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# THE SCIENCE OF WAR

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# THE SCIENCE OF WAR ▶▶WEAPONS

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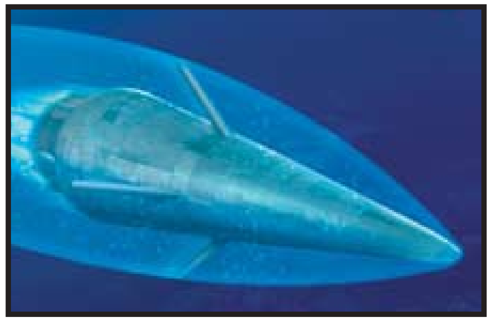
The art of war, according to Sun Tzu's 2,000-year-old text of the same name, is largely a matter of strategy, but the science of war begins squarely with weapons. Physics and engineering—and more often today, chemistry and biology—drive the creation of new military tools, from smart bombs and stealth aircraft to nerve gases and plastic explosives. Thus it is with a collection of articles about weapons that we are launching online a special anthology of *Scientific American's* recent coverage on war.



In this issue, scientists share their expertise on one terror of the ancient battlefield, the trebuchet, as well as several modern-day scourges, including land mines, third world submarines and biological arms. Additional articles feature in-depth research by staff editors on more futuristic threats—in the form of swift subsea systems and so-called non-lethal weapons. The complete table of contents appears below.

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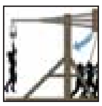
2  ANCIENT WEAPONS | The Trebuchet
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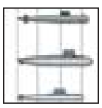
6  BLACK MARKET WEAPONS | Third World Submarines
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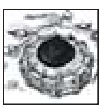
12  HIDDEN WEAPONS | The Horror of Land Mines
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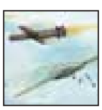
22  NON-LETHAL WEAPONS | Fighting Future Wars
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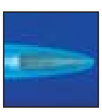
28  SWIFT SUBSEA WEAPONS | Warp Drive Underwater
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Traveling inside drag-cutting bubbles, secret torpedoes and other subsea naval systems can move hundreds of miles per hour.

# The Trebuchet

Originally Published in the July 1995 Issue

*Recent reconstructions and computer simulations reveal the operating principles of the most powerful weapon of its time*

by Paul E. Chevedden, Les Eigenbrod, Vernard Foley and Werner Soedel

Centuries before the development of effective cannons, huge artillery pieces were demolishing castle walls with projectiles the weight of an upright piano. The trebuchet, invented in China between the fifth and third centuries B.C.E., reached the Mediterranean by the sixth century C.E. It displaced other forms of artillery and held its own until well after the coming of gunpowder. The trebuchet was instrumental in the rapid expansion of both the Islamic and the Mongol empires. It also played a part in the transmission of the Black Death, the epidemic of plague that swept Eurasia and North Africa during the 14th century. Along the way it seems to have influenced both the development of clockwork and theoretical analyses of motion.

The trebuchet succeeded the catapult, which in turn was a mechanization of the bow [see "Ancient Catapults," by Werner Soedel and Vernard Foley; SCIENTIFIC AMERICAN, March 1979]. Catapults drew their energy from the elastic deformation of twisted ropes or sinews, whereas trebuchets relied on gravity or direct human power, which proved vastly more effective.

### Recovering Lost Knowledge

The average catapult launched a missile weighing between 13 and 18 kilograms, and the most commonly used heavy catapults had a capacity of 27 kilograms. According to Philo of Byzantium, however, even these machines could not inflict much damage on walls at a distance of 160 meters. The most powerful trebuchets, in contrast, could launch missiles weighing a ton or more. Furthermore, their maximum range could exceed that of ancient artillery.

We have only recently begun to reconstruct the history and operating principles of the trebuchet. Scholars as yet have made no comprehensive effort to examine all the available evidence. In particular, Islamic technical literature has been neglected. The most important surviving technical treatise on these machines is Kitab aniq fi al-manajaniq (An Elegant Book on Trebuchets), written in 1462 C.E. by Yusuf ibn Urunbugha al-Zaradkash. One of the most profusely illustrated Arabic manuscripts ever produced, it provides detailed construction and operating information. These writings are particularly significant because they offer a unique insight into the applied mechanics of premodern societies.

We have made scale models and computer simulations that have taught us a great deal about the trebuchet's operation. As a result, we believe we have uncovered design principles essentially lost since the Middle Ages. In addition, we have found historical materials that push back the date of the trebuchet's spread and reveal its crucial role in medieval warfare.

Historians had previously assumed that the diffusion of trebuchets westward from China occurred too late to affect the initial phase of the Islamic conquests, from 624 to 656. Recent work by one of us (Chevedden), however, shows that trebuchets reached the eastern Mediterranean by the late 500s, were known in Arabia and were used with great effect by Islamic armies. The technological sophistication for which Islam later became known was already manifest.

The Mongol conquests, the largest in human history, also owed something to this weapon. As a cavalry nation, the Mongols employed Chinese and Muslim engineers to build and operate trebuchets for their sieges. At the investment of Kaffa in the Crimea in 1345–46, the trebuchet's contribution to biological warfare had perhaps its most devastating impact. As Mongol forces besieged this Genoese outpost on the Crimean peninsula, the Black Death swept through their ranks. Diseased corpses were then hurled into the city, and from Kaffa the Black Death spread to the Mediterranean ports of Europe via Genoese merchants.

The trebuchet came to shape defensive as well as offensive tactics. Engineers thickened walls to withstand the new artillery and redesigned fortifications to employ trebuchets against attackers. Architects working under al-Adil (1196–1218), Saladin's brother and successor, introduced a defensive system that used gravity-powered trebuchets mounted on the platforms of towers to prevent enemy artillery from coming within effective range. These towers, designed primarily as artillery emplacements, took on enormous proportions to accommodate the larger trebuchets, and castles were transformed from walled enclosures with a few small towers into clusters of large towers joined by short stretches of curtain walls. The towers on the citadels of Damascus, Cairo and Bosra are massive structures, as large as 30 meters square.

### Simple but Devastating

The principle of the trebuchet was straightforward. The weapon consisted of a beam that pivoted around an axle that divided the beam into a long

**During their heyday, trebuchets received much attention from engineers—indeed, the very word "engineering" is intimately related to them. In Latin and the European vernaculars, a common term for trebuchet was "engine" (from ingenium, "an ingenious contrivance"), and those who designed, made and used them were called ingeniators.**

and short arm. The longer arm terminated in a cup or sling for hurling the missile, and the shorter one in an attachment for pulling ropes or a counterweight. When the device was positioned for launch, the short arm was aloft; when the beam was released, the long end swung upward, hurling the missile from the sling.

Three major forms developed: traction machines, powered by crews pulling on ropes; counterweight machines, activated by the fall of large masses; and hybrid forms that employed both gravity and human power. When traction machines first appeared in the Mediterranean world at the end of the sixth century, their capabilities were so far superior to those of earlier artillery that they were said to hurl "mountains and hills." The most powerful hybrid machines could launch shot about three to six times as heavy as that of the most commonly used large catapults. In addition, they could discharge significantly more missiles in a given time.

Counterweight machines went much further. The box for the weight might be the size of a peasant's hut and contain tens of thousands of kilograms. The projectile on the other end of the arm might weigh between 200 and 300 kilograms, and a few trebuchets reportedly threw stones weighing between 900 and 1,360 kilograms. With such increased capability, even dead horses or bundled humans could be flung. A modern reconstruction made in England has tossed a compact car (476 kilograms without its engine) 80 meters using a 30-ton counterweight.

During their heyday, trebuchets received much attention from engineers—indeed, the very word "engineering" is intimately related to them. In Latin and the European vernaculars, a common term for trebuchet was "engine" (from ingenium, "an ingenious contrivance"), and those who designed, made and used them were called ingeniators.

Engineers modified the early designs to increase range by extracting the most possible energy from the falling counterweight and to increase accuracy by minimizing recoil. The first difference between counterweight machines and their traction forebears is that the sling on the end of the arm is much longer. This change affects performance dramatically by increasing the effective length of the throwing arm. It also opens the way for a series of additional improvements by making the angle at which the missile is released largely independent of the angle of the arm. By varying the length of the sling ropes, engineers could ensure that shot left the machine at an angle of about 45 degrees to the vertical, which produces the longest trajectory.

At the same time, so that more of the weight's potential energy converts to motion, the sling should open only when the arm has reached an approximately vertical position (with the counterweight near the bottom of its travel). Observations of the trebuchet may have aided the emergence of important medieval insights into the forces associated with moving bodies.

### Swinging Free

The next crucial innovation was the development of the hinged counterweight. During the cocking process, the boxes of hinged counterweight machines hang directly below the hinge, at an angle to the arm; when the arm of the trebuchet is released, the hinge straightens out. As a result of this motion, the counterweight's distance from the pivot point, and thus its mechanical advantage, varies throughout the cycle.

The hinge significantly increases the amount of energy that can be delivered through the beam to the projectile. Medieval engineers observed that hinged counterweight machines, all else being equal, would throw their projectiles farther than would fixed-weight ones. Our computer simulations indicate that hinged counterweight machines delivered about 70 percent of their energy to the projectile. They lose some energy after the hinge has opened fully, when the beam begins to pull the counterweight sideways.

Although it exacts a small cost, this swinging of the counterweight has a significant braking effect on the rotating beam. Together with the transfer of energy to the sling as it lifts off and turns about the beam, the braking can bring the beam nearly to a stop as it comes upright. The deceleration eases the strain on the machine's framework just as the missile departs. As a result, the frame is less likely to slide or bounce. Some pieces of classical-era artillery, such as the onager, were notorious for bucking and had to be mounted on special compressible platforms. The much gentler release of the trebuchet meant that engineers did not have to reposition the frame between shots and so could shoot more rapidly and accurately. A machine of medium size built by the Museum of Falsters Minder in Denmark has proved capable of grouping its shots, at a range of 180 meters, within a six-meter square.

### Capturing the Trebuchet's Lessons

Later engineers attempted to capture the great power that trebuchets represented. Some of these efforts are made visible in historical records by the proliferation of counterweight boxes in the form of the mathematical curve called the saltcellar, or salinon. The counterweight boxes of the more elaborate trebuchets took this shape because it concentrated the mass at the farthest distance from the hinge and also reduced the clearance necessary between the counterweight and the frame. The same form reappeared on later machines that incorporated pendulums, such as pendulum-driven saws and other tools.

Most attempts to extend the trebuchet's principles failed because the counterweight's power could not be harnessed efficiently. Success came only in timekeeping, where it was not the trebuchet's great force but rather its regular motion that engineers sought. Pendulums were a dramatic step forward in accuracy from earlier controller mechanisms.

Although the pendulum is usually associated with the time of Galileo and Christiaan Huygens, evidence for pendulum controllers can be traced back to a family of Italian clockmakers to whom Leonardo da Vinci was close. Indeed, da Vinci explicitly says some of his designs can be used for telling time. His drawings include a hinge between the pendulum shaft and bob, just as advanced trebuchets hinged their counterweights, and show notable formal resemblances to fixed counterweight machines as well. In the case of earlier clockwork, there is a marked similarity both in form and in motion between the saltcellar counterweight and a speed controller called the strob. The strob oscillates about its shaft just as the counterweight does before quieting down at the end of a launch.

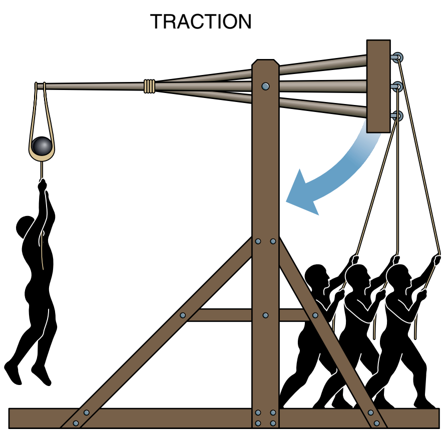
Trebuchets also appear to have played a role in the greatest single medieval advance in physical science, the innovations in theoretical mechanics associated with Jordanus of Nemore. The key to Jordanus's contribution is his concept of positional gravity, a revival in the Middle Ages of the idea of a motion vector, or the directedness of a force. Jordanus held that for equal distances traveled, a weight was "heavier," or more capable of doing work, when its line of descent was vertical rather than oblique. In particular, he compared cases in which the descents were linear with those that followed arcs. Eventually this understanding led to the notion that work is proportional to weight and vertical distance of descent, no matter what path is taken.

The connection is clear. Engineers knew that machines with hinged coun-

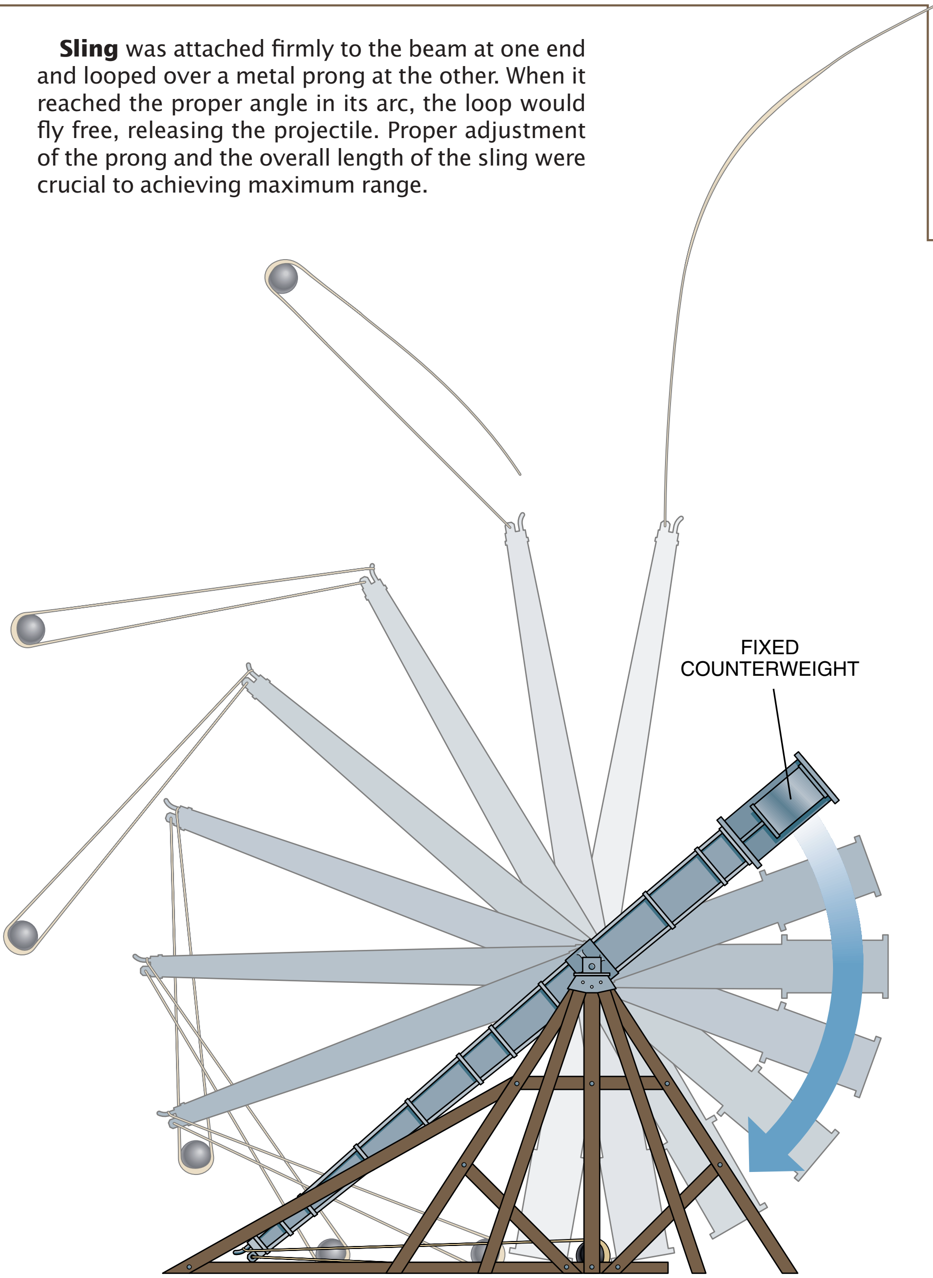
## The Physics of the Trebuchet

The motion of the trebuchet is simple enough in its essentials to have inspired medieval studies of motion, but its details are subtle and require computer simulations to interpret accurately. Only recently have we come to understand how the rotation of the counterweight plays a crucial role in transferring energy to the beam and thence to the sling and projectile.

**Sling** was attached firmly to the beam at one end and looped over a metal prong at the other. When it reached the proper angle in its arc, the loop would fly free, releasing the projectile. Proper adjustment of the prong and the overall length of the sling were crucial to achieving maximum range.




**Earliest trebuchets** were powered by crews pulling on ropes rather than by counterweights. Crews of as many as 250 men pulled to send projectiles 100 meters or more. In this example of a small traction machine, the sling-holder's weight flexed the beam and increased the range.

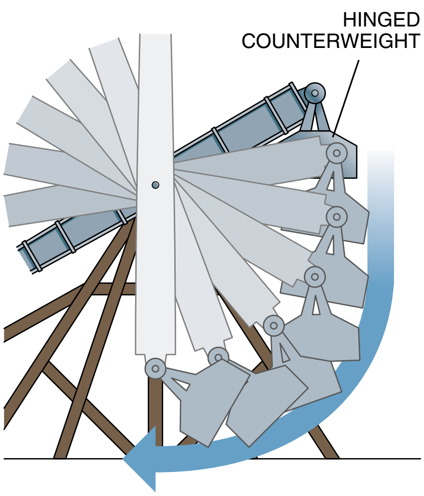



**Addition of counterweights** increased the power of the trebuchet. The elimination of the pulling ropes made possible another innovation: by placing a trough under the trebuchet beam to hold the projectile, engineers could lengthen the sling and increase the range even further. The sling rotates faster after the shot is airborne, so its length controls the launch angle.

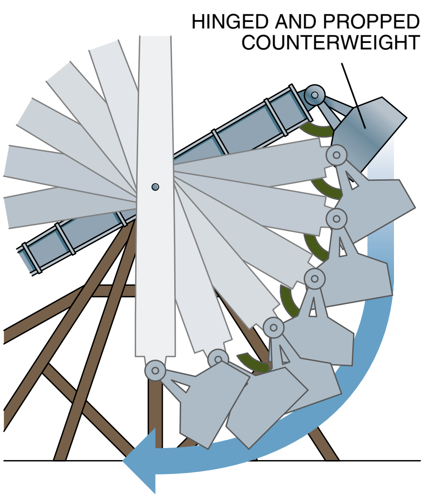
terweights, in which the weight descends essentially straight down during the first, crucial part of the launch cycle, would throw stones farther than would their fixed counterweight equivalents, in which the mass travels in a curve.

Other aspects of Jordanus's work may show military connections as well. The suspension of the hinged counterweight, with the constantly changing leverage of its arm, may have spurred Jordanus's related attempts to analyze the equilibrium of bent levers and to emphasize that it was the horizontal distance between the mass on a lever arm and its fulcrum that determined the work it could do. Observations of the differing distances to which fixed and hinged counterweight machines could throw their stones may have helped Jordanus in his pioneering efforts to define the concept of work, or force times distance. Jordanus's observations are usually studied as an example of pure physics, based on the teachings of earlier natural philosophers, such as Archimedes. The closeness of his mechanics to trebuchet function, however, suggests that engineering practice may have stimulated theory. Closing the circle, Galileo later incorporated such Jordanian ideas as virtual displacement, virtual work and the analysis of inclined planes to support such newer mechanics as his famous analysis of the trajectory of cannon shot.

Galileo's theoretical innovations came only after the replacement of trebuchets by cannon, a process that took nearly two centuries and was not fully accomplished until metallic shot replaced stones. The last instance of trebuchet use comes from the New World, at the siege of Tenochtitlán (Mexico City) in 1521. As ammunition was running critically low, Cortés eagerly accepted a proposal to build a trebuchet. The machine took several days to build, and at the first launch the stone went straight up, only to return and smash it. In view of the tremendous power of these devices, and the finesse required to make them function properly, would-be replicators should take careful note.




**Hinged counterweight** machines added yet another increment to the range by improving the efficiency with which the trebuchet converted gravitational energy to projectile motion. The center of gravity of the weight fell straight down during the first phase of acceleration; as the hinge straightened, the rotation of the weight around its center of gravity added to the energy transferred. Continued rotation helped to slow the beam as the projectile was released, reducing strain on the mechanism. The smoothness of the trebuchet's action meant it did not have to be repositioned after each shot and so could discharge more missiles in a given time.




**Propped counterweights** allowed engineers to squeeze even more energy out of the counterweight. By propping up the counterweight at an angle before firing, they gave it slightly farther to fall. This innovation also increased the distance between the center of gravity of the counterweight and the pivot around which the trebuchet beam rotated.

*—Vernard Foley*

JARED SCHNEIDMAN DESIGN

## *The Authors*


PAUL E. CHEVEDDEN, LES EIGENBROD, VERNARD FOLEY and WERNER SOEDEL combine engineering and history in their studies of the trebuchet. Chevedden, a historian specializing in premodern siege tactics and fortifications, teaches at Salem State College in Massachusetts. He received his Ph.D. from the University of California, Los Angeles, in 1986. Eigenbrod, an associate professor of mechanical engineering technology at Purdue University, teaches statics, dynamics and finite-element analysis. He spent 24 years in industry before going to Purdue. Foley, an associate professor at Purdue, specializes in the history of technology and science. This is his fifth article for Scientific American. Soedel is a professor of mechanical engineering at Purdue, with a strong interest in mathematical models and simulations of machinery. He reports that his idea of a good time is to sit in the garden and read history books.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SCIENTIFIC AMERICAN

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# Third World Submarines

## The proliferation of submarines may be a threat to established navies and regional stability, but to arms manufacturers it is a market opportunity

by Daniel J. Revelle and Lora Lumpe

During the spring of 1993, Iran put the first of its new Russian-built Kilo-class submarines through sea trials in the Persian Gulf. Its presence raises the specter of an Iranian attempt to close the Strait of Hormuz, the narrow waterway through which a fourth of the world's oil now passes.

Throughout the cold war, the U.S. Navy's highest priority mission was to engage Soviet nuclear-powered submarines in a global game of hide-and-seek. As that threat has faded, conflicting priorities have emerged. On one hand, the U.S. Navy is concerned about the threat that growing Third World naval forces pose to its ability to operate in coastal waters around the world. On the other hand, concern about the fate of the cold war industrial base is creating pressures for the U.S. to join former allies and enemies in supplying advanced diesel-powered attack submarines to developing countries.

More than 20 developing countries currently operate over 150 diesel attack submarines. North Korea has 25 such vessels, India 18, Turkey 15, Greece 10, Egypt 8, Libya 6 and Pakistan 6. Many of these boats are obsolescent, poorly maintained or operated by ill-trained crews. Others, however, could be a match for many vessels in the navies of the industrial world.

DANIEL J. REVELLE and LORA LUMPE worked together in the Arms Sales Monitoring Project at the Federation of American Scientists (FAS) in Washington, D.C. Revelle received a degree in physics from Carleton College in Northfield, Minn., and is currently a graduate student in aerospace engineering at the University of Colorado at Boulder. Lumpe directs the FAS's Arms Sales Monitoring Project and edits a bimonthly newsletter on weapons exports.

Third World nations have purchased their most advanced vessels from Russia and western European countries, both of which have a submarine manufacturing base far in excess of their own needs. Hans Saeger, sales director for the German submarine builder HDW, has estimated that NATO countries have the capacity to build 19 vessels a year, although NATO members generally purchase only two or three. The incentive to employ the remaining capacity is strong.

Germany in particular is a major exporter of submarines. Its sales are of exceptional concern because they frequently involve the transfer not only of vessels but also of production equipment and know-how for building submarines. Such "coproduction" deals promote sales, but they also lead to an increase in the number of nations competing to sell submarines, thus making proliferation even more difficult to contain. Germany has made coproduction agreements with South Korea, India and Argentina—the last has been licensed to produce two additional submarines for reexport.

Russia looks to weapon sales as a source of desperately needed hard currency. The Russian navy stated several years ago that it intended to continue producing two diesel submarines a year, keeping one for itself and selling the other for ready cash. Soviet customers have included Libya, North Korea, India and Algeria. More recently Iran purchased two of the Kilo boats with the option to buy a third.

Other nations are in the business, too. France has supplied its Daphne and more modern Agosta models to Pakistan. China has sold somewhat outdated Romeo-class submarines to North Korea and Egypt. Sweden is marketing submarines to Malaysia and is looking for other sales in South Asia. The Netherlands is considering the sale of 10 submarines to Taiwan in what is expected to be the last big sale of the century. Britain, meanwhile, is selling off four new Upholder-class diesel boats that its fleet no longer has the money to support, even offering to lease them complete with mercenary crews.

Although the U.S. Navy has purchased only nuclear-powered attack submarines since the 1960s, the U.S. government recently gave approval for domestic production of diesel vessels. In a 1992 report to Congress, the navy argued: "Construction of diesel submarines for export in U.S. shipyards would not support the U.S. submarine shipbuilding base and could encourage future development and operation of diesel submarines to the detriment of our own forces." Nevertheless, in April 1994 the State Department gave Ingalls shipyard in Pascagoula, Miss., the go-ahead to produce HDW's Type 209 under a license from the German firm. Egypt wants to buy two of these boats but cannot afford to purchase them directly from Germany. The vessels built by Ingalls will be bought using U.S. military aid, which may be spent only on weapons of American manufacture.

Once this new production line is in place, economic considerations will probably generate pressure to make further sales to developing countries. Taiwan and Saudi Arabia are the next likely customers for U.S.-made Type 209 vessels.

As shrinking military budgets add to economic woes, arms manufacturers are aggressively seeking to expand their markets. Submarine merchants have targeted nations bordering on the Gulf of Oman, the Mediterranean, the Arabian Sea and northern Indian Ocean, the South China Sea, and Pacific waters near the north Asian coast. If successful, their sales campaign could pose serious risks to international stability.

Even a handful of modern, well-maintained diesel submarines could have made a significant difference in the Persian Gulf War. If Saddam Hussein had bought six modern vessels "and positioned three of them on either side of the Strait of Hormuz, that would have complicated matters," according to U.S. vice admiral James Williams. "One diesel sub can make a great difference to how you drive your ships," he asserts.

During the Falklands/Malvinas war, a single Argentine Type 209 managed to elude 15 British frigates and destroyers and the antisubmarine aircraft of two carriers. The San Luis maneuvered into torpedo range of the British fleet and launched three torpedoes, although all three shots were unsuccessful. Early in the conflict a British submarine sank the Argentine cruiser General Belgrano with two straight-running torpedoes of a design that dated to World War II.

Both the U.S. and British navies are developing active antitorpedo weapons for the turn of the century, but at present evasion and electronic countermeasures are the only way to avoid a torpedo already in the water. Courtesy of the industrial nations, most Third World navies now have advanced torpedoes that can home in on a ship and explode just underneath its keel for maximum damage.

Some also possess submarine-launched antiship missiles. The U.S. has sold the Harpoon missile to Israel, Pakistan and others, and the French are marketing a submarine-launched version of the Exocet missile.

The deadliness of submarine-launched weaponry makes early detection and destruction of attacking submarines a crucial factor in antisubmarine warfare (referred to as ASW). Submarines in general are obviously much more difficult to detect than are surface ships or aircraft. Diesel attack submarines can be very quiet. When moving slowly, they can rely for days on battery power, eliminating engine noise or any need to surface or snorkel for air.

Diesel submarines have a relatively short range, and so they tend to inhabit littoral waters rather than the mid-ocean depths. Indeed, most developing countries have only a few vessels deployed defensively near their own coastlines, leading some analysts to deride them as mere "intelligent minefields." Nevertheless, the task of tracking and destroying these submarines can be complex and fraught with pitfalls.

**Swedish, German, Italian, Russian and South Korean shipyards are developing air-independent propulsion (AIP) systems, which eliminate the need for frequent snorkeling and may enable a vessel to remain at depth for up to a month.**

The "shallow" areas that usually harbor diesel submarines may be as deep as 300 meters, giving a vessel plenty of space to hide. At the same time, the bottom is close enough that false sonar echoes can mask a boat's location, much as "ground clutter" can hide low-flying aircraft from radar. Ships, oil rigs and sea life can add noise in coastal waters, further complicating the ASW operator's job. Magnetic anomaly detectors, used to find submarines in the open ocean, can be especially confounded by the clutter of a shallow seafloor and the "magnetic garbage" that litters the coastal plain.

To detect submarines and determine their location, ASW operators must catalogue other sound sources in the region where submarines might travel and map thermal, depth and salinity profiles and bottom conditions that can affect the path of acoustic emissions and sonar returns [see "The Amateur Scientist," page 90]. The U.S. Navy has only begun to turn its attention to this problem for waters such as the Persian Gulf, which was free of submarines until 1992. At that time, Iran acquired its first Kilo boat, and the U.S. assigned two Los Angeles–class nuclear-powered attack submarines to patrol and map the area.

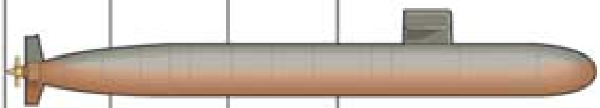
Although diesel submarines have many advantages when deployed under appropriate conditions, they are not without weaknesses. Their engines make more noise than do nuclear reactors and cannot drive a submarine as fast. When running at high speed under electric power, a submarine can deplete its batteries in a few hours. Even at slower speeds it must still approach the surface to take in air every four to 10 days, depending on the submarine's capabilities and the captain's willingness to risk running out of power to avoid detection. Consequently, ASW forces can prevail by blanketing an area with vessels and aircraft. Admiral Henry Mauz, U.S. Atlantic commander in chief, explains, "If you don't let him snorkel, you hold him down. Pretty soon he can't work—it's too hot, too steamy, too much carbon dioxide and monoxide."

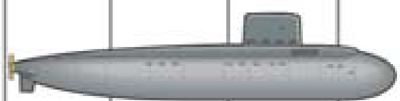
The newest submarine designs aim to reduce these liabilities. The Kilo and Type 209, for example, emit much less noise when snorkeling than do their predecessors. Moreover, Swedish, German, Italian, Russian and South Korean shipyards are developing air-independent propulsion (AIP) systems, which eliminate the need for frequent snorkeling and may enable a vessel to remain at depth for up to a month. Sweden has tested and incorporated into its next-generation design an AIP system using a Stirling engine, an external combustion engine that does not burn fuel explosively and is thus much quieter than a standard gasoline or diesel engine. Other designs may use liquid oxygen and high-efficiency combustion systems, or chemical fuel cells with up to five times the net energy density of lead-acid batteries.

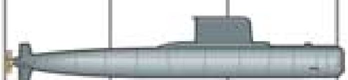
Most submarine fleets fielded by Third World countries do not currently present an insuperable threat to naval

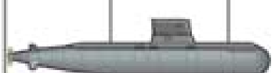
# Attack Submarines for Sale

Diesel-powered attack submarines now being sold to developing nations are smaller and slower than are the superpowers' nuclear versions (such as the U.S. Los Angeles–class vessel pictured immediately below). Nevertheless, they pose a significant threat to shipping and to naval forces that might wish to intervene in regional conflicts.









| | LENGTH (METERS) | MAXIMUM SPEED (KNOTS) | DIVING DEPTH (METERS) | ARMAMENT |
|---|---|---|---|---|
| **LOS ANGELES** *U.S.* | 110 | 30 | 450 | 4 Torpedo tubes<br>16 Missile tubes<br>18 Torpedoes<br>4 Subroc missiles<br>12 Submarine-launched cruise missiles<br>6 Harpoon antiship missiles |
| **AGOSTA** *FRANCE* | 68 | 20.5 | 300 | 4 Torpedo tubes<br>20 Torpedoes or Exocet missiles |
| **KILO** *RUSSIA* | 73 | 25 | N/A | 6 Torpedo tubes<br>12 Torpedoes or 24 mines |
| **TYPE 209 (SSK-1500)** *GERMANY* | 64 | 22.5 | N/A | 8 Torpedo tubes<br>14 Torpedoes<br>Strap-on mine-laying pods |
| **UPHOLDER** *U.K.* | 70 | 20 | > 250 | 6 Torpedo tubes<br>18 Torpedoes or Harpoon antiship missiles |
| **VÄSTERGÖTLAND** *SWEDEN* | 49 | 20 | > 300 | 10 Torpedo tubes<br>18 Torpedoes |
| **ZEELEEUW** *NETHERLANDS* | 68 | 21 | 300 | 4 Torpedo tubes<br>20 Torpedoes or Harpoon antiship missiles |

operations. U.S. Navy representatives point out that "only a relatively small proportion of the ocean is less than 1,000 feet deep, and most of that is less than 30 miles from shore. Controlling the deeper water," they contend, "guarantees battle group operation safety and 'bottles up' potential threats in restricted shallow water areas, where they are more susceptible to mines and other forces, while ensuring the sea lanes of communication remain open."

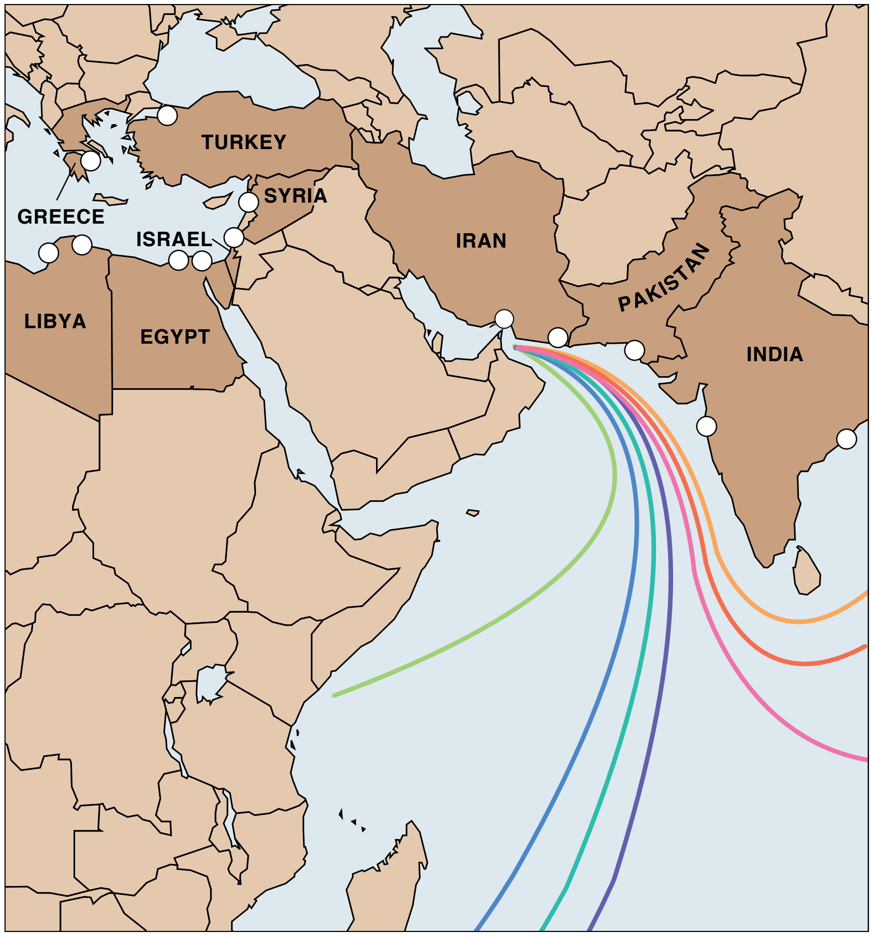
The new Kilos, to be based in southern Iran, are regarded by one U.S. intelligence official as so easy for U.S. aircraft to find and destroy that eliminating them would be little more than a "live fire exercise." Less capable submarines do not necessarily pose a serious danger even in large numbers. North Korea's fleet, for example, consists of antiquated Chinese-built Romeo-class vessels, a type the Soviet Union stopped selling in 1960. Libya's submarine crews have a reputation for being poorly trained, and their boats are so shoddily maintained that only one or two out of six may be operable—not one has routinely gone to sea since 1985.

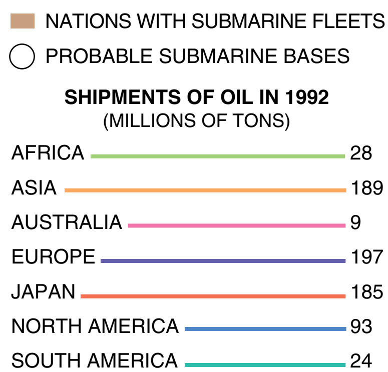
Faced with this mixed situation, the U.S. Navy has taken two contradictory positions. In its posture statement the service pledges to "ensure we maintain the ASW edge necessary to prevail in combat along the littoral," thus implicitly acknowledging that its current ASW forces are adequate to meet existing and near-term threats. At the same time, officials are justifying a new nuclear attack submarine program and several new helicopter, sonar, radar, torpedo and ship defense projects based in large part on the peril that could arise from diesel submarines in shallow water.

Indeed, the dangers that submarine fleets of the developing world present to U.S. forces will increase if nations continue to export more advanced and stealthy diesel submarines and weapon systems. Are there ways to limit the spread of the submarines?

It is difficult to convince exporters that halting the sale of submarines to the Third World would be in their best interests, but the idea of forgoing potential sales is not unprecedented. In 1987, when Western countries became sufficiently alarmed about ballistic missile proliferation, they managed to put aside their financial interests to limit the sale of missiles and related technology. The Missile Technology Control Regime (MTCR) bars the transfer of missiles, equipment or know-how that could lead to widespread proliferation.

Missiles were an object of special concern because they could penetrate




**PERSIAN GULF** has been the site of submarine operations since 1992, when Iran received its first submarine from Russia and built a base at Bandar Abbas. The U.S. then assigned two Los Angeles–class nuclear-powered attack submarines to patrol and map the area. Roughly a quarter of the world's oil passes this single maritime choke point.

enemy defenses and were highly suitable for surprise attack—destabilizing characteristics also shared by submarines. Attack submarines in the hands of rogue states raise the specter of terrorism against commercial shipping and could also wreak havoc against major-power forces attempting to operate in littoral waters. As with the MTCR, the best way to stop the spread of submarines to potentially hostile regimes is to control the export of these weapons worldwide. Routine sales of ballistic missile capabilities are no longer considered a legitimate commercial opportunity for nations to exploit. The same can be done for submarines.The market may not be such a large one for the developed countries to give up. Modern submarines cost too much for most countries—Pakistan, for example, would pay $233 million for each of three Agosta 90 models it is seeking to purchase from France. But China is competing with France for the Pakistani sale. Both countries are offering generous financing packages that reduce the profitability of the deal. In today's buyers' market, cash-paying customers are few. In the U.S. deal with Egypt, the revenues that Ingalls shipyard would receive are U.S. taxpayer dollars, already required to be spent on U.S. goods and services.

## Diesel Submarines in Third World Countries

Nearly two dozen developing nations currently possess diesel-powered attack submarines. Many of these countries are seeking to expand or modernize their fleets, and a handful of additional nations intend to join the submarine club. Meanwhile a growing set of exporters (including some former and current submarine buyers) is competing for the developing nations' business. The U.S., which has not made diesel submarines for about 30 years, is about to reenter the export market.

| IMPORTERS | HAVE | PLAN |
|---|---|---|
| ALGERIA | 2 | – |
| CHILE | 4 | – |
| COLOMBIA | 2 | – |
| CUBA | 3 | – |
| ECUADOR | 2 | – |
| EGYPT | 8 | 2–6 |
| GREECE | 10 | – |
| INDONESIA | 2 | – |
| IRAN | 2 | – |
| ISRAEL | 3 | 2 |
| LIBYA | 6 | – |
| MALAYSIA | – | ? |
| PAKISTAN | 6 | 3 |
| PERU | 9 | – |
| PHILIPPINES | – | ? |
| SAUDI ARABIA | – | ? |
| SINGAPORE | – | ? |
| SOUTH AFRICA | 3 | – |
| SYRIA | 3 | – |
| TAIWAN | 4 | 4 |
| VENEZUELA | 2 | – |

| CO-PRODUCERS | HAVE | PLAN |
|---|---|---|
| ARGENTINA | 4 | 4 |
| BRAZIL | 4 | 3 |
| CHINA | 45 | – |
| INDIA | 18 | 6 |
| NORTH KOREA | 25 | – |
| SOUTH KOREA | 4 | 8 |
| TURKEY | 15 | 7 |

| EXPORTERS |
|---|
| CHINA |
| FRANCE |
| GERMANY |
| NETHERLANDS |
| RUSSIA |
| SWEDEN |
| U.K. |

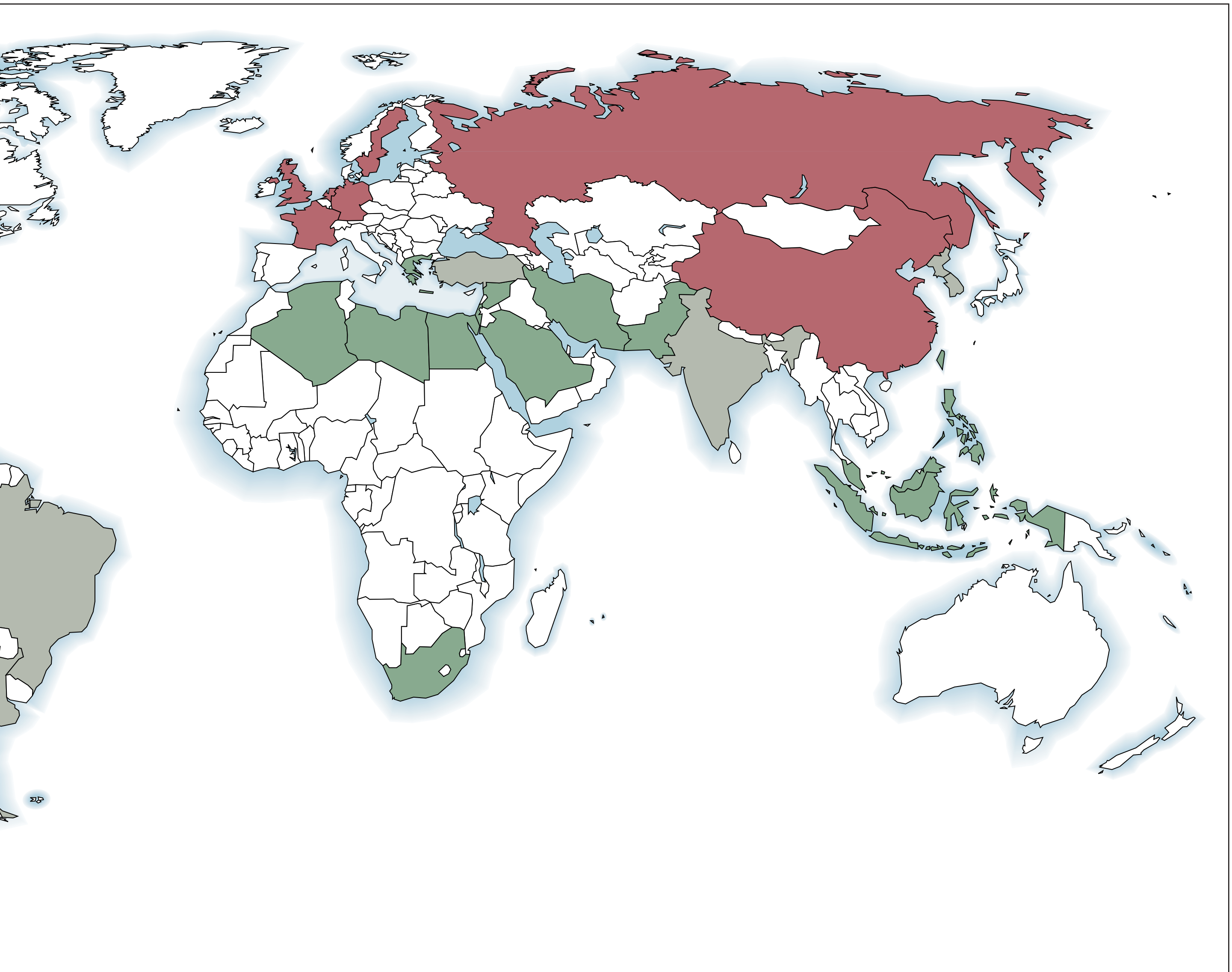
*PRIMARY SOURCE: International Institute for Strategic Studies*

Many submarine sales involve agreements to license the designs and technology for building the boats. Thus, the purchaser may become independent and may even compete with the original seller for future orders. Brazil, Argentina, South Korea and India, all former submarine purchasers, have produced some of their own vessels. It was precisely such proliferation of production capabilities that spurred formation of the MTCR. The developed countries may similarly wish to act before losing control of the world trade in submarines, along with the market itself, to Third World submarine producers.

Submarine exports are sometimes justified on the basis of the need to preserve the defense industrial base, but the capabilities that are preserved may not be all that useful for a modern nation's own defense. Germany has sold Type 209 submarines for nearly 20 years, but there is not a single Type 209 in the German navy. Of greater aid in maintaining a submarine industrial base in Germany and Sweden are current domestic construction orders for submarines with air-independent propulsion systems, which will provide work through the late 1990s. For the U.S., production of diesel vessels in Mississippi would not help maintain nuclear submarine production in Virginia and Connecticut, although it would help keep Ingalls afloat. Instead it would create a production line whose output the U.S. Navy is interested neither in purchasing nor in seeing proliferated around the globe.

A good step toward eventual control of submarine exports might be to restrict the sale of advanced submarine-launched weapons, such as modern torpedoes and antiship cruise missiles. These weapons, a single one of which can sink a large surface vessel, are particularly destabilizing. Furthermore, the U.S. could set an example by stopping the export of Harpoon missiles. These antiship weapons allow a submarine to attack a target such as an aircraft carrier from as far away as 90 miles, well beyond the reach of its inner defenses.

Missile and torpedo sales valued in the hundreds of thousands of dollars may be easier for governments to resist than submarine sales worth hundreds of millions. Whereas even the most basic torpedo can sink a ship, more modern weapons, which are faster, stealthier, longer range and better guided and which can defeat modern countermeasures, could place naval forces in imminent peril. By limiting sales of undersea ordnance to the most basic types, exporters would limit the threat from existing boats. An agreement restricting coproduction or sale of submarine production technology would be another



logical move toward cessation of submarine exports in general.

Countries that purchase submarines would be expected to object to restrictions on their availability. An outright ban on sales would affect neighbors and enemies equally, however. An effective international agreement could prevent naval arms races before they begin.

Given the long lifetime of submarines and other advanced weapons, exporting them even to countries that are now staunch allies is a risky business. Iran had six German Type 209 submarines on order at the time of its fundamentalist revolution. Had those weapons been delivered, Iran would likely have used them to great effect against Kuwaiti and Iraqi oil shipments during the Iran-Iraq war and could have turned them against the U.S. fleet when it intervened to protect those deliveries. Although Third World submarines do not pose an overwhelming threat at present, continued sales of modern submarines and munitions have led to real and serious proliferation risks.

Submarine-producing countries need to look beyond short-term commercial interests to long-term security necessities and organize a regime whereby the sale of advanced submarines is slowed or halted entirely.

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Originally published in the May 1996 Issue

# The Horror of Land Mines

*Land mines kill or maim more than 15,000 people each year. Most victims are innocent civilians. Many are children. Still, mines are planted by the thousands every day*

by Gino Strada

*Finally, the terrible bloodshed in Rwanda had come to an end. Alphonsine and her family were returning to their house when Alphonsine stepped on an unseen mine. At the hospital in Kigali, run by the surgical team of the relief organization* EMERGENCY, *I and other physicians did what we could to repair the damage. The explosion had smashed Alphonsine's legs and fractured her left forearm. We had to amputate both legs above the knee. Her sister sustained a penetrating brain injury from a metallic fragment; she never regained consciousness and died six hours after surgery. Their father, who had been meters away from the two girls, had only multiple small wounds in his chest.*

As a surgeon for EMERGENCY, I have treated many children such as Alphonsine and her sister—victims of a new kind of war. The great majority of modern conflicts are now internal rather than international: they are civil wars, struggles for independence, ethnic and racial "cleansings," terrorist campaigns. Today armies of irregulars without uniforms routinely fight with devastating weapons in the midst of crowded areas. Many armed groups deliberately mix with the population to avoid identification. Sometimes they actually use civilians as shields. Quite often, targeting and terrorizing large civilian groups are part of an army's primary military strategy.

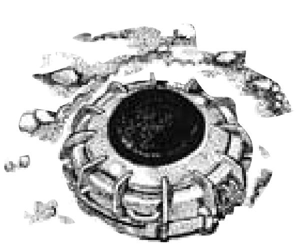
Accordingly, civilians have increasingly become victims of war. During World War I, they represented only 15 percent of all fatalities, but by the end of World War II the percentage had risen to 65 percent, including Holocaust casualties. In today's hostilities, more than 90 percent of all of those injured are civilians. Numerous research institutes, among them the Stockholm International Peace Research Institute and the International Peace Research Institute in Oslo, and humanitarian organizations involved in victim assistance have confirmed these figures.

One of the most dramatic aspects of this catastrophic change is the ever more widespread use of inhumane weapons such as antipersonnel mines. They characteristically pose an indiscriminate and persistent threat. Land mines do not distinguish the foot of a combatant from that of a playing child. Land mines do not recognize cease-fires or peace agreements. And once laid, they can maim or kill for many decades after any hostilities have ended. For this reason, the antipersonnel mine has been referred to as "a weapon of mass destruction in slow motion."

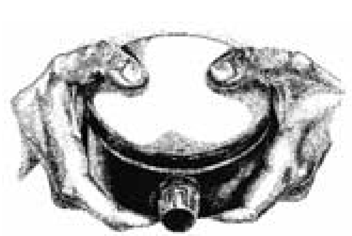
Mines have been used in various guises since the beginning of the century, but military philosophy has evolved over the years to make more cunning use of them. They are no longer seen simply as weapons for denying an enemy certain lands, or for channeling an enemy's troop movements, or for protecting key installations. Instead they are now often laid to deprive a local population access to water sources, wood, fuel, pathways and even burial grounds. In many countries, in fact, helicopters, artillery and other remote means have been used to scatter mines randomly over villages or agricultural land as deliberate acts of terrorism against the civilian population.

In technical terms, an antipersonnel mine (also known as an AP mine) can be defined as a device designed to kill or maim the person who triggers it. (In

## Patterns of Injuries

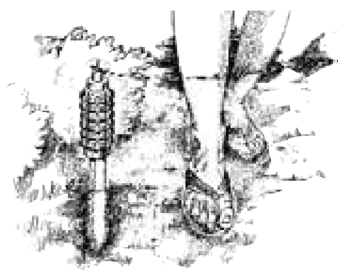


PATTERN A INJURIES are most often caused by small blast mines, such as the VS-50 mine shown at the right. These weapons, less than 10 centimeters in diameter, most often amputate a foot or leg, depending on how they are stepped on. Rarely do they produce wounds higher than the knee or on the opposite leg.



PATTERN B INJURIES, result from stepping on antipersonnel mines such as the PMN ((*above*). These mines are not much larger than small blast mines, but they pack far more explosive material. As a result, they often blow off the lower leg and cause further harm to the thighs, genitals or buttocks.

PATTERN C INJURIES are produced by the PFM-1, the so-called butterfly mine (*left*). These mines explode only after cumulative pressure has been applied to their wings, which help them initially to glide to the ground after being released from a helicopter. Because they are usually being handled when they go off, these mines amputate fingers or hands and damage the face and chest as well. Almost all victims are children, who eat the mines as toys.



PATTERN D INJURIES indicate that a person has tripped a fragmentation mine, such as the POMZ-2 "stake" mine above. These mines usually kill anyone who comes into direct contact with them by discharging metallic shards over a wide area.

PAMELA BLOTNER *The Arms Project/PHR (drawings)* contrast, antitank mines, usually called ATMs, are specifically designed for blowing up tanks and vehicles. They explode only when compressed by something weighing hundreds of kilograms.) AP mines are generally rather small in diameter, frequently less than 10 centimeters across, and difficult to detect. In some cases, the color and shape of the mine help to camouflage it so that it becomes virtually invisible at a glance.

A land mine is activated when the victim triggers the firing mechanism, usually by applying direct pressure to the mine itself or by putting tension on a trip wire. That action sets off the detonator, which in turn ignites the booster charge, a small amount of high-quality explosive. The detonation of the booster charge detonates the land mine's main charge, completing the explosive chain.

In recent years, mine technology has evolved significantly. The development of plastic mines, as well as those containing a minimum amount of metal, has made these weapons cheaper, more reliable, more durable and harder to detect and dismantle. In addition, remote deployment systems (such as helicopters) have made it possible to deliver thousands of mines to a broad territory within just a few minutes. Laying mines in this way also makes it impossible to record exactly where they land, so recovering them is all the more difficult.

## Mine Pollution

Unfortunately, land-mine technology is quite simple and its price very low—most weapons cost in the range of $3 to $15. As a result, they have been profitably manufactured and sold by a rising number of countries in past years, including many in the developing world. Approximately 50 nations have produced and exported antipersonnel mines, and at least 350 models are currently available, not only to official armies but essentially to all fighting groups and armed factions worldwide.

The number of unexploded mines in place around the globe is not known. According to several sources (including the United Nations, the U.S. State Department and various humanitarian agencies), at least 100 million are now scattered across 64 countries. Because neither manufacturers nor users typically keep records, though, these figures very likely underestimate the real situation. Whatever the case, a significant portion of the world undeniably suffers from what might be considered "land-mine pollution."

The agencies offering victim assistance or operations to clear mines estimate that during the past two decades these weapons have killed or maimed approximately 15,000 people each year. Of these victims, about 80 percent were civilians. In fact, the actual number is probably even higher given that many accidents occur in remote areas without medical facilities and so are not documented. In a mined area, many everyday activities—gathering wood or food, drawing water, farming, playing, tending livestock—become highly risky. I have personally treated 1,950 people injured by mines; of them, 93 percent were civilians, and 29 percent were children younger than the age of 14.

## The Damage Mines Inflict

Practically speaking, antipersonnel mines can be divided into two large groups: blast mines and fragmentation mines. Blast mines usually respond to pressure—for example, from a descending foot on a sensitive plate. The injuries to the body from blast mines are direct consequences of the explosion itself. In contrast, fragmentation mines are usually activated by trip wires. When they explode, a large number of metallic fragments fly outward for a considerable distance. These fragments are either contained inside the mine or result from the rupture of its segmented outer case.

The type of mine, the specifics of its operation, its position on the ground, the position of the victim and the characteristics of the environment at the explosion site all affect the nature and extent of the damage a mine causes. Victims suffer from a broad range of injuries. Nevertheless, four general patterns are recognizable. I apologize if the description I shall offer of those injuries is disturbing to many readers. Yet to grasp how truly awful these weapons are, one must be aware of what they do and how they do it.

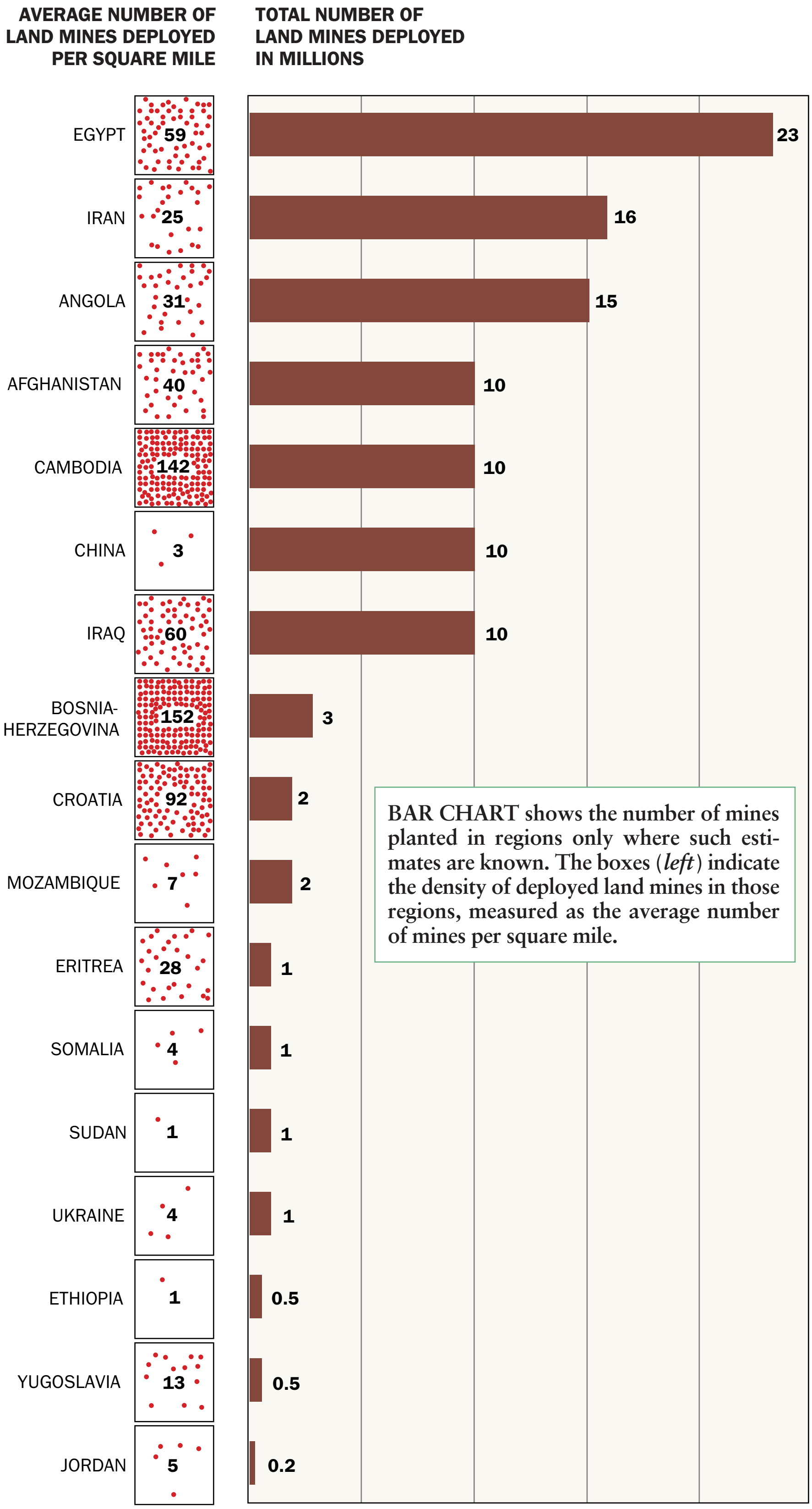
Small blast mines, having diameters of less than 10 centimeters, produce a very common pattern of injury that we call Pattern A. Among the most common mines in this group are the Italian scatterable mines TS-50 and SB-33 and the hand-laid VS-50 and VAR-40, the U.S.-made M14, and the Chinese Type 72. Typically, these weapons amputate the foot or leg. In some cases, only part of the foot may be blown off, depending on how the mine was placed and how it was stepped on. In most cases, the injuries from these types of mines occur below the knee, and no major wounds are present higher on the body or on the opposite leg.

Larger antipersonnel blast mines, such as those in the Russian PMN series, usually cause a different type of injury (Pattern B). This difference arises in part simply from the discrepancy in the size of the weapon. The diameter of the "small" VS-50 is 9.0 centimeters, whereas a PMN is 11.2 centimeters. The shock waves from both mines explode outward at the same high speed, approximately 6,800 meters per second, seven times the speed of a high-velocity bullet. But the cone of the explosion—the volume carrying the explosive force—is much wider for the larger mine. The large mines also contain much more high-quality explosive material. A VS-50, for instance, has 42 grams of RDX-TNT; a PMN-2 carries 150 grams of TNT; and a PMN contains 240 grams.

Victims stepping on these large antipersonnel mines invariably suffer a traumatic amputation. Quite often the lower part of the leg is blown off. A piece of the tibia (the large bone in the shin) may protrude from the stump, and the remaining muscles are smashed and pushed upward, giving the injury a grotesque cauliflowerlike appearance. Occasionally, the lower leg is blown off completely, along with the knee. Large wounds are often sustained in the thigh, the genitals or the buttocks. In many patients the opposite leg is also damaged, bearing gaping wounds or open fractures. As a result, sometimes parts of both legs are lost. Penetrating injuries of the abdomen or chest are also fairly common. The Russian PFM-1, the so-called butterfly mine, causes a third pattern of injury (Pattern C). This mine earned its nickname because it sports small wings that enable it to glide to the ground after it is released from a helicopter. A huge number of them were dropped during the conflict in Afghanistan.

As has often been pointed out, the PFM-1 is particularly fiendish because it is a "toy mine"—a weapon masquerading as a plaything. Specialists insist that the shape of the PFM-1 is dictated by function, but the fact remains that it is attractive to children.

A unique feature of these mines is that they are activated by distortion or cumulative pressure on their wings; in other words, they do not necessarily go off when first touched. In Afghanistan my co-workers and I were told several times that a child had taken the butterfly—or "green parrot," as the Afghans call it—and played with it for hours with friends before any explosion occurred. The term "toy mine" therefore seems totally justified. In our group's surgical experience of treating more than 150 victims of this type of mine, we have never seen a single injured adult.




BAR CHART shows the number of mines planted in regions only where such estimates are known. The boxes (*left*) indicate the density of deployed land mines in those regions, measured as the average number of mines per square mile.

Technically, the PFM-1 is just another type of small, scatterable blast mine, but because of the peculiar damage it causes, it deserves a separate description. The PFM-1 is usually being held when it goes off, so it traumatically amputates one or both hands at the wrist. In less severe cases, only two or three fingers are destroyed. Very often the blast does further harm to the chest and the face. Injuries to one or both eyes are very common, producing partial or complete blindness.

Antipersonnel fragmentation mines cause the fourth pattern of injury (Pattern D). Within this group are the "bounding" fragmentation mines, such as the Italian Valmara-69, the U.S.-manufactured M16 series and the Russian OZM series. These weapons are laid on the ground but, when triggered, jump into the air before exploding so that they can disperse their fragments over the maximum range and to the most lethal effect. Directional fragmentation mines—including the U.S.-made M18A1 (or "Claymore") and the Russian MON and POMZ "stake" mines, which aim their projectiles toward a target—are also in this class of weapon. All these mines are typically operated by trip wires.

The defining feature of fragmentation mines is that they fire metallic shards over a wide area. The Valmara-69, for example, explodes at a height of 50 to 100 centimeters—roughly the level of a man's waist—and projects some 1,000 bits of metallic shrapnel across a 360-degree spread. Mine specialists consider this mine to have a "killing zone" with a 25-meter radius and an "injury zone" of up to 200 meters.

Fragmentation mines produce injuries throughout the body. The size of the wound depends in part on the size of the penetrating splinter. If the victim is meters away from the site of the explosion, the fragments will frequently penetrate the abdomen, the chest or the brain, particularly if a bounding mine is involved. For shorter distances, the injuries resemble those of Pattern B. Still, doctors rarely treat traumatic amputations caused by fragmentation mines because the weapons usually kill in an instant anyone who activates them by direct contact.

In northern Iraq, during the Persian Gulf War, for instance, we observed six casualties from the explosion of a Valmara-69. The two persons who were trying to defuse the mine to recover its aluminum content—worth about $1 on

BORIS STAROSTA

the local market—were immediately killed. At the same time, four other people nearby, including two young shepherds, were severely injured. Only two of them survived.

The injury patterns I have described identify the prevalent distribution of wounds that a patient may suffer, but they do not correspond cleanly to levels of severity. A traumatic amputation of the foot with only a small wound in the thigh—a Pattern A casualty—might be life-threatening if the thigh injury involves the femoral artery. Commonly, the patient who sustains a land-mine injury is in critical condition. Often a vital structure is directly damaged, or the wounds (including the traumatic amputations) are so extensive that the patient is imperiled by hemorrhagic shock. In such an emergency situation, identifying a pattern of injury with a specific category of land mine can provide useful information to the surgical team (and also to any personnel involved in clearing the area of mines).

### The Challenge of Treating Victims

For several reasons, surgery on mine injuries is a complex and challenging discipline. Often the medical team has to work in hazardous areas where the fighting is ongoing. The available facilities are typically primitive. Scarce resources, the lack of proper hygiene, and sometimes even the absence of water and electricity make the job extremely difficult. Furthermore, the surgeons must be trained to deal with all kinds of emergencies: vascular, thoracic, abdominal, orthopedic and so on. Fragments of bone, for example, can become "secondary bullets." I once had to reconstruct the axillary artery in the shoulder of a patient that had been completely severed by a piece of bone from the patient's traumatically amputated foot.

From the technical point of view, the keystone operation is the debridement, or surgical cleansing, of the wound. When a blast mine goes off, stones, mud, grass and even pieces of the patient's clothes or shoes can be pushed deep into the tissues by the ascending explosion. The removal of all foreign bodies and, even more important, the excision of all dead, dying or weakened tissue from the lesions are of paramount importance in preventing life-threatening postsurgical infections. Most patients who recover from land-mine accidents never truly regain their ability to take an active part in family life or society. Rehabilitating these patients under the best circumstances is often immensely problematic. And many victims live in developing countries, where poor living conditions make it even more difficult to overcome physical and psychological handicaps. Moreover, beyond the tremendous human cost that mines claim in lives and suffering, they also impose a severe social and economic burden on entire societies and nations. An army's decision to mine agricultural land has long-term devastating effects on farming communities, who rely on the land for survival. The presence of land mines also deters many wartime refugees from returning to their homes. The displaced people tend to become permanent refugees who overload the economic and social structures of the regions to which they flee.

In 1980 the U.N. adopted what is commonly known as the Convention on Inhumane Weapons. Although this convention and its protocols were supposed to guarantee protection to civilians, events during the rest of that decade demonstrated all too clearly the inadequacy of those regulations. In recent years, more than 400 humanitarian organizations in nearly 30 countries have launched a campaign to raise the international community's awareness of the devastating effects of antipersonnel mines. They have urged the U.N. and national governments to ban the production, stockpiling, sale, export and use of mines. The campaign has had significant results, and several countries have decided to stop the production or export of land mines, at least temporarily.

### A Deadly Legacy

In September 1995 a U.N. review conference of the convention gathered in Vienna. International diplomacy focused the discussion on various technical and military aspects of land-mine use. From a humanitarian point of view, the Vienna conference was a fiasco. A total ban on these indiscriminate weapons—the only real solution—was not even taken into consideration. Moreover, it seems unlikely that a ban will be proposed in the session of the conference that is currently under way in Geneva. Certainly most countries and citizens of the world now realize the horrors of nuclear bombs. It is astonishing that those same countries do not object to the daily massacre of innocent civilians by way of antipersonnel mines.

Still, the world in the next century faces a terrible legacy. Many of the mines dropped decades ago may have effective lifetimes of centuries. Indeed, even if no more mines are laid in the future, those that are already in place will cause colossal tragedy and will challenge relief organizations of tomorrow. We may hope that the international community will soon make the issue of land mines a top priority and provide the funds needed to carry on essential humanitarian activities. Emergency surgical assistance and the subsequent rehabilitation of victims, as well as operations to clear mines and to educate people about their dangers, will in fact remain the only options for easing the suffering of hundreds of thousands of people. Even for a veteran war surgeon, looking at the body of a child torn to pieces by these inhumane weapons is startling and upsetting. This carnage has nothing to do with military strategy. It is a deliberate choice to inflict monstrous pain and mutilation. It is a crime against humanity.

### *The Author*

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# The Specter of Biological Weapons

*States and terrorists alike have shown a growing interest in germ warfare. More stringent arms-control efforts are needed to discourage attacks*

by Leonard A. Cole

In 1995, on a whim, I asked a friend: Which would worry you more, being attacked with a biological weapon or a chemical weapon? He looked quizzical. "Frankly, I'm afraid of Alzheimer's," he replied, and we shared a laugh. He had elegantly dismissed my question as an irrelevancy. In civilized society, people do not think about such things.

The next day, on March 20, the nerve agent sarin was unleashed in the Tokyo subway system, killing 12 people and injuring 5,500. In Japan, no less, one of the safest countries in the world. I called my friend, and we lingered over the coincidental timing of my question. A seemingly frivolous speculation one day, a deadly serious matter the next.

That thousands did not die from the Tokyo attack was attributed to an impure mixture of the agent. A tiny drop of sarin, which was originally developed in Germany in the 1930s, can kill within minutes after skin contact or inhalation of its vapor. Like all other nerve agents, sarin blocks the action of acetylcholinesterase, an enzyme necessary for the transmission of nerve impulses.

The cult responsible for the sarin attack, Aum Shinrikyo ("Supreme Truth"), was developing biological agents as well. If a chemical attack is frightening, a biological weapon poses a worse nightmare. Chemical agents are inanimate, but bacteria, viruses and other live agents may be contagious and reproductive. If they become established in the environment, they may multiply. Unlike any other weapon, they can become more dangerous over time.

Certain biological agents incapacitate, whereas others kill. The Ebola virus, for example, kills as many as 90 percent of its victims in little more than a week. Connective tissue liquefies; every orifice bleeds. In the final stages, Ebola victims become convulsive, splashing contaminated blood around them as they twitch, shake and thrash to their deaths.

For Ebola, there is no cure, no treatment. Even the manner in which it spreads is unclear, by close contact with victims and their blood, bodily fluids or remains or by just breathing the surrounding air. Recent outbreaks in Zaire prompted the quarantine of sections of the country until the disease had run its course.

The horror is only magnified by the thought that individuals and nations would consider attacking others with such viruses. In October 1992 Shoko Asahara, head of the Aum Shinrikyo cult, and 40 followers traveled to Zaire, ostensibly to help treat Ebola victims. But the group's real intention, according to an October 31, 1995, report by the U.S. Senate's Permanent Subcommittee on Investigations, was probably to obtain virus samples, culture them and use them in biological attacks.

Interest in acquiring killer organisms for sinister purposes is not limited to groups outside the U.S. On May 5, 1995, six weeks after the Tokyo subway incident, Larry Harris, a laboratory technician in Ohio, ordered the bacterium that causes bubonic plague from a Maryland biomedical supply firm. The company, the American Type Culture Collection in Rockville, Md., mailed him three vials of *Yersinia pestis*.

Harris drew suspicion only when he called the firm four days after placing his order to find out why it had not arrived. Company officials wondered about his impatience and his apparent unfamiliarity with laboratory techniques, so they contacted federal authorities. He was later found to be a member of a white supremacist organization. In November 1995 he pled guilty in federal court to mail fraud.

To get the plague bacteria, Harris needed no more than a credit card and a false letterhead. Partially in response to this incident, an antiterrorism law enacted this past April required the Centers for Disease Control and Prevention to monitor more closely shipments of infectious agents.

What would Harris have done with the bacteria? He claimed he wanted to conduct research to counteract Iraqi rats carrying "supergerms." But if he had cared to grow a biological arsenal, the task would have been frighteningly simple. By dividing every 20 minutes, a single bacterium gives rise to more than a billion copies in 10 hours. A small vial of microorganisms can yield a huge number in less than a week. For some diseases, such as anthrax, inhaling a few thousand bacteria—which would cover an area smaller than the period at the end of this sentence—can be fatal.

Kathleen C. Bailey, a former assistant director of the U.S. Arms Control and Disarmament Agency, has visited several biotechnology and pharmaceutical firms. She is "absolutely convinced" that a major biological arsenal could be built with $10,000 worth of equipment in a room 15 feet by 15. After all, one can cultivate trillions of bacteria at relatively little risk to one's self with gear no more sophisticated than a beer fermenter and a protein-based culture, a gas mask and a plastic overgarment.

Fortunately, biological terrorism has thus far been limited to very few cases.

One incident occurred in September 1984, when about 750 people became sick after eating in restaurants in an Oregon town called The Dalles. In 1986 Ma Anand Sheela confessed at a federal trial that she and other members of a nearby cult that had clashed with local Oregonians had spread salmonella bacteria on salad bars in four restaurants; the bacteria had been grown in laboratories on the cult's ranch. After serving two and a half years in prison, Sheela, who had been the chief of staff for the cult leader, Bhagwan Shree Rajneesh, was released and deported to Europe.

But as a 1992 report by the Office of Technology Assessment indicated, both biological and chemical terrorism have been rare. Also rare has been the use of biological agents as weapons of war. Perhaps the first recorded incident occurred in the 14th century, when an army besieging Kaffa, a seaport on the Black Sea in the Crimea in Russia, catapulted plague-infected cadavers over the city walls. In colonial America a British officer reportedly gave germ-infested blankets from a smallpox infirmary to Indians in order to start an epidemic among the tribes. The only confirmed instance in this century was Japan's use of plague and other bacteria against China in the 1930s and 1940s.

### Grim Reality

As the 20th century draws to a close, however, an unpleasant paradox has emerged. More states than ever are signing international agreements to eliminate chemical and biological arms. Yet more are also suspected of developing these weapons despite the treaties. In 1980 only one country, the Soviet Union, had been named by the U.S. for violating the 1972 Biological Weapons Convention, a treaty that prohibits the development or possession of biological weapons.

Since then, the number has ballooned. In 1989 Central Intelligence Agency director William Webster reported that "at least 10 countries" were developing biological weapons. By 1995, 17 countries had been named as biological weapons suspects, according to sources cited by the Office of Technology Assessment and at U.S. Senate committee hearings. They include Iran, Iraq, Libya, Syria, North Korea, Taiwan, Israel, Egypt, Vietnam, Laos, Cuba, Bulgaria, India, South Korea, South Africa, China and Russia. (Russian leaders insist that they have terminated their biological program, but U.S. officials doubt that claim.

The first five of these countries—Iran, Iraq, Libya, Syria and North Korea—are especially worrisome in view of their histories of militant behavior. Iraq, for example, has acknowledged the claims of U.N. inspectors that during the 1991 Persian Gulf War it possessed Scud missiles tipped with biological warheads. A 1994 Pentagon report to Congress cited instability in eastern Europe, the Middle East and Southwest Asia as likely to encourage even more nations to develop biological and chemical arms.

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Reversing this trend should be of paramount concern to the community of nations. Indeed, the elimination of biological as well as chemical weaponry is a worthy, if difficult, goal. The failure of this effort may increase the likelihood of the development of a man-made plague from Ebola or some other gruesome agent.

Dedication to biological disarmament in particular should be enhanced by another grim truth: in many scenarios, a large population cannot be protected against a biological attack. Vaccines can prevent some diseases, but unless the causative agent is known in advance, such a safeguard may be worthless. Antibiotics are effective against specific bacteria or classes of biological agents, but not against all. Moreover, the incidence of infectious disease around the world has been rising from newly resistant strains of bacteria that defy treatment. In this era of biotechnology, especially, novel organisms can be engineered against which vaccines or antibiotics are useless.

Nor do physical barriers against infection offer great comfort. Fortunately, most biological agents have no effect on or through intact skin, so respiratory masks and clothing would provide adequate protection for most people. After a short while, the danger could recede as sunlight and ambient temperatures destroyed the agents. But certain microorganisms can persist indefinitely in an environment. Gruinard Island, off the coast of Scotland, remained infected with anthrax spores for 40 years after biological warfare tests were carried out there in the 1940s. And in 1981 Rex Watson, then head of Britain's Chemical and Biological Defense Establishment, asserted that if Berlin had been bombarded with anthrax bacteria during World War II, the city would still be contaminated.

Although many Israelis did become accustomed to wearing gas masks during the 1991 Persian Gulf War, it seems unrealistic to expect large populations of civilians to wear such gear for months or years, especially in warm regions. U.N. inspectors in Iraq report that in hot weather they can scarcely tolerate wearing a mask for more than 15 minutes at a time.

Calls for more robust biological defense programs have grown, particularly after the Persian Gulf War. Proponents of increased funding for biological defense research often imply that vaccines and special gear developed through such work can protect the public as well as troops. But the same truths hold for both the military and civilians: unless an attack organism is known in advance and is vulnerable to medical interventions, defense can be illusory.

Indeed, the Gulf War experience was in certain respects misleading. Iraq's biological weapons were understood to be anthrax bacilli and botulinum toxin. (Although toxins are inanimate products of microorganisms, they are treated as biological agents under the terms of the 1972 Biological Weapons Convention.) Both are susceptible to existing vaccines and treatments, and protection of military forces therefore seemed possible. Research that would lead to enhanced defense against these agents is thus generally warranted.

But the improbabilities of warding off attacks from less traditional agents deserve full appreciation. Anticipating that research can come up with defens-

A 1969 United Nations report indicated that the expense of stockpiling gas masks, antibiotics, vaccines and other defensive measures for civilians could exceed $20 billion. That figure, when adjusted for inflation, would now be about $80 billion.

es against attack organisms whose nature is not known in advance seems fanciful. Moreover, even with all its limitations, the cost of building a national civil defense system against biological and chemical weapons would be substantial. A 1969 United Nations report indicated that the expense of stockpiling gas masks, antibiotics, vaccines and other defensive measures for civilians could exceed $20 billion. That figure, when adjusted for inflation, would now be about $80 billion.

Vaccines and protective gear are not the only challenges to biological defense. Identifying an organism quickly in a battlefield situation, too, is problematic. Even determining whether a biological attack has been launched can be uncertain. Consequently, the Pentagon has begun to focus more on detection.

In May 1994 Deputy Secretary of Defense John Deutch produced an interagency report on counterproliferation activities concerning weapons of mass destruction. Biological agent detectors in particular, he wrote, were "not being pursued adequately." To the annual $110 million budgeted for the development of biological and chemical weapons detection, the report recommended adding $75 million. Already under way were Pentagon-sponsored programs involving such technologies as ion-trap mass spectrometry and laser-induced breakdown spectroscopy, approaches that look for characteristic chemical signatures of dangerous agents in the air. The army's hope, which its spokespersons admit is a long way from being realized, is to find a "generic" detector that can identify classes of pathogens.

Meanwhile the military is also advancing a more limited approach that identifies specific agents through antibody-antigen combinations. The Biological Integrated Detection System (BIDS) exposes suspected air samples to antibodies that react with a particular biological agent. A reaction of the antibody would signify the agent is present, a process that takes about 30 minutes.

BIDS can now identify four agents through antibody-antigen reactions: *Bacillus anthracis* (anthrax bacterium), *Y. pestis* (bubonic plague), botulinum toxin (the poison released by botulism organisms) and staphylococcus enterotoxin B (released by certain staph bacteria). Laboratory investigations to identify additional agents through antibody-antigen reactions are in progress. But scores of organisms and toxins are viewed as potential warfare agents. Whether the full range, or even most, will be detectable by BIDS remains uncertain.

The most effective safeguard against biological warfare and biological terrorism is, and will be, prevention. To this end, enhanced intelligence and regulation of commercial orders for pathogens are important. Both approaches have been strengthened by provisions in the antiterrorism bill enacted earlier this year. At the same time, attempts to identify and control emerging diseases are gaining attention. One such effort is ProMED (Program to Monitor Emerging Diseases), which was proposed in 1993 by the 3,000-member Federation of American Scientists.

Although focusing on disease outbreaks in general, supporters of ProMED are sensitive to the possibility of man-made epidemics. The ProMED surveillance system would include developing baseline data on endemic diseases throughout the world, rapid reporting of unusual outbreaks, and responses aimed at containing disease, such as providing advice on trade and travel. Such a program could probably distinguish disease outbreaks from hostile sources more effectively than is currently possible.

In addition, steps to strengthen the 1972 Biological Weapons Convention through verification arrangements—including on-site inspections—should be encouraged. The 139 countries that are parties to the convention are expected to discuss incorporating verification measures at a review conference in December of this year. After the last review conference, in 1991, a committee to explore such measures was established. VEREX, as the group was called, has listed various possibilities ranging from surveillance of the scientific literature to on-site inspections of potential production areas, such as laboratories, breweries and pharmaceutical companies.

Given the ease with which bioweapons can be produced, individuals will always be able to circumvent international agreements. But the absence of such agents from national arsenals—and tightened regulations on the acquisition and transfer of pathogens—will make them more difficult to obtain for hostile purposes. Verification can never be foolproof, and therefore some critics argue that verification efforts are a waste of time. Proponents nonetheless assert that sanctions following a detected violation would provide at least some disincentive to cheaters and are thus preferable to no sanctions at all. Furthermore, a strengthened global treaty underscores a commitment by the nations of the world not to traffic in these weapons.

The infrequent use of biological weapons to date might be explained in many ways. Some potential users have probably lacked familiarity with how to develop pathogens as weapons; moreover, they may have been afraid of infecting themselves. Nations and terrorists alike might furthermore be disinclined to use bioagents because they are by nature unpredictable. Through mutations, a bacterium or virus can gain or lose virulence over time, which may be contrary to the strategic desires of the people who released it. And once introduced into the environment, a pathogen may pose a threat to anybody who goes there, making it difficult to occupy territory.

But beneath all these pragmatic concerns lies another dimension that deserves more emphasis than it generally receives: the moral repugnance of these weapons. Their ability to cause great suffering, coupled with their indiscriminate character, no doubt contributes to the deep-seated aversion most people have for them. And that aversion seems central to explaining why bioweapons have so rarely been used in the past. Contrary to analyses that commonly ignore or belittle the phenomenon, this natural antipathy should be appreciated and exploited. Even some terrorists could be reluctant to use a weapon so fearsome that it would permanently alienate the public from their cause.

### The Poison Taboo

In recognition of these sentiments, the 1972 Biological Weapons Convention describes germ weaponry as "repugnant to the conscience of mankind." Such descriptions have roots that reach back thousands of years. (Not until the 19th century were microorganisms understood to be the cause of infection; before then, poison and disease were commonly seen as the same. Indeed, the Latin word for "poison" is "virus.")

Among prohibitions in many civilizations were the poisoning of food and wells and the use of poison weapons. The Greeks and Romans condemned the use of poison in war as a violation of *ius gentium*—the law of nations. Poisons and other weapons considered inhumane were forbidden by the Manu Law of India around 500 B.C. and among the Saracens 1,000 years later. The prohibitions were reiterated by Dutch statesman Hugo Grotius in his 1625 opus *The Law of War and Peace,* and they were, for the most part, maintained during the harsh European religious conflicts of the time.

Like the taboos against incest, cannibalism and other widely reviled acts, the taboo against poison weapons was sometimes violated. But the frequency of such violations may have been minimized because of their castigation as a "defalcation of proper principles," in the words of the 18th- and 19th-century English jurist Robert P. Ward. Under the law of nations, Ward wrote, "Nothing is more expressly forbidden than the use of *poisoned* arms" (emphasis in original).

Historian John Ellis van Courtland Moon, now professor emeritus at Fitchburg State College in Massachusetts, contends that growing nationalism in the 18th century weakened the disinclinations about poison weapons. As a result of what Moon calls "the nationalization of ethics," military necessity began to displace moral considerations in state policies; nations were more likely to employ any means possible to attain their aims in warfare.

In the mid-19th century, a few military leaders proposed that toxic weapons be employed, although none actually were. Nevertheless, gas was used in World War I. The experience of large-scale chemical warfare was so horrifying that it led to the 1925 Geneva Protocol, which forbids the use of chemical and bacteriological agents in war. Images of victims gasping, frothing and choking to death had a profound impact. The text of the protocol reflects the global sense of abhorrence. It affirmed that these weapons had been "justly condemned by the general opinion of the civilized world."

Chemical and biological weapons were used in almost none of the hundreds of wars and skirmishes in subsequent decades—until Iraq's extensive chemical attacks during the Iran-Iraq war. Regrettably, the international response to Iraqi behavior was muted or ineffective. From 1983 until the war ended in 1988, Iraq was permitted to get away with chemical murder. Fear of an Iranian victory stifled serious outcries against a form of weaponry that had been universally condemned.

The consequences of silence about Iraq's behavior, though unfortunate, were not surprising. Iraqi ability to use chemical weapons with impunity, and their apparent effectiveness against Iran,

## Potential Biological Agents

***Bacillus anthracis.*** Causes anthrax. If bacteria are inhaled, symptoms may develop in two to three days. Initial symptoms resembling common respiratory infection are followed by high fever, vomiting, joint ache and labored breathing, and internal and external bleeding lesions. Exposure may be fatal. Vaccine and antibiotics provide protection unless exposure is very high.

**Botulinum toxin.** Cause of botulism, produced by *Clostridium botulinum* bacteria. Symptoms appear 12 to 72 hours after ingestion or inhalation. Initial symptoms are nausea and diarrhea, followed by weakness, dizziness and respiratory paralysis, often leading to death. Antitoxin can sometimes arrest the process.

***Yersinia pestis.*** Causes bubonic plague, the Black Death of the Middle Ages. If bacteria reach the lungs, symptoms—including fever and delirium—may appear in three or four days. Untreated cases are nearly always fatal. Vaccines can offer immunity, and antibiotics are usually effective if administered promptly.

**Ebola virus.** Highly contagious and lethal. May not be desirable as a biological agent because of uncertain stability outside of animal host. Symptoms, appearing two or three days after exposure, include high fever, delirium, severe joint pain, bleeding from body orifices, and convulsions, followed by death. No known treatment.

prompted more countries to arm themselves with chemical and biological weapons. Ironically, in 1991 many of the countries that had been silent about the Iraqi chemical attacks had to face a chemically and biologically equipped Iraq on the battlefield.

To its credit, since the Persian Gulf War, much of the international community has pressed Iraq about its unconventional weapons programs by maintaining sanctions through the U.N. Security Council. Council resolutions require elimination of Iraq's biological weapons (and other weapons of mass destruction), as well as information about past programs to develop them. Iraq has been only partially forthcoming, and U.N. inspectors continue to seek full disclosure.

But even now, U.N. reports are commonly dry recitations. Expressions of outrage are rare. Any country or group that develops these weapons deserves forceful condemnation. We need continuing reminders that civilized people do not traffic in, or use, such weaponry. The agreement by the U.S. and Russia to destroy their chemical stockpiles within a decade should help.

Words of outrage alone, obviously, are not enough. Intelligence is important, as are controls over domestic and international shipments of pathogens and enhanced global surveillance of disease outbreaks. Moreover, institutions that reinforce positive behavior and values are essential.

The highest priority of the moment in this regard is implementation of the Chemical Weapons Convention, which outlaws the possession of chemical weapons. It lists chemicals that signatory nations must declare to have in their possession. Unlike the Biological Weapons Convention, the chemical treaty has extensive provisions to verify compliance, including short-notice inspections of suspected violations. It also provides added inducements to join through information exchanges and commercial privileges among the signatories.

In 1993 the chemical treaty was opened for signature. By October 1996, the pact had been signed by 160 countries and ratified by 64, one less than the number required for the agreement to enter into force. One disappointing holdout is the U.S. In part because of disagreements over the treaty's verification provisions, the U.S. Senate recently delayed a vote on the pact.

Implementing this chemical weapons treaty should add momentum to the current negotiations over strengthening the Biological Weapons Convention. Conversely, failure of the Chemical Weapons Convention to fulfill expectations will dampen prospects for a verification regime for the biological treaty. The most likely consequence would be the continued proliferation of chemical and biological arsenals around the world. The longer these weapons persist, the more their sense of illegitimacy erodes, and the more likely they will be used—by armies and by terrorists.

As analysts have noted, subnational groups commonly use the types of weapons that are in national arsenals. The absence of biological and chemical weapons from national military inventories may diminish their attractiveness to terrorists. According to terrorism expert Brian M. Jenkins, leaders of Aum Shinrikyo indicated that their interest in chemical weapons was inspired by Iraq's use of chemicals during its war with Iran.

Treaties, verification regimes, global surveillance, controlled exchanges of pathogens—all are the muscle of arms control. Their effectiveness ultimately depends on the moral backbone that supports them and the will to enforce them rigorously.

By underscoring the moral sense behind the formal exclusion of biological weapons, sustaining their prohibition becomes more likely.

## Defenses against Biological Weapons

**Respirator or gas mask.** Filters, usually made of activated charcoal, must block particles larger than one micron. Overgarments are also advisable to protect against contact with open wounds or otherwise broken skin.

**Protective shelter.** Best if a closed room, ideally insulated with plastic or some other nonpermeable material and ventilated with filtered air.

**Decontamination.** Such traditional disinfectants as formaldehyde are effective for sterilizing surfaces.

**Vaccination.** Must be for specific agent. Some agents require several inoculations over an extended period before immunity is conferred. For many agents, no vaccine is available.

**Antibiotics.** Effective against some but not all bacterial agents (and not effective against viruses). For some susceptible bacteria, antibiotic therapy must begin within a few hours of exposure—before symptoms appear.

**Detection systems.** Only rudimentary field units currently available for a few specific agents. Research is under way to expand the number of agents that can be detected in battlefield situations or elsewhere.

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# Fighting Future Wars

*U.S. military planners hope to rely on improved versions of the technologies tested in the Gulf War to help fight the next Saddam Hussein. They may be preparing for the wrong conflict*

by Gary Stix, *staff writer*

George Patton, Dwight Eisenhower and Colin Powell all came to Fort Leavenworth on the Kansas bluffs overlooking the Missouri River to learn about the tactics and weaponry they would need in battle. This past May a new generation of military leaders peered into Sun workstations at this former Indian-fighting post to discern the future of warfare. On their screens, a North Korean force rolled across the demilitarized zone; short-range ballistic missiles carrying chemical weapons hit their mark in South Korean cities. U.S. and South Korean army divisions, with support from U.S. Marines and a French and a British brigade, slowly drove the invading troops back.

One of the U.S. units, a division called a mobile strike force, pretended to mimic the digital fighting force of the future. Pictures of the battlefield, supplied by ground, airborne and satellite sensors, provided a field commander with a sweeping view of the disputed territory, even at night. This "God's-eye" battlefield perspective helped to cement a victory.

The hostilities were what is known in Department of Defense parlance as a "Desert Storm equivalent"—a standoff against a "rogue state," an Iran or an Iraq or a North Korea. For the Pentagon, rogues are the most likely new enemy, the nuclear pretenders that pose the real menace in the post-cold-war world. According to the Clinton administration's 1993 "bottom-up review," the document that assesses the current military force structure, the U.S. should be prepared to fight two Desert Storm equivalents almost simultaneously.

But the young officers may be getting the wrong perspective from the images on those color screens. The classic rogue power relying on heavy-handed, Soviet-style fighting techniques may be an endangered species. Policy experts, technical gurus and defense contractors have begun to study a range of other potential threats, from a newly hatched superpower to a regional power with dramatically altered fighting tactics, to legions of mercenary hackers that bring down banks and stock exchanges with computer viruses and other malevolent software. The vast array of scenarios is a measure of the speculative turn that has gripped the military-planning establishment. Without the tangible presence of a superpower, new menaces can emerge from any quarter. At the same time, the most pressing drain on military resources is created by the Bosnias and the Haitis, the smaller-scale conflicts and crises that often turn contemporary soldiering into glorified police work.

The American military's high-tech expertise was honed over decades of cold war with the Soviet Union. During the 1980s, the Soviets put forward the notion that military forces should be able to detect an enemy and destroy it from a distance. As radar-laden surveillance aircraft and intelligent antitank missiles became more pivotal in the contest, however, the U.S. acquired a clear advantage. "If the key to future war-

BATTLEGROUND CIRCA 2020 may replace massed troops and armor with networks of intelligent mines and unpiloted drones that can perform reconnaissance and launch or plant weapons. Highly dispersed special forces may scout for targets and evaluate battle damage. Remotely fired missiles may become the main instrument for destroying enemy targets.

fare would be the rapid processing of electronically acquired information, how could a society that was virtually incapable of manufacturing a simple personal computer keep up in the technological race?" writes Eliot A. Cohen of the Paul H. Nitze School of Advanced International Studies at Johns Hopkins University.

### Replaying Desert Storm

World War III never came, but the Gulf War did. The U.S. armed forces held up the victory over Iraq as proof of the validity of their technophilic approach to fighting, involving intelligence from air and space and the use of stealth fighters and laser-guided bombs. (No matter that, notwithstanding the domination of the air, the coalition forces missed destroying installations involved in the Iraqi nuclear weapons program and mobile missile launchers.) Much of the subsequent effort of military leaders has gone toward burnishing the accomplishments of the Gulf. The army's war games, such as the exercise at Fort Leavenworth, have been oriented toward improving the digital layout of the battlefield—in essence, fighting a more efficient Gulf War.

A coterie of defense analysts, both inside and outside the Pentagon, have nonetheless begun to explore concepts of high-tech war that move beyond a replay of Desert Storm. The inspiration for some of this soul-searching comes from the Pentagon's Office of Net Assessment, a future-oriented planning office headed by Andrew Marshall, a former cold-war strategist.

One reason for a reassessment is that, within a few decades, the threat to the U.S. may come not from a small rogue regional power but instead from what has come to be known as a "peer competitor": in essence, a new superpower, such as China, a resurgent Russia or perhaps even India. In any future conflict, the U.S. and its allies may not have a monopoly, or even a strategic advantage, in the arena of advanced technology. Furthermore, regional powers have learned their own lessons from the Gulf War and are looking for ways to use and counter precision-guided weapons, computers and space-based communications.

Andrew F. Krepenevich, Jr., a former army colonel who collaborated with Marshall, now directs the Defense Budget Project, a think tank in Washington, D.C., that continues to examine radical changes in the character of warfare. He points to articles in Third World technical journals that talk about the Gulf War as the example of what to avoid when confronting an "extraregional superpower," a code phrase for the U.S. or any large industrial state. In a paper published af-


BARRY ROSS

ter the Gulf conflict, V. K. Nair, a retired Indian military officer, outlined how a developing nation could have countered "ill-conceived adventurism" by the U.S. by crippling naval forces with land- or submarine-based nonnuclear missiles. "The possibility of the loss of one or more aircraft carriers would be a totally unacceptable risk in terms of economic and personnel losses for the United States," he wrote.

In world arms markets, an advanced weapons stockpile is available virtually for the asking. Short-range ballistic missiles and, in particular, information technologies have become commodities. Unlike nuclear weapons systems that often arose from secret work at national laboratories, Krepenevich points out that information systems have come from commercial companies. Although the U.S. and the Soviet Union largely succeeded in preventing access to the technologies needed to fabricate nuclear weapons, they would now be incapable of doing so for the memory chips or microprocessors that are the brains of "smart" weaponry.

### A Real No-Man's-Land

Think tanks and strategists have begun to ponder what it will mean to fight in the 21st century. Many of their speculations on what is often called a "revolution in military affairs" seek a way to fight another large power without resorting to nuclear weapons or to find the means to stay far enough away from an adversary to avoid a nuclear menace or chemical or biological armaments. Future war, in fact, may let former nuclear war planners retread a few of the scenarios conceived for a face-off with the Soviets. It might rely on nuclear-weapons delivery vehicles—cruise or other long-range missiles—armed with conventional warheads.

The lethality and precision of the weaponry, and the ability to detect an enemy virtually anywhere, suggest it will become all quiet on every front—the idea of close engagement, still a fixture of the Gulf War, will fade. Michael Mazaar of the Center for Strategic and International Studies describes "disengaged" conflict, a war fought from a distance that proceeds without a massing of troops and weapons. Missiles fired from hundreds or thousands of miles away, or even from the continental U.S., might converge on a single location or several strategic targets at once.

In this long-term scenario, aircraft carriers, tanks, fighters and bombers may cease to have a primary role in the postmodern theater of war. Most U.S. forces might be stationed at home. During the first stages of a conflict, long-range missiles would destroy air defenses or other key infrastructure. Later, inexpensive staging platforms would be needed to field large numbers of missiles, weapons systems far less expensive than the submarines and aircraft carriers now used. Some analysts have even toyed with the notion of a missile-laden Boeing 747 or a subsurface tug carrying a barge crammed with projectiles.

The navy, in fact, has begun to consider building an arsenal ship, which might be a tankerlike vessel loaded with hundreds of vertically launched cruise missiles or other projectiles. The arsenal ship, which would be partially submerged to avoid detection, is estimated to cost less than a fifth of the purchase price of a $4.5-billion aircraft carrier. Instead of a crew numbering in the thousands, it might need fewer than 50 people.

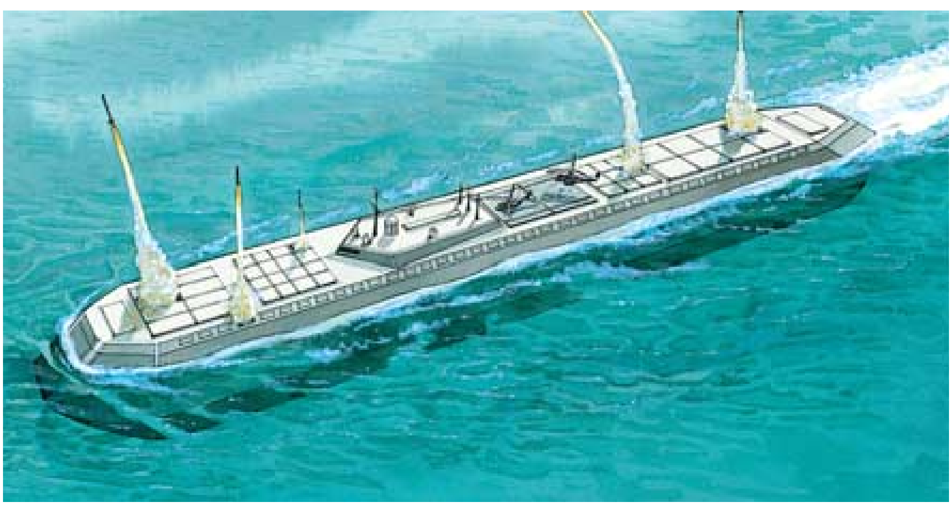
Big changes would occur in land warfare as well. At least in the early stages of a conflict, in a step toward the science-fiction fantasy of robotic warfare, most human soldiers might be kept well away from the battlefield. The reconnaissance and targeting role will increasingly be taken over by unpiloted aircraft, highly novel versions of those flown during Desert Storm and in Bosnia. Tiny, low-cost sensors in the air or on the ground might be deployed by the hundreds or thousands, forming a network that could beam a composite image of an unfolding skirmish.

Electronic intelligence today depends heavily on large aircraft filled with sensors—the air force's advanced warning and control system (AWACS) or the army's joint surveillance target-attack radar system (JSTARS). Precisely because the battle view supplied would become ever more crucial, an AWACS or a JSTARS would be increasingly vulnerable: if shot down, it could cause an electronically illuminated battlefield to go dark. Safety in numbers may be the answer. A research group at the Massachusetts Institute of Technology's Lincoln Laboratory has contemplated building drones smaller than a model airplane. Eventually, large numbers of these minute craft could collectively act as battle surveyors. Sikorsky Aircraft has fashioned a flying-saucerlike vehicle, powered by rotary motors, that could act as a scout or drop mines or sensors. "If you have 1,000 unmanned aerial vehicles, you can afford to lose 100," says Martin C. Libicki of the National Defense University.

At least in theory, land-based weapons could also become smart, numerous and relatively cheap. Lethal robots may look less like the Terminator than like a mine. Military contractor Textron Systems Division, for example, already has a "wide area mine" that uses sensors to detect a tank or helicopter and then launches projectiles at it.

The few manned units sent to the battlefield would consist of dispersed special operations units that could perform reconnaissance missions or determine battle damage. Contingents spread out over the landscape might ride in stealthy attack helicopters or commercially purchased Jeeps, the chassis only lightly armed but crammed full of sensors and communications and jamming gear. Toward the latter stages of a conflict, more conventional armored and infantry forces would arrive; combat might still end by occupying territory.

Future war might become a contest


BARRY ROSS

ARSENAL SHIP, with a design perhaps based on that of commercial tankers, could carry hundreds of missiles. The semisubmersible vessel might one day play a strategic role—deploying weapons to their targets—that now is filled by the airplanes on a carrier.

for domination of space, as both sides try to deploy and preserve communications and surveillance satellites. Concocting lasers or weapons that employ the kinetic energy of a high-impact collision to kill satellites might give aging Strategic Defense Initiative scientists a chance to dust off old research papers. Single-stage-to-orbit launch vehicles might be needed to place a network of satellites over a battle area.

The most important changes may relate not to the technology but to the way these systems transform military organization—and the pace at which decisions are made. "The real innovation may be the ability to integrate sensors and weapons to coordinate forces effectively," says Andrew Marshall of the Office of Net Assessment. In the year 2020 the panoramic image of battle that emerges from the mesh of sensors may make military commanders more into split-second air-traffic controllers than deliberative strategists and tacticians. The same commander may order weapons strikes from air, land or sea—or maybe even space. In some cases, targeting information may be beamed directly from a satellite or an unmanned aerial vehicle to a soldier in the field.

## War by Wire

Debate on high-tech fighting culminates in the question of whether information technologies—a computer virus, for one—could make conventional military hardware obsolete and whether they would make possible a virtual invasion of the continental U.S. A battle of the bits would be fought by destroying an enemy's information assets, its financial, electrical, telecommunications and air-traffic-control networks. Direct strikes at the military would not be ruled out: cracking a government computer is already a not infrequent hacker rite of passage. In addition, more than 95 percent of military communications travel over public networks.

Daniel T. Kuehl is a professor of military strategy at the National Defense University, who earlier in his career worked for the Strategic Air Command planning where to aim nuclear weapons at the Soviet Union. He now teaches at the School of Information Warfare and Strategy, established two years ago at this graduate military school. The program offers courses in cyber-war similar to those that have recently sprouted throughout the military. It joins a number of offices in the Pentagon and the various services that bear the name "information warfare."

Kuehl's students will return to the armed forces and other government posts to help defend against attacks on information resources. "How do you know you're under attack and who did it?" Kuehl asks his classes. Other points for discussion: Does the military have any responsibility for defending the stock market against malicious attack? Should a nation declare war when a major financial system is brought down through electronic means? Should it respond with conventional or nuclear weapons? When is victory achieved in such a conflict? Should the U.S. engage in offensive information maneuvers to destroy or muddle databases an enemy uses to choose targets?

## Tofflerian Wave Theory

These questions often get mixed with a large helping of popular sociology. The School of Information Warfare and Strategy may be the first graduate program to frame a course of study around the ideas of mass-market authors Alvin and Heidi Toffler, perhaps best known these days as consultants to Speaker of the House Newt Gingrich. The Tofflers have had a pervasive influence on the military. In a monograph entitled "Envisioning Future Warfare," recently retired army Chief of Staff General Gordon Sullivan cites Alvin Toffler in 10 of 38 references.

At the school of information warfare, the world becomes segmented by the Tofflers' "wave" theory, the notion that society—and war itself—is passing into a postindustrial information age that follows a "second wave" industrial era characterized by the use of tanks and bombers and a "first wave" agrarian economy that employed muskets and spears. "As the Third Wave war-form takes shape, a new breed of 'knowledge warriors' has begun to emerge—intellectuals in and out of uniform dedicated to the idea that knowledge can win, or prevent, wars," the Tofflers write earnestly in War and Anti-War.

> Debate on high-tech fighting culminates in the question of whether information technologies a computer virus, for one—could make conventional military hardware obsolete and whether they would make possible a virtual invasion of the continental U.S.

Elite corps of knowledge warrior-hackers may not be able completely to replace conventional divisions of 20,000 armed grunts. John I. Alger, dean of the information warfare school, lapses into Tofflerese to explain why. "Most of the world still has second-wave armies, and we still have to concern ourselves with physical destruction as a threat to the U.S.," he says.

This vision of wars to come may emerge from reading too many futuristic treatises. Not everyone in the defense establishment warms to embracing the new fighting methods so quickly. The military still treasures its aircraft carriers and fighter planes. Reticence may also stem from a fear that the new technologies may not work as expected. Two sides lobbing missiles at each other may revive an apocalyptic form of trench warfare in which each side bloodies the other but fails to achieve victory. "It may be a long-range equivalent of 1914," says Daniel Gouré of the Center for Strategic and International Studies in reference to the World War I stalemate.

And flooding more information to soldiers may not give them a better grasp of an unfolding battle. The U.S. military has wrestled with the travails of the information age since the Vietnam War. Instead of streamlining the management of war, the expanding communications infrastructure in Southeast Asia led to a burgeoning of support personnel. Five percent of all troops there—a unit larger than a division—handled communications. In his 1985 book, Command in War, historian Martin van Creveld of the Hebrew University in Israel notes that "the communications establishment made possible by the revolution in technology, and necessary in order to deal with the consequences of specialization and complexity, had itself turned into a major source of both specialization and complexity. The cure was part of the disease."

Things have not necessarily changed. The U.S. Army has stated its intention of using high technology to decrease the size of its forces. But this past August, in a war game that deployed armored units to test digital communications systems, soldiers found they had more work—time spent putting information into computers or connecting one system to another, according to a report in the independent newsletter Inside the Army. After the exercise, an officer offered the opinion that the targeting efficiency of a new tank, the M1A2, might improve fighting capability more than advanced digital communications could.

In another war game in 1994, a digital battalion became confused when a nonautomated opponent lit fires to fool, or "spoof," infrared sensors deployed by the high-tech forces. What is more, the digital soldiers performed no

## A Faster, Cheaper, Smaller Military?

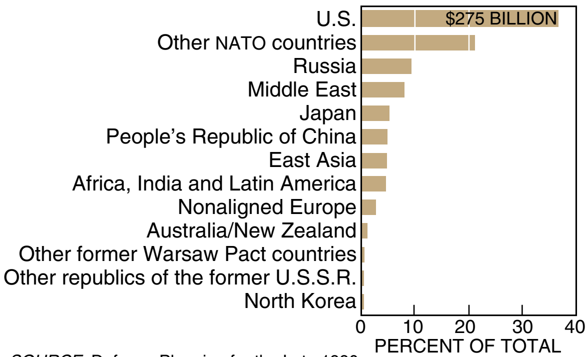
Defense budgets have dropped somewhat in inflation-adjusted dollars from their cold-war average of $300 billion. Nevertheless, with expenditures totaling about $260 billion for the current fiscal year, the U.S. spends more on defense than every prospective enemy and neutral country combined. "We could probably cut defense spending by $35 billion and still remain the world's preeminent military power," notes Lawrence Korb, a senior fellow at the Brookings Institution and a former assistant secretary of defense in the Reagan administration. (The chart below conveys an idea of the magnitude of U.S. spending for 1993.)

A war that emphasizes precision-guided missiles and commercially procured information and transport technologies might cost less to fight than one that relies on large weapons systems, a Seawolf submarine and an F-22 fighter. Moreover, readying military forces to fight two almost simultaneous Desert Storm–like conflicts may prove an unnecessary extravagance in an era of budget tightening. The Defense Budget Project, an independent research organization, has recommended that preparing to fight only one regional conflict may be a means to free up funding to experiment with new technologies—an arsenal ship or networks of unmanned aerial vehicles.

But the track record on embracing wholly new types of warfare is not particularly good. In 1978, more than a decade before the end of the cold war, physicist Philip Morrison and political scientist Paul F. Walker wrote a book on military spending that suggested that a relatively inexpensive national defense could be built around precision munitions, thereby forgoing vulnerable weapons platforms such as the aircraft carrier. Budgets, they asserted, could be cut by 40 percent. Their ideas, of course, have remained no more than academic treatise. "We want to say warfare is changing, but not ours," Morrison remarks today.

Scenarios for future wars, in fact, could simply become a means of preserving the status quo. "Is the Pentagon's Revolution in Military Affairs a scam?" writes Steven Aftergood of the Federation of American Scientists. "Could it be just another, more seductive way of packaging military programs to help sustain defense budgets at a time when the long-standing military justification for existing structures and programs has diminished sharply?"

**GLOBAL MILITARY EXPENDITURES IN 1993**




*SOURCE:* Defense Planning for the Late 1990s, *by Michael O'Hanlon (Brookings Institution, 1995)*

better than other units that had fought the same opponent without advanced equipment.

Issues of cost and technical feasibility also pervade the debate over the naval arsenal ship. The new vessel might not be such a bargain. It has to travel with other ships for protection. An electronic message posted on the Internet lampooned the idea: "One low-tech incoming, and we could double the national debt," a suggestion of what might happen to an arsenal ship if targeted by an inexpensive missile.

### Low-Intensity Conflict

If the military is looking for the nature of war in the next century, it may be looking in the wrong place. By some accounts, the generals have yet to learn the lessons—or adapt their war-fighting methods—to the type of conflict that has predominated since World War II. This argument represents a broadside on the school of military thinking associated with Carl von Clausewitz, the Prussian army officer whose writings on war are often distilled to the cliché that war is a continuation of politics by other means. This intersecting notion of politics and armed conflict can be linked to the idea that the modern state and its armies are the only legitimate purveyor of organized violence. Anyone else taking up arms is either an outlaw or a bandit.

A number of military historians have declared the Clausewitzian world of states fighting states to be effectively dead. In his book The Transformation of War—published, in a grim irony, on the day the ground offensive of the Gulf War was launched in 1991—van Creveld argues that the terms of modern warfare and the costs of advanced weapons systems are making traditional combat ever less likely. In a nuclear era, all sides must exercise restraint or risk mutual annihilation. This measure of self-control, van Creveld believes, also extends to the use of chemical and biological arms. Few nations would dare to unleash them against an enemy, for fear that the retaliation, by the attacked state or one of its more powerful allies, might be a nuclear strike. (Unfortunately, chemical and biological weapons might still become the inexpensive weapons of choice among terrorists, who would not be constrained by this vulnerability.)

In a world populated by nuclear weapons and their cousins, war has not gone away but simply shifted to another arena. Van Creveld maintains that most conflicts—Somalia, Rwanda and even Bosnia—do not involve state against state and that these wars take place largely without deploying advanced weaponry. Of the 100 or so wars fought since World War II, more than 80 have been characterized as low-intensity conflicts, many of which are civil wars or ethnic hostilities. They are often engendered over scarcity of resources [see "Environmental Change and Violent Conflict," by Thomas F. Homer-Dixon, Jeffrey H. Boutwell and George W. Rathjens; SCIENTIFIC AMERICAN, February 1993]. Low-level struggles, despite the modest sound of the name, often attain genocidal levels of bloodshed. The Nigerian civil war claimed the lives of more than one million people from 1967 to 1970, and turmoil between Hindus and Muslims in India took a toll of one million from 1947 to 1949. The neat categorizations on the nature of warfare set out in the Clausewitzian universe have been completely lost in the strife.

Peacekeeping has therefore become the order of the day. Unfortunately, that order flummoxes many in a military elite that has spent decades preparing to stop waves of Soviet tanks from rolling across across the West German border. These officers, too, still experience lingering effects of a post-Vietnam syndrome, that soldiers should leave the barracks only to protect clear-cut threats to the national interest. In a 1993 U.S. Army manual this type of quasi-police activity is relegated to a chapter with the Orwellian title "Operations Other Than War."

The various service branches do train for what is reduced to the inevitable acronym "OOTW." The army, for one, has set up a peacekeeping institute at its Army War College in Carlisle, Pa. But the military and Congress have a decidedly ambivalent relationship to these types of conflicts. Chairman of the Joint Chiefs of Staff General John Shalikashvili commented last year: "My fear is we're becoming mesmerized by operations other than war, and we'll take our mind off what we're all about, [which is] to fight and win our nation's wars."

Nevertheless, the military has devoted some effort to devising weapons and tactics more appropriate to the next Somalia than the B-2 bomber and the Trident submarine are. The army, the Department of Energy, the Advanced Research Projects Agency and other research institutes have labored on technologies that would minimize the bloodshed, or at least the public-relations sting, of these nasty and brutish affairs.

Lawrence Livermore National Laboratory has devised an infrared sensing system, called Lifeguard, that could be used by peacekeepers or even police to detect the precise location from which a sniper's bullets originate. The Advanced Research Projects Agency has equipped U.S. soldiers on a peacekeeping mission in Macedonia with a combination rescue-radio and satellite-location receiver that beeps when a soldier or vehicle gets within 500 meters of the Serbian border. (Crossing the border inadvertently could cause an international incident.)

A set of unusual technologies has begun to contribute to peacekeeping. "Nonlethal" weapons are intended to stun or immobilize but spare their victims. A chemical that makes a street slippery or sticky, rendering it impassable to traffic and passersby, may deflect public condemnation. "Rather than shooting a 14-year-old boy, you stop him with sticky glue," says Andrew J. Bacevich of the Nitze School at Johns Hopkins. "You can do an operation without having the media lambaste you for inhumane and cruel treatment."

U.S. marines dispersed a mix of sticky foam, concertina wire and small, pointed objects that look like jacks to hold off crowds of Somalis during the withdrawal of U.N. peacekeeping troops in early March, says Charles S. Heal, the marine officer who coordinated the use of these weapons. The troops had a five-minute respite before the Somalis put down planks and used a number of other ploys that enabled them to traverse the barrier.

Threats of force were perhaps as effective in Mogadishu. Training a visible laser used to illuminate targets on trespassers who made their way onto a runway kept loyalists to warlord Mohammed Farah Aidid outside the airport perimeter. "The guys had seen enough Schwarzenegger movies to know it worked," says Anthony Fainberg of the recently disbanded Office of Technology Assessment.

The nonlethals are subject to the same dynamics as other weapons technologies—any armament engenders countermeasures. "Sand spread on the stickum-coated pavement would presumably stick (what else?) and provide a sandpaper surface on which one could walk or drive," writes Richard L. Garwin, an IBM fellow and a longtime adviser on defense technologies and arms control. "Before sand could be spread, attaching a pad of newspaper on the sole…would allow one step per page—enough to cross a small region of stickum-covered pavement at high speed."

Nonlethals also bear a taint of deadliness and may prove inhumane. "The grime from hell," as Garwin calls one hypothetical weapon, a thin layer of paint that can be sprayed onto an aggressor's windshield to obscure vision, could certainly cause a fatal loss of vehicle control. An international ban was recently approved on lasers that permanently blind victims, a type of weapon classified as nonlethal.

### Low-Tech Retaliation

Soldiers armed with weapons that do not kill face a fundamental dilemma in fighting a war. "To paraphrase Clausewitz," van Creveld says, "those who think war can be waged without bloodshed should be wary of an opponent coming along and cutting off their heads." While the West concocts kinder and gentler weapons, determined irregular fighters in the Third World (or elsewhere) may fail to observe a protocol that avoids deaths. The quintessential postindustrial war machine is a Somali "technical," a pickup truck with an automatic weapon mounted in the back.

Moreover, a Somali warlord or his ilk may not have to gain an ultimate strategic advantage to win. He may indulge in the subtleties of information warfare and global public relations by manipulating the power of satellite news broadcasting to influence an event without recourse to superior weaponry. The impact of television imagery of a dead U.S. soldier being dragged through the streets of Mogadishu most likely contributed to the U.S. decision to call off a hunt to track down Aidid and to set a date for a withdrawal of its troops.

A tribal leader, meanwhile, may conduct information warfare with technologies that predate Thomas Edison. Aidid's followers in Somalia reportedly communicated U.S. troop activity at the Somali airport to their peers by beating wooden sticks on oil barrels. To avoid detection, Aidid shunned use of the telephone altogether.

Messages encoded as drumbeats will leave suites of infrared sensors undisturbed. Technological sophistication, a prerequisite for strategic dominance in a regional theater of war, may thus founder in the chaos of a Saigon or a Mogadishu. "We're getting a lot of clever ideas about how to fight a Gulf War more efficiently," remarks Libicki of the National Defense University. "But we rarely get anything about how to fight a Vietnam more efficiently."

The disparity between war as a technological tour de force and the realities of low-level conflict have yet to be reconciled by the leaders of large standing armies. Precision bombing may achieve some success in Bosnia. But decisions to proceed with air strikes become muddied when U.N. troops are chained as hostages to Serb military targets. War at a distance—the vision put forth by the seers of future conflict—may quickly erode in the ambiguities of OOTW. Peacekeeping may confound the complex stratagems of nuclear planners, who have defined the nature of warfare for the past half century. The fragile cold-war balance of power has given way to a fog of peacetime.

### *Further Reading*

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Originally Published in the May 2001 Issue

# WARP D

## UNDER

**Traveling inside drag-cutting bubbles,**

# RIVE WATER

BY STEVEN ASHLEY

**secret torpedoes and other subsea naval systems can move hundreds of miles per hour**

*When the Russian submarine K-141* Kursk *sank last August, rumors rapidly arose that the mysterious blasts that sent the big boat to the bottom of the Barents Sea were connected to the testing of an ultrahigh-speed torpedo. Several months earlier, when American businessman* Edmond Pope was arrested in Moscow on charges of espionage, it was said that he had been trying to buy the plans for an ultrahigh-speed torpedo. Although the details surrounding both the tragic naval accident and the celebrated spy case remain unsettled, evidence does suggest that both incidents revolved around an amazing and little-reported technology that allows naval weapons and vessels to travel submerged at hundreds of miles per hour—in some cases, faster than the speed of sound in water. The swiftest traditional undersea technologies, in contrast, are limited to a maximum of about 80 mph.

Of late, it has become increasingly apparent that the world's major naval powers are developing the means to build entire arsenals of innovative underwater weapons and armadas of undersea watercraft able to operate at unprecedented speeds. This high-velocity capability—a kind of "warp drive" for water—is based on the physical phenomenon of supercavitation. This fluid-mechanical effect occurs when bubbles of water vapor form in the lee of bodies submerged in fast-moving water flows. The trick is to surround an object or vessel with a renewable envelope of gas so that the liquid wets very little of the body's surface, thereby drastically reducing the viscous drag. Supercavitating systems could mean a quantum leap in naval warfare that is analogous in some ways to the move from prop planes to jets or even to rockets and missiles.

Although current funding levels for supercavitation research are said to be modest (around $50 million in the U.S., for example), the list of potential supercavitating weapons and naval vessels is extensive and altogether startling. It includes high-speed underwater bullets aimed at mines, homing torpedoes, boats—even low-flying aircraft and helicopters—from submerged gun-pods that look like the turrets on World War II–era aerial bombers. Other possibilities include high-velocity antiship and antitorpedo torpedoes and "midrange unguided engagement breakers," which are larger weapons intended to force an end to a conflict between two submarines. Also envisioned are small, superfast surface craft as well as nuclear-capable subsea missiles designed to neutralize entire aircraft-carrier battle groups.

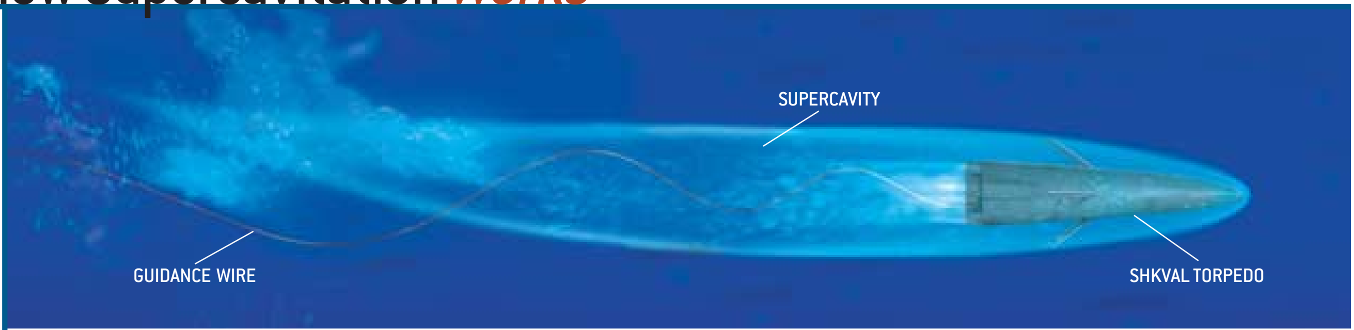
Some naval experts believe that supercavitating systems could alter the nature of undersea warfare, changing stealthy cat-and-mouse stalking contests between large submarines into something resembling aerial combat, featuring noisy high-speed dogfights among small, short-range "subfighters" shooting underwater bullets at one another after having been launched from giant "subcarriers."

## Overview/*Swift Subsea Weapons*

- The world's major navies are developing arsenals of innovative high-speed undersea weapons and vessels based on the phenomenon of supercavitation, which allows them to reduce hydrodynamic drag by traveling inside self-generated bubbles of water vapor and gas.
- The Russian navy has already deployed a rocket-powered supercavitating torpedo—the Shkval (Squall)—that is said to go 230 miles per hour. Cash-strapped Russia is looking to sell an improved version of the weapon to other countries. The Shkval has already turned up in France, China and Iran.
- The extensive list of potential supercavitating naval weapons includes short-range underwater projectiles to destroy mines and incoming torpedoes, high-velocity torpedoes, large subsea missiles for destroying entire battle groups, small ultrahigh-speed surface ships, and perhaps even supercavitating submarines. A long-range, multistage strategic torpedo/missile tipped with nuclear warheads that could possibly defeat "Star Wars" defenses has also been envisioned.

PHILIP HOWE (*preceding page*)

## How Supercavitation *Works*




WATER FLOWING RAPIDLY around an object causes the fluid pressure to fall. At speeds beyond about 50 meters per second, the pressure drops sufficiently to allow the water to dissociate into water vapor, forming a gas bubble behind the object (cavitation). When the gas bubble fully encloses the object, it is called supercavitation. Slender axisymmetric bodies, such as the high-speed Russian Shkval torpedo (above) create long ellipsoidal supercavities. High-velocity fluid flow (from the right) produces supercavitation above the top surface.

Other experts point to the possibility of fielding long-distance, multistage supercavitating torpedoes/ missiles fitted with nuclear warheads ("long-range guided preemptive weapons") that could prove to be a relatively cheap and effective counter to future "Star Wars" missile defense systems. These devices could dash in from many miles out at sea entirely underwater, pop out of coastal waters close to their targets, and drop their lethal payloads before any aerial or space-based defenses could react.

Surprisingly, we now know of at least one supercavitating weapon that has existed for many years. In 1977, after more than a decade of research and development, the Soviet navy secretly introduced a rocket-powered torpedo called the Shkval (Squall) that can "fly" through water at 100 meters per second (about 230 miles per hour) or more inside a self-generated gas cavity. Although this nuclear-tipped underwater missile is in some ways a bit crude and less than entirely effective, news of it in the early 1990s forced the Western military powers to take notice of supercavitating technology.

There's no doubt that many significant challenges beyond the merely technical would have to be addressed before any of these next-generation technologies achieves reality. Environmental concerns as well as navigation issues would have to be considered, for instance. Probably the biggest barrier to advancement would be finding sufficient capital to develop and build supercavitating marine systems. Nevertheless, history shows that military technology often finds financial support when money for other purposes is scarce.

"Since very few of these things have been built so far, in many ways we're at a stage similar to that of the airplane right after the Wright brothers first flew," says Robert Kuklinski, an engineer and hydrodynamics research scientist at the Naval Undersea Warfare Center (NUWC) Division Newport in Rhode Island, the lead U.S. Navy laboratory investigating supercavitating systems. "But unlike then, we know a lot more about the underlying physics and technology than those early aerial pioneers did."

Propelling a body through water takes considerable effort, as every swimmer knows. Speeding up the pace makes the task even harder because skin friction rises with increased velocity. Swimming laps entirely underwater is even more difficult, as water produces 1,000 times more drag resistance than air does.

### Supercavitation Fundamentals

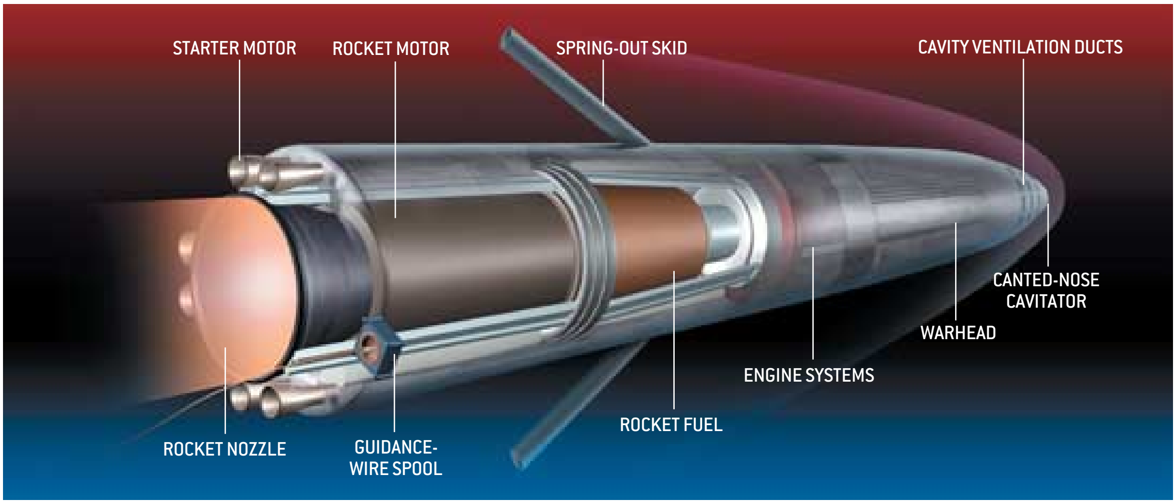
NAVAL ARCHITECTS AND marine engineers vie constantly with these age-old problems when they streamline the shapes of their hull designs to minimize the frictional drag of water and fit their ships with powerful engines to drive them through the waves. It can come as a shock, therefore, to find out that scientists and engineers have come up with a new way to overcome viscous drag resistance and to move through water at high velocities. In general, the idea is to minimize the amount of wetted surface on the body by enclosing it in a low-density gas bubble.

"When a fluid moves rapidly around a body, the pressure in the flow drops, particularly at trailing edges of the body," explains Marshall P. Tulin, director of the Ocean Engineering Laboratory at the University of California at Santa Barbara and a pioneer in the theory of supercavitating flows. "As velocity increases, a point is reached at which the pressure in the flow equals the vapor pressure of water, whereupon the fluid undergoes a phase change and becomes a gas: water vapor." In other words, with insufficient pressure to hold them together, the liquid water molecules dissociate into a gas.

"Under certain circumstances, especially at sharp edges, the flow can include attached cavities of approximately constant pressure filled with water vapor and air trailing behind. This is what we call natural cavitation," Tulin says. "The cavity takes on the shape necessary to conserve the constant pressure condition on its boundary and is determined by the body creating it, the cavity pressure and the force of gravity," he explains. Naval architects and marine engineers typically try to avoid cavitation because it can distort water flow to rob pumps, turbines, hydrofoils and propellers of operational effi-

RUSSIAN SQUALL

The Russian Shkval torpedo (*in cutaway*) is thought to feature a flat disk cavitator at the nose to create a partial cavity that is expanded into a supercavity by gases injected from forward-mounted vents. Small starter rockets get the weapon moving until a cavity is formed, whereupon the large central rocket kicks in.




ciency. It can also lead to violent shock waves (from rapid bubble collapse), which cause pitting and erosion of metal surfaces.

Supercavitation is an extreme version of cavitation in which a single bubble is formed that envelops the moving object almost completely. At velocities over about 50 meters per second, (typically) blunt-nosed cavitators and prow-mounted gas-injection systems produce these low-density gas pockets (what specialists call supercavities). With slender, axisymmetric bodies, supercavities take the shape of elongated ellipsoids beginning at the forebody and trailing behind, with the length dependent on the speed of the body.

The resulting elliptically shaped cavities soon close up under the pressure of the surrounding water, an area characterized by complex, unsteady flows. Most of the difficulties in mathematically modeling supercavitating flows arise when considering what Tulin calls "the mess at the rear" of cavities, known as the collapse or closure region. In reality, the pressures inside gas cavities are not constant, which leads to many of the analysis problems, he says.

However they're modeled, as long as the water touches only the cavitator, supercavitating devices can scoot along the interiors of the lengthy gas bubbles with minimal drag.

CAVITATORS

Different nose geometries can be used to create supercavities—flat disks, cones, "gear-shaped" plates and cones (*top* and *middle*), faceted concavities and cavitators with inscribed cones that move in and out like the tips of ballpoint pens (*bottom*).

PHILIP HOWE

## U.S. Supercavitation Efforts

ALTHOUGH SUPERCAVITATION research in this country focused on high-speed propeller and hydrofoil development in the 1950s, the U.S. Navy subsequently opted to pursue other underwater technologies, particularly those related to stealth operations, rather than high-velocity capabilities. As a result, experts say, the U.S. Navy currently has no supercavitating weapons and is now trying to catch up with the Russian navy.

Supercavitating weapons work in the U.S. is being directed by the Office of Naval Research (ONR) in Arlington, Va. In general, the ONR's efforts are aimed at developing two classes of supercavitating technologies: projectiles and torpedoes.

The first class of weapons is represented by RAMICS (for Rapid Airborne Mine Clearance System), a soon-to-be-requisitioned helicopter-borne weapon that destroys surface and near-surface marine mines by firing supercavitating rounds at them. The 20-millimeter flat-nosed projectiles, which are designed to travel stably through both air and water, are shot from a modified rapid-fire gun with advanced targeting assistance. (The fielded RAMICS projectiles are expected to be enlarged to 30-millimeter caliber.) Raytheon Naval & Maritime Integrated Systems in Portsmouth, R.I., is the chief contractor for RAMICS, and engineers at C Tech Defense Corporation in Port Angeles, Wash., developed the projectiles [*see box on page 35*]. The U.S. Navy is also considering deploying a surface ship–borne, deck-mounted RAMICS-type close-in weapons system that could destroy deadly wake-following torpedoes.

The next step in supercavitating projectile technology will be an entirely subsurface gun system using Adaptable High-Speed Undersea Munitions (AHSUM). These would take the form of supercavitating "kinetic-kill" bullets that are fired from guns in streamlined turrets fitted to the submerged hulls of submarines, surface ships or towed mine-countermeasure sleds. The sonar-directed AHSUM system is hoped to be the underwater equivalent of the U.S. Navy's Phalanx weapons system, a radar-controlled rapid-fire gun that protects surface vessels from incoming cruise missiles.

The other supercavitating technology of interest to the ONR is a torpedo with a maximum velocity of about 200 knots. Substantial technical and system challenges stand in the way of the desired torpedo in the areas of launching, hydrodynamics, acoustics, guidance and control, and propulsion, to name a few, according to ONR program manager Kam Ng. NUWC

The U.S. Navy opted to pursue stealth rather than HIGH VELOCITY. With no supercavitating weapons, the U.S. Navy is now trying to CATCH UP with the Russian navy.

Newport is doing the applied research and some of the basic research work as well. The effort is supported by the Applied Research Laboratory at Pennsylvania State University (ARL/Penn State), the University of Florida, Anteon Corporation and Lockheed Martin.

With regard to the computational fluid dynamics (CFD) work on the torpedo being done at ARL/Penn State, "we're trying to simulate the conditions in which the torpedo would operate, which is the so-called two-phase flow regime where there's both water and gas," Ng says. "We want to know what the water is doing, what the gas cavity is like, and how we make sure the gas cavity encloses the body at all times. Remember, once the cavity is disrupted, the wetted surface increases and the speed is going to drop off very quickly.

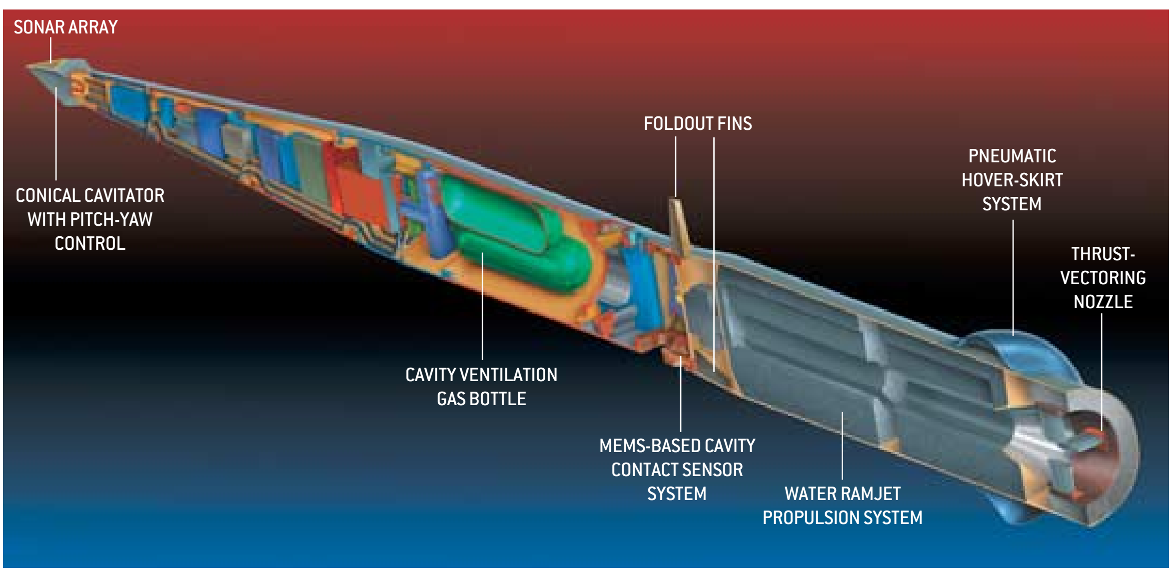
"So far the CFD is doing a fairly good job, but it's not yet to the point that we're happy with it," he continues. "It's both a matter of computational issues and our fundamental understanding of the physics. This is not a Newtonian fluid we're working with here; it's much more complex than a single-phase flow."

## Profile of a Supercavitating Torpedo

AS THE FOREMOST existing example of a supercavitating device, the Russian Shkval underwater missile is ideal for the purpose of illuminating the basic parts of a first-generation design. The torpedo, which is reportedly 27 feet long and weighs 5,940 pounds, is "really a big projectile with a rocket on the end," jokes Yuriy N. Savchenko, who directs the research group at the Ukrainian Institute of Hydromechanics in Kiev, where most of the fundamentals of supercavitating weapons technology were first developed.

In general, the weapon consists of a large cylindrical hull containing a solid-rocket motor that tapers to a cone enclosing the warhead. The wide aperture of a rocket nozzle protrudes from the center of the aft end encircled by eight small cylinders, which are said to be small starter rockets. These get the Shkval moving up to supercavitation speed, whereupon the main engine cuts in. Nestled between two of the starter motor nozzles is thought to be a spool of guidance wire that unravels as the torpedo makes its way through the water. The wire would allow submarine personnel to control the weapon's operation and warhead detonation.

Up front, things get a bit more speculative. Experts believe that the nose of the torpedo features what is likely to be a flat disk with a circular or perhaps elliptical shape. This is the all-important cavitator, which creates the gas cavity in which the craft moves. The cavitator disk will be tilted forward at the top, providing an "angle of attack" to generate the lift needed to support the forebody of the device. The cavitator's edge is apt to be sharp, which hydrodynamicists say creates the cleanest or least turbulent gas/water boundary, what they call a "glassy" cavity. Just aft of the cavitator sit several rings of ventilation ducts that inject rocket exhaust and steam into the cavitation bubble to enlarge it. About two thirds of the way back from the nose are four spring-out cylinders angled toward the stern. Although they loosely resemble fins, these spring-tensioned skids actually support the aft end of the torpedo by allowing it to bounce off the inner cavity surface. Western experts believe that the Shkval actually "pre-

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PROTOTYPE WEAPON A future supercavitating torpedo based on U.S. Navy design concepts could feature a range of innovative cavitator, sensing, control and propulsion technologies.

cesses" slowly around the cavity's circumference, repeatedly ricocheting off the walls as it makes its way through the water.

The Shkval is considered to be somewhat unrefined because it can travel only along a straight trajectory, but future supercavitating vehicles are being designed to maneuver through the water. Steering is possible through the use of cavity-piercing control surfaces such as fins, and thrust-vectoring systems, which are directional nozzles for jet exhaust. Extreme care must be taken to keep the body inside the cavity during turns, however, because should it stray from the cavity, the force of slamming into the surrounding wall of water would abruptly turn it into "a crushed Coke can," according to Ivan Kirschner, an engineer at Anteon's Engineering Technology Center in Mystic, Conn.

"Three-dimensional pitch and yaw maneuvers could also be accomplished by moving or rotating the nose cavitator in two planes simultaneously," Kirschner continues, "although such devices would be more complicated." Researchers have also considered using forward-actuated canards.

Supercavitating vehicles could be highly agile if the control surfaces were coordinated correctly, says NUWC's Kuklinsky. The idea is to skew the cavity to one side to create the desired side forces with an articulated nose cavitator or with control surfaces and then track the vehicle in it. If the fore and aft control systems operate in phase so that the "back end keeps up with what the front is doing, very fast turns can be accomplished," he notes.

Part of the solution to the control problem is to install a reliable, real-time feedback control loop that can keep abreast of cavity conditions in the rear of the craft and make the appropriate response to measured changes. As supercavitating systems travel unsupported inside low-density gas bubbles, their afterbodies often bang off the inside wall of cavities. Specialists call this the "tail-slap" phenomenon, which is regularly observed in high-speed test photography of supercavitating devices. The ONR has sponsored the development of a "tail-slap" sensor—a monitoring system based on microelectromechanical components that will track intermittent afterbody contact with the cavity.

SUBSEA GUNS The U.S. Navy is developing underwater launchers for rotating gun turrets that would be fitted below the waterline to fire "kinetic-kill" projectiles at mines, obstacles, surface craft, homing torpedoes—even low-flying airplanes and helicopters.

## Advanced Propulsion Systems

AN IMPORTANT POINT regarding future supercavitating vehicles is the fact that transitions from normal underwater travel into the supercavitating regime and back out again can be accomplished by artificially ventilating a partial cavity to maintain and expand it through the velocity transitions. Thus, a small natural cavity formed at the nose (at lower speeds) can be "blown up" into a large one that fully encloses the entire body. Conversely, braking maneuvers can be eased by augmenting the bubble with injection gases to maintain and then slowly reduce its size so as to gradually scrub speed.

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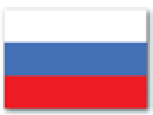
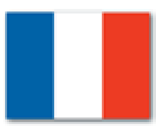
# International *Supercavitation Research*



RUSSIA: Although Russia leads the world in supercavitating weapons technology based on its early and extensive work in the field, it is unclear exactly how much progress that country has made in recent years. A significant classified program on supercavitating weapons is reportedly ongoing at TsAGI, the renowned Central Aerohydrodynamic Institute in Zhukovsky, which is thought to have done much of the engineering work on the Shkval underwater missile. Western experts believe that Russian researchers were the first to attain fully submerged supersonic speeds through water. Some say that TsAGI engineers are investigating the possibility of developing supercavitating submarines as well.

UKRAINE: Much of the fundamental technology that underlies the Russian Shkval torpedo came out of the Ukrainian Institute of Hydromechanics in Kiev, which in Soviet times was directed by academician Georgy Logvinovich, one of the pioneers of supercavitation theory. That facility contains a sophisticated water-tank testing system in which wire-riding models are catapulted or jet-propelled through water while under close observation. Researchers at the Institute of Hydromechanics, who are known for their successful semianalytic mathematical approach and extensive testing work, have been trading information about supercavitating technology with their American counterparts since the fall of the Soviet Union.



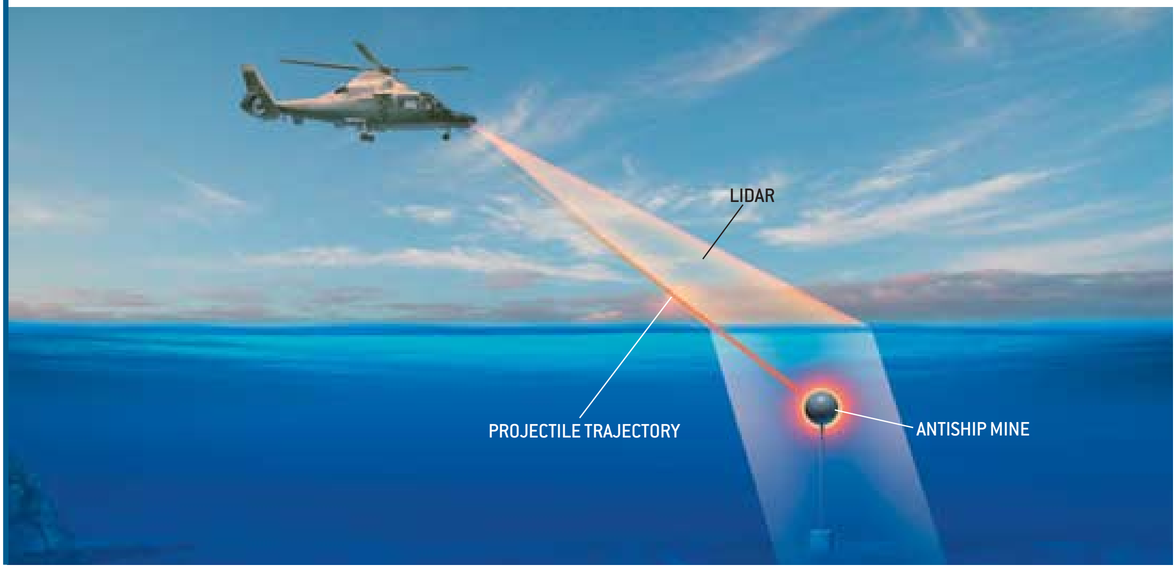
FRANCE: In the past decade, under the supervision of the Directorate of Research, Studies and Techniques (DRET), France has supported a program called Action Concertée Cavitation. Reliable sources report that the government is strongly, if covertly, pursuing supercavitating weaponry. For example, France has reportedly purchased several Shkvals from the Russians for evaluation. Tests of prototype air-launched antimine supercavitating projectiles are being performed at the French-German Research Institute of Saint-Louis.

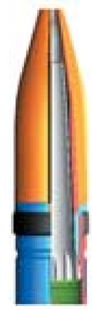
GERMANY: The German Federal Office for Defense Technology and Procurement in Koblenz is cooperating with U.S. Navy researchers in a joint development program on new cavitator designs and the modeling of homing systems for torpedoes. Engineers have also completed initial development of a supercavitating torpedo prototype that is expected to begin trials soon in the U.S.

## Neutralizing *Mines*

EVERYONE HAS SEEN action-movie heroes avoid fusillades of bullets by diving several feet underwater. The bullets ricochet away or expend their energy surprisingly rapidly as a result of drag and lateral hydrodynamic forces.

When the Office of Naval Research was asked to find a cost-effective way to stop thousand-dollar surface mines from damaging or destroying multimillion-dollar ships, they turned to supercavitating projectiles. The result was RAMICS—the Rapid Airborne Mine Clearance System, which is being developed for the U.S. Navy by a team led by Raytheon Naval & Maritime Integrated Systems in Portsmouth, R.I. Operating from helicopters, RAMICS will locate subsurface sea mines with an imaging blue-green lidar (light detection and ranging) system, calculate their exact position despite the bending of light by water refraction, and then shoot them with supercavitating rounds that travel stably in both air and water. The special projectiles contain charges that cause the deflagration, or moderated burning, of the mine's explosives.



**ANTIMINE PROJECTILE** Supercavitating projectiles shot from above the ocean surface must fly stably in both air and water—a difficult engineering task. The RAMICS round (*partially visible*) was developed by C Tech Defense Corporation.

Most existing and anticipated autonomous supercavitating vehicles rely on rocket-type motors to generate the required thrust. But conventional rockets entail some serious drawbacks—limited range and declining thrust performance with the rise of pressure as depth increases. The first of these problems is being addressed with a new kind of high-energy-density power-plant technology; the second problem may be circumvented by using a special kind of supercavitating propeller screw technology.

"Getting up to supercavitation speeds requires a lot of power," says researcher Savchenko. "For maximum range with rockets, you need to burn high-energy-density fuels that provide the maximum specific impulse." He estimates that a typical solid-rocket motor can achieve a maximum range of several tens of kilometers and a top speed of perhaps 200 meters per second. After considering propulsion systems based on diesel engines, electric motors, atomic power plants, high-speed diesels, and gas turbines, Savchenko concluded that "only high-efficiency gas turbines and jet propulsion systems burning metal fuels (aluminum, magnesium or lithium) and using outboard water as both the fuel oxidizer and coolant of the combustion products have real potential for propelling supercavitating vehicles to high velocities."

Aluminum, which is relatively cheap, is the most energetic of these metal fuels, producing a reaction temperature of up to 10,600 degrees Celsius. "One can accelerate the reaction by fluidizing [melting] the metal and using water vapor," Savchenko explains. In one candidate power-plant design, the heat from the combustion chamber would be used to melt stored aluminum sheets at about 675 degrees C and to vaporize seawater as well. The resulting combustion products turn turbine-driven propeller screws.

This type of system has already been developed in Russia, according to media reports there. The U.S. also has experience with these kinds of systems. Researchers at Penn State's Applied Research Laboratory are operating an aluminum-burning "water ramjet" system, which was developed as an auxiliary power source for a naval surface ship.

In the novel American design, powdered aluminum feeds into a whirlