He notes that chlorine-containing chemicals trapped in the vortex were the immediate cause of ozone destruction, but he suggests that without the change in the SAO, the hole might never have appeared or might have remained shallow.

Ozone specialists, and even his co-author Hurrell, won't go that far. Even before the change in midlatitude atmospheric behavior, they say, the Antarctic vortex was sufficiently cold and long-lasting to produce an ozone hole—given enough humanmade chemicals to catalyze destruction. But the stronger vortex, says atmospheric chemist Richard Stolarski of the Goddard Space Flight Center in Greenbelt, Maryland, could have lowered the threshold by further chilling the vortex and confining the chemicals for longer. "A stronger vortex should make it easier to get an ozone depletion effect," he says, and thus bring on the hole earlier than otherwise.

The strengthened vortex could also delay the departure of the ozone hole in the mid-21st century as concentrations of ozone-depleting chemicals decline, at least if Van Loon and Hurrell are right about its ultimate cause: a warming of the tropical oceans. About the time the SAO was weakening and the ozone hole appeared, they note, the tropical Pacific suddenly warmed, and it has yet to return to normal (*Science*, 28 October 1994, p. 544). And when Van Loon and Hurrell made a longer survey of data on tropical ocean temperature and SAO strength, they found a consistent inverse correlation. They have not, however, worked out just how the influence could be transmitted from the tropical sea surface to the midlatitudes.

Murky mechanisms aside, the strengthened vortex may be here to stay if, as some other climate researchers speculate, the warming of the tropical Pacific is part of a greenhouse-driven global warming. A greenhouse-warmed climate, after all, is likely to persist for centuries. Connecting the appearance of the ozone hole to the buildup of greenhouse gases is a bold leap, even by the standards of earth science. But 25 years ago, who would have thought a puff of chlorofluorocarbons in your deodorant could wreak havoc in the stratosphere half a world away?

Sunburn Alert

Should you shop for sunscreen with a higher sun protection factor as the protective layer of ozone over most of the globe thins? It stands to reason that ozone depletion over the past 2 decades is allowing more harmful ultraviolet light (UV) to reach the surface, but because no global network of ultraviolet detectors exists to record any upward trend, scientists haven't been able to say for sure. Now the satellite-borne Total Ozone Mapping Spectrometer (TOMS), which brought much of the bad news about ozone depletion over the past 15 years, has confirmed that the news about UV is equally bad, with surface radiation in the DNA-damaging region of the spectrum increasing by as much as 12% per decade at high latitudes.

Isolated measurements at the surface had already hinted at the upward trend. So had the TOMS record of ozone loss, which is based on measurements of the increase in UV reflected back to space from the ground and lower atmosphere at wavelengths that ozone absorbs. As long as the fraction reflected from clouds and haze hasn't changed, the TOMS record should correspond to an increase in UV reaching the ground. But no one had tested that assumption until Jay Herman and his colleagues at the Goddard Space Flight Center in Greenbelt, Maryland, which operates TOMS and processes its data, reanalyzed the seventh and most thoroughly processed data set, which covers the period from 1980 to 1994.

To see whether any change in clouds and haze had altered the surface effects of stratospheric ozone loss, Herman and his colleagues examined TOMS data at ultraviolet wavelengths outside the range absorbed by ozone. Because ozone loss doesn't affect those wavelengths, they can serve as a monitor of changes in the ultraviolet reflectivity of haze and clouds. The data showed for the first time that there has been no long-term change, Herman announced at the IUGG meeting. And that adds to researchers' confidence that the increasing amounts of UV leaking through the damaged ozone shield are actually reaching the surface.

With the way open to interpreting the latest TOMS ozone loss data as an indicator of surface UV increases, Herman reported that around a latitude of 40°—over Japan, the United States, southern Europe, and New Zealand—ultraviolet light at DNA-damaging wavelengths must have increased at a rate of about 8% per decade in the spring, early summer, and autumn. At higher latitudes, the low temperatures that foster ozone loss appear to have boosted the inferred increase to 10% to 12% per decade. Only the tropics and subtropics have been spared any UV increases, Herman reported.

Sasha Madronich of the National Center for Atmospheric Research, who has extracted UV trends from TOMS data in the past, calls the new analysis "a very nice, important piece of work." Among other things, he says, it should open the way to seeing UV slow its increase as restrictions on the release of ozone-destroying chemicals take effect. And it should allow investigators to watch UV actually abate if and when the ozone layer begins to repair itself. But only TOMS will tell.

–**Richard A. Kerr**

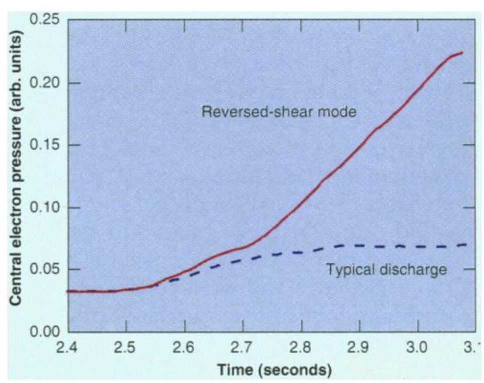
PHYSICS

Researchers Build a Secure Plasma Prison

In the halls and committee rooms of the Capitol, where the federal research budget is taking shape, the news for the U.S. fusion program has been unrelentingly bad. But in the laboratories themselves, where researchers use magnetic fields to cage hot plasma, or ionized gas, within donut-shaped vessels called tokamaks, nature is offering some encouragement. First there were the record fusion-power outputs achieved at Princeton University's Tokamak Fusion Test Reactor (TFTR) in 1993 and again late last year. Now groups at TFTR and, independently, at the DIII-D tokamak at General Atomics in San Diego are claiming a more fundamental triumph.

By tailoring the magnetic fields with unprecedented finesse, they appear to have achieved a goal that had eluded tokamak researchers for more than 30 years: taming the plasma instabilities that rattle and tear the fragile magnetic cage, allowing particles to leak out and limiting a tokamak's performance. In the process, the groups report in papers submitted to *Physical Review Letters* and presented at workshops, they increased the central density of the plasma by as much as threefold and reduced the particle leakage by a factor of 50, to "the irreducible minimum that must prevail," says Dieter Sigmar of the Plasma Fusion Center at the Massachusetts Institute of Technology. Sigmar, who is unaffiliated with either project, calls the achievement "a startling discovery that [fusion researchers] were no longer even hoping to find."

The groups are quick to caution that, so far, they have tamed the instabilities in only part of the plasma, and only in a limited range of temperatures and field strengths.



SOURCE: PRINCETON PLASMA PHYSICS LABORATORY

Fever line. A reversed shear field boosts the density—and hence power—of a fusion plasma.

But they say that the work, done in plasmas of deuterium—a low-power grade of fusion fuel—could at least double TFTR's power output when the researchers switch to the deuterium-tritium mix likely to fuel a working reactor. The improved confinement and power could also slash the size and cost of a working fusion reactor by 50%, says Charles Kessel, a Princeton theorist whose predictions helped guide the experiments.

If these results hold up over a broader range of conditions, they "might make fusion much more practical" in the long term, says Michael Mauel of Columbia University and a co-author on the DIII-D paper. Their more immediate impact, however, could be felt in Princeton, for they are likely to serve as a justification for extending the life of TFTR, now scheduled to be shut down at the end of this fiscal year (see box).

The effort to tame plasma instabilities goes back to the earliest days of fusion research in the 1950s, when researchers began designing magnetic fields to confine plasmas. Because charged particles gyrate tightly around magnetic field lines but travel easily along them, like rings sliding along a wire, physicists reasoned that they could trap a plasma by creating hoop-shaped field lines—say, by bending a cylindrical coil of current-carrying wires, which produces field lines paralleling its axis, into a donut. The particles should be able to cross the field lines only when they collided and suddenly changed direction.

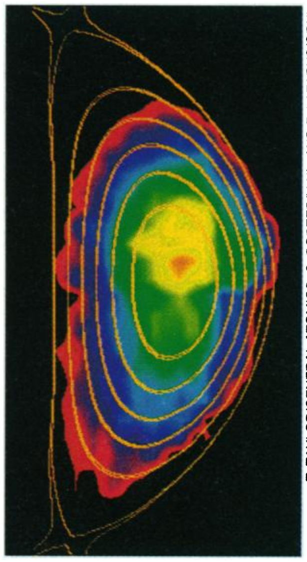
But because the outer hoops are longer—and hence weaker—than the inner ones, particles can drift out of this cage. To solve the problem, early fusion researchers found that they had to give the curving field lines a slight twist, causing them to spiral through the donut. That way, the particle drifts on opposite sides of each spiral cancel out. In a tokamak, this twist is applied by an electrical current running the long way around the donut, through the plasma itself. When the current is strongest in the center of the plasma—as it usually is, that being the easiest arrangement to produce—the spirals wrap most tightly in the center and gradually loosen toward the tokamak's walls.

Because of the larger and more complicated orbits of particles in this geometry, they take larger "steps" when they collide, and the minimum leakage rate across the field lines is roughly 100 times higher than in a straight field (where, of course, the particles would leak out along field lines almost instantly). But that's nothing compared to another disadvantage of this field geometry: An infinite variety of wave modes roil the hot, high-pressure plasma. These instabilities boost the particle leakage by another factor of 100. "That's what we've been trying to understand and improve on since the late '60s," says TFTR researcher Mike Zarnstorff. "It's taken a long time."

In the 1980s, tokamak researchers developed tricks for creating partial barriers to this "anomalous diffusion" and opened the way to the recent record-setting power outputs, says Zarnstorff. But the clues that led to the latest leap forward came from an unexpected direction: theoretical calculations by Kessel and several co-workers indicating that a working reactor might function more economically with plasma currents that were "hollow," or pipelike, in cross section, instead of peaked in the center. Pressure gradients within the plasma naturally generate such hollow currents, so that "you get that [current] for free," says Kessel.

As it happens, such hollow currents would also force the magnetic spirals to tighten from the center out to the edge of the plasma—the reverse of the usual pattern. In a paper on the topic last year, Kessel and co-workers had noted that earlier tokamak experiments had suggested that the region of tightening spirals, or "reversed magnetic shear," might also be stable enough to reduce the anomalous diffusion drastically.

So the TFTR and DIII-D groups set about trying to tailor their magnetic fields to the pattern Kessel had described. When TFTR's plasma reacted to the reversed shear created by the hollow current profiles, Zarnstorff recalls, its central pressure suddenly shot up. "Your first reaction is, 'Holy smokes. How can this possibly be?' It's something you thought you'd never see." Diffusion of particles dropped by a factor of 50 and the leakage of heat actually fell below what theorists thought was the absolute minimum—a mystery that no one has yet explained satisfactorily. The DIII-D researchers saw a similar transformation, although Gerald Navratil, a Columbia University physicist on sabbatical at General Atomics, concedes that the TFTR results are "probably more dramatic."



T. TAYLOR/GENERAL ATOMICS; G. PORTER/LLNL; AND E. LAZARUS/ORNL

Caged fury. An x-ray image shows the density of electrons in a plasma trapped within a reversed shear field at General Atomics' DIII-D tokamak. Lines trace the magnetic flux.

Learning whether the new results really do open the way to higher power outputs and, ultimately, to smaller and cheaper fusion reactors will take "a whole family of experiments on TFTR," says Rush Holt, assistant director of the Princeton Plasma Physics Laboratory. In spite of the grim outlook for the fusion program as a whole (*Science*, 23 June, p. 1691), physicists at TFTR may get a chance to explore the promise of the new results. And even if the fusion program doesn't go on to build on the achievement, its scientific luster won't be dimmed, says Holt. "Sometimes," he says, "people lose sight of the really beautiful and intricate physics that is being accomplished here."

–James Glanz

A Reprieve for Princeton Tokamak?

Fusion researchers' newfound ability to tame plasmas, trapping them for longer than ever before (see main text), may have come at an opportune time for Princeton University's Tokamak Fusion Test Reactor (TFTR). Just last week the Department of Energy (DOE) assembled a blue-ribbon panel of plasma physicists in Princeton to review the scientific case for extending TFTR's operating life, now due to end in October, for 1 to 3 years. Swayed in part by the prospect of wringing even higher powers from tamer plasmas, the panel seems likely to recommend a reprieve, says John Willis, division director for confinement systems in DOE's office of fusion energy.

Earlier this month, a separate panel of scientists convened by the White House had recommended the reprieve as part of a broad plan to keep fusion research afloat while other major projects are delayed, canceled, or scaled back (*Science*, 23 June, p. 1691). And the physicists at Princeton agreed that TFTR could put the time to good use, says Willis. "People were enthusiastic about what TFTR could offer in a technical program for the next 3 years," he says. The panel, says Willis, emphasized that TFTR is the only tokamak outfitted to study deuterium-tritium plasmas—the mixture likely to fuel a working reactor—and that it is still far from the end of its working life.

But Willis cautions that the panelists' final reports aren't due for several weeks. And he adds that the physicists' enthusiasm for TFTR may have to defer to the harsh new fiscal realities emerging from Congress.

–J.G.