinner here or higher pressure there, and the implosion becomes slightly asymmetrical; as it progresses, the asymmetry grows and mixing renders the fuel less pure and not hot enough to burn. Despite the 192 exquisitely coordinated lasers and the apparent simplicity of the fuel-capsule design—fuel inside an ablator shell—the core still gets messy, and ignition remains out of reach.

Schmitt and Molvig decided to address the problem by reconceptualizing the fuel capsule.

"Instead of using a fuel capsule that looks simple but is actually quite complex in function," Molvig explains, "we are proposing one that looks more complex but is functionally much simpler."

Neatly pressed and wrinkle-free

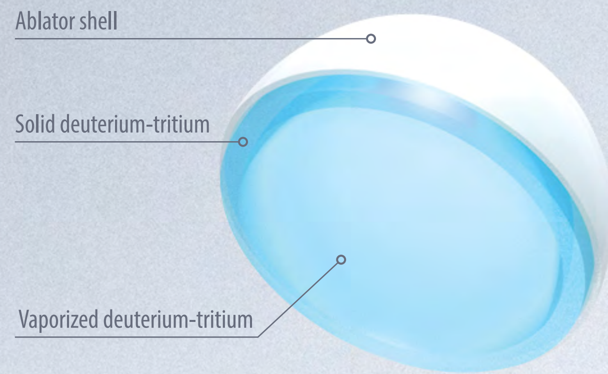
Schmitt and Molvig designed the Revolver fuel capsule to be an onion-like series of concentric spherical shells with the DT fuel at the center. The outermost shell, made of low-density beryllium metal, is the ablator. It starts the recoil implosion when laser heating ejects a fraction of its mass outward as ionized plasma; the beryllium not ejected accelerates quickly inward. Because of imperfections in the laser drive and material properties, asymmetries that look like wrinkles in the imploding shell develop and expand until they reach a copper layer surrounded by plastic. The plastic smooths the irregularities until their impact on the pressure variations impinging upon the copper shell is largely erased, and the copper shell's original spherical symmetry causes any residual wrinkles to restart their growth from small perturbations.

Now the copper carries the pressure kick inward, but with a higher density than the beryllium, forming an impulsive hammer to quickly strike the innermost metal shell, made of tungsten, which is denser still and extremely strong. Asymmetries reemerge along the way but are once again muted by a cushioning layer of plastic, this time surrounding the tungsten shell. That shell encapsulates the DT fuel and compresses it with adequate spherical symmetry for fusion to emerge and grow to ignition.

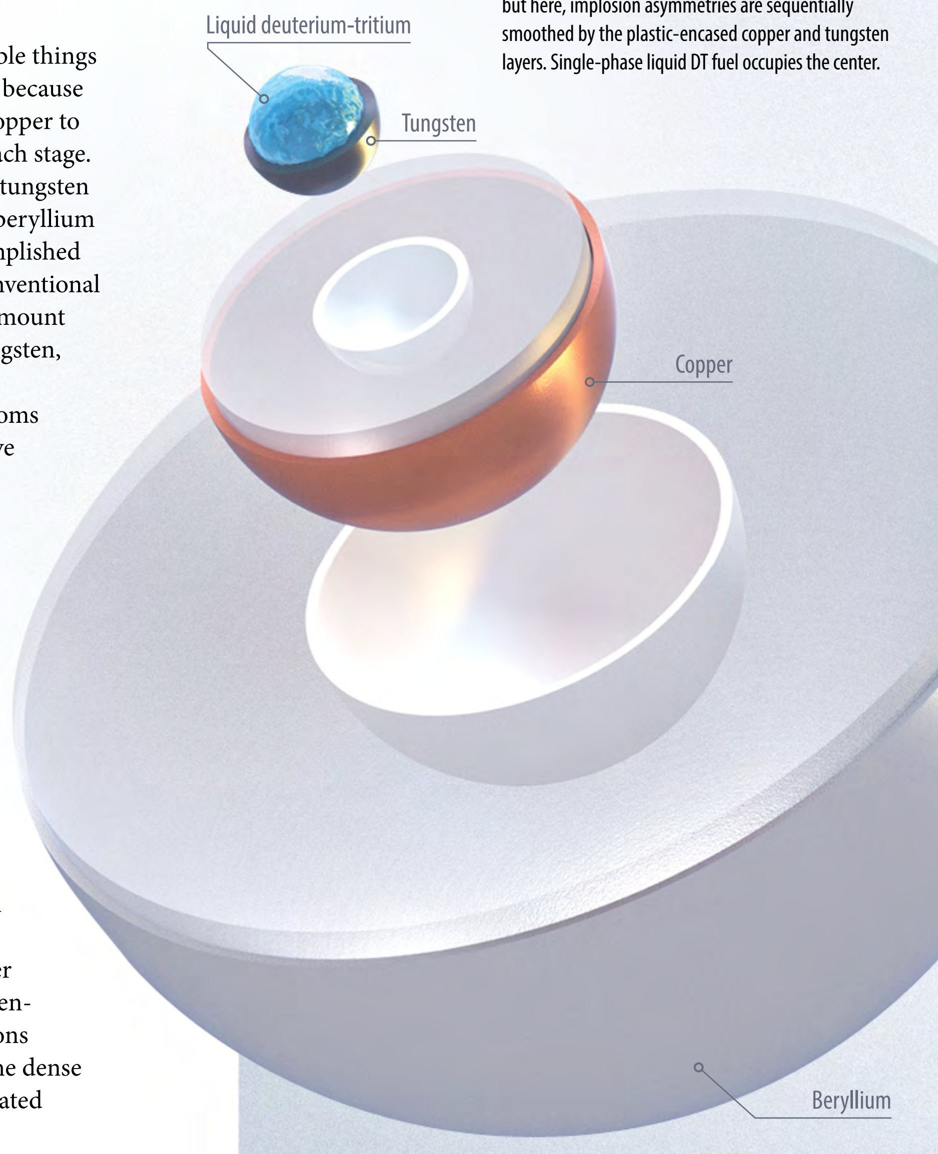
At each plastic-encased metal layer, two valuable things happen. Extant asymmetries are smoothed out, and because the metals get progressively denser—beryllium to copper to tungsten—the implosion's pressure is amplified at each stage. The net effect is a factor-of-100 amplification in the tungsten shell's pressure on the DT fuel relative to the initial beryllium ablation. This manner of pressure gain can be accomplished with a slower fuel-implosion speed than that of a conventional target. That slower speed dramatically reduces the amount of mixing between the fuel and the surrounding tungsten, keeping the fuel purity high.

Crucially, this approach also means that the atoms in the tungsten shell, though rapidly vaporized, move inward as a monolithic envelope. They contain the nuclear core so that the fusion-generated heat and radiation remain in play for a relatively long time—supplying energy to spawn successive fusion reactions rather than leaking away and taking their energy with them. Consequently, solar-core conditions are maintained over a sustained burn with minimal losses in a way never before seen in any other target design. In the end, about half the fuel fuses before the energy buildup explodes the core, as contrasted with only 10 or 15 percent for a conventional target.

With these sustained, symmetrical burns, other difficult-to-manage conditions can be relaxed a bit. For example, the diameter of the fuel only needs to converge by a factor of nine, which is easier to keep tidy than the factor of 34 needed for a conventional NIF target. Lower-temperature burn conditions are also feasible, using less total fuel. And because the dense tungsten is so effective at trapping the fusion-generated



(Above) Inside the containment shell of a conventional NIF target is a cryogenically maintained mixture of solid and vaporized deuterium-tritium (DT) fuel, with the solid along the interior wall of the shell and the vapor in the cavity at the center. That capsule is placed inside a hohlraum for oven-style heating.



(Below) The new direct-drive design doesn't use a hohlraum. Lasers converge directly on an outer surface of beryllium metal. Like the conventional design, the outer layer's ablation drives the capsule's implosion, but here, implosion asymmetries are sequentially smoothed by the plastic-encased copper and tungsten layers. Single-phase liquid DT fuel occupies the center.

radiation to avoid energy losses—as contrasted with the conventional design, in which the very lightweight DT fuel must stand in, rather less effectually, as its own containment envelope—high implosion speeds and their concomitant mixing problems can be reduced.

But perhaps the biggest benefit is this: because of these reduced fuel-implosion requirements and the fact that the outer capsule radius is large, the energy needed to produce the requisite pressure drive at its surface drops from the level of hohlraum-generated x-rays down to what can be obtained from a brief ultraviolet laser pulse striking the surface of the fuel capsule directly. This "direct-drive" laser intensity can be relatively low, effectively eliminating pernicious laser-plasma instabilities that can rob a conventional target of energy and induce gross asymmetries in its implosion. Yet even with reduced intensity, seven times more laser energy can be deposited into the outer shell because none of it is wasted heating the hohlraum itself.

SO WHAT IF IT WORKS IN SIMULATIONS? AFTER ALL, ON PAPER, **EVERYTHING ELSE WAS SUPPOSED TO WORK TOO.**

Deep inside, as a result of direct laser-energy deposition and subsequent shell smoothing, the DT fuel rapidly reaches peak convergence and then lingers in a stable burn for three to four times longer than in a conventional target. Ultimately, the brief laser pulse is converted to a single, sharp pressure pulse on the innermost metal shell, generating a clean, enduring, spherical fusion zone. At least, that's the expectation.

Say yay or nay?

Still, with something as notoriously elusive as ignition, every new proposal invites skepticism. So, what specifically do the naysayers say when they say nay?

Some say that direct drive is a problem, since NIF's current configuration—which would cost a pretty penny to change—was designed for a hohlraum, with lasers entering from above and below but not from all sides. But Schmitt's research indicates that the existing laser configuration can be arranged to cover the entire target surface many times over. Every spot on the target would be covered by overlapping between 5 and 7 of the facility's 192 laser spots. And the inequality in beam strength caused by the target's "poles" being hit at nearly right angles while its "equator" is hit at more grazing incidence can be sufficiently offset by adjusting the laser intensity profiles of the individual laser beams. What little degree of uneven cooking remains should, in principle, be smoothed out by the copper and tungsten shells and their cushioning layers.

Some naysayers argue that the Revolver target might be too large and complex to control. It must be manufactured to extraordinarily tight tolerances, with nearly perfectly concentric spherical shells, to avoid introducing asymmetries that will grow over the large implosion distance. It's certainly true that no such target has yet been manufactured or tested in a live experiment, and nothing short of that guarantees it will actually work. But Schmitt tried it in simulations. He offset the tungsten-encased DT fuel within the target by a conservatively large distance and still obtained adequate implosion symmetry to induce ignition. He also tried offsetting the entire target within NIF's target chamber—a broadsword-rather-than-scalpel approach to introducing laser-drive asymmetry—and again obtained a successful result.

In addition, Revolver benefits from the simplicity of using a single-phase liquid DT fuel, which, in theory, should provide a uniform-density fuel region to be compressed. By comparison, to generate and maintain a conventional target's geometrically precise annular layer of solid DT fuel surrounding a central DT vapor pocket necessitates stringent cryogenic-handling procedures. "We have a concept to allow the target to be constructed and used at room temperature," says Schmitt, "which would greatly simplify the fielding of future high-yield experiments at NIF."

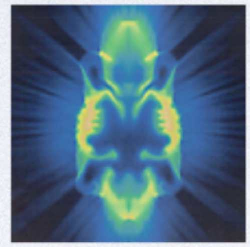
Besides all of that, Revolver is also simpler in the sense that it eliminates the hohlraum and the x-ray drive-asymmetry baggage that comes with it.

So far so good. But then there's the wide swath of naysayers comprised of anyone, really, with any knowledge of the disappointing history of the decades-long quest for ignition. They say: So what if it works in simulations? After all, on paper, everything else was supposed to work too. Simulations can't fully capture the nuances of such an intense region of high temperature and density. The computing requirements are too great to obtain more than just an approximation, and key properties of matter under such extreme conditions, such as opacity and "equation of state" (which links a material's behavior to its temperature), are only known approximately anyway.

This is an undeniably valid concern. One can't rely on anything—certainly nothing so grand or elusive as ignition—demonstrated by simulation alone. But supercomputers and simulations have been getting better, with both Los Alamos and Lawrence Livermore being absolutely state-of-the-art in this area. And importantly, the triple metal-layered target's slower, lower-temperature implosion brings the simulations into a domain where material properties are better known. It's not a sure thing, but it means the simulations are more believable for this approach than others. Besides which, notes Schmitt, "Revolver is relatively insensitive to changes in equation-of-state or opacity models because the radiation is trapped in the fuel region, and the entire fuel region ignites simultaneously." By contrast, the physics of conventional-target ignition—with multiple shocks that must precisely converge at the vapor pocket to produce exacting conditions for hot-spot ignition and burn propagation—is extremely challenging to fully capture in simulations.

Okay, but with these kinds of concerns about predictive uncertainty, why use three metal shells instead of two? Why not just have the ablating beryllium layer impact the tungsten layer directly, without copper in between? Why introduce the extra design complexity and increase the odds of something not working as expected—either in simulations or in experiments?

"I wish we didn't have to," answers Schmitt. "There are people working on two-shell, indirect-drive designs too. But with our direct-drive approach, it's not the way to go. The imploding ablator shell can't transfer energy to the tungsten shell fast enough before the tungsten shell converges, so the fuel doesn't get hot and dense enough to ignite. It's like trying to drive a nail with a bag of sand. The copper shell is our hammer."



(Right) Simulations with conventional targets at NIF reveal that complex asymmetries develop by the time the fusion begins. Instead of resulting in a clean, spherical region with consistent temperature and density amenable to a nuclear "burn," these asymmetries reduce the fusion's effectiveness and energy output, forestalling ignition.

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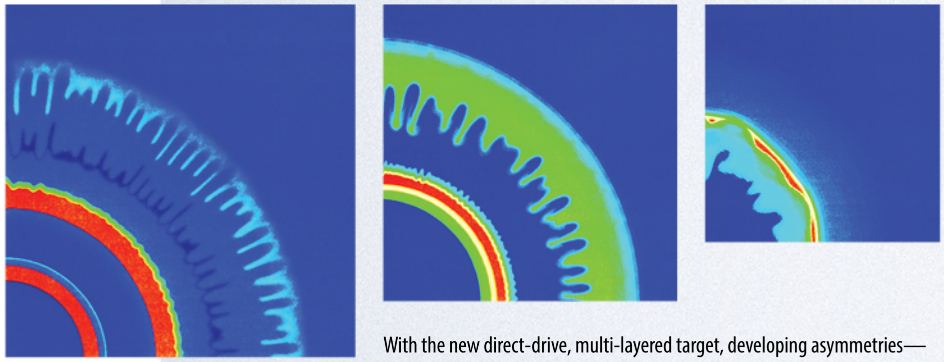

With the new direct-drive, multi-layered target, developing asymmetries—shown here in sequence, starting with the outer beryllium shell (left), then the copper (middle), and finally the tungsten (right) enclosing the nuclear fuel—are attenuated upon encountering each subsequent metal shell encased in a plastic cushioning layer. According to this simulation, the DT region in the last frame has sufficiently uniform conditions to produce simultaneous and prolonged ignition.

Illuminate. Implode. Ignite.

Initial testing, led by Los Alamos team member Scott Hsu, was carried out with the OMEGA laser at the University of Rochester's Laboratory for Laser Energetics, using scaled versions of the outer ablator shell. The limited laser energy available at that facility, compared to NIF, required miniaturization of the target to only about 20 percent of the diameter of the intended design. Nonetheless, the results were promising, showing no problems with laser-plasma instabilities, energy losses, or the scientists' ability to predict the imploding capsule's profile. Intermediate testing with two-shell targets is slated for OMEGA this winter.

Subsequent steps will involve a series of increasingly realistic experiments at NIF to determine if there are any obvious show-stoppers. But this is chess, not checkers, and even if each experiment goes according to plan, the final test that (hopefully) results in successful ignition will require several more years of concerted effort to build and field the full-scale triple-shell design. Then, even if everything works and ignition is achieved, a fusion-based power plant would still be a long way off because "ignition" indicates only that the fusion energy generated exceeds the laser energy transferred into the target—not the electrical energy that went into the laser. The laser itself is only about 1 percent efficient, so the overall process would still be a net loss. Besides which, creating controlled, ignition-level fusion in the laboratory, while revolutionary, is not the same thing as a functional power plant. In the most direct extension of a NIF-style setup, one would need, at minimum, some kind of apparatus for carrying fusion-generated heat off to boilers and turbines and a system for shuttling spent targets out and fresh targets in, assuming the technology can be scaled to the power-plant level at all.

Schmitt and Molvig readily acknowledge these hurdles.

"It's a mistake to look too far ahead to fusion-based electrical power generation," says Molvig. "With successful ignition, we can assess what happens if we adjust various parameters and then update our simulations accordingly, to make them truly predictive. From there we can explore suitable configurations for fusion-based technologies. But we have to start with a reliable, reproducible system. Make a Model T, then evolve to a Ferrari."

The predictive-simulation capability Molvig mentions would also represent a major leap forward in capability for one of Los Alamos's key mission areas, that of understanding, maintaining, and servicing the nation's aging nuclear-weapons stockpile without detonating any weapons to obtain the necessary test data. Yet, beyond power plants and the weapons arsenal, there is also the academic study of nuclear fusion itself: a vital area of both pure and applied science.

"We're trying to build, harness, and learn from an artificial solar core," Schmitt says. "This was always going to be a long game. But it's an incredibly worthwhile game, and ignition is the crucial next step." LDRD

—Craig Tyler

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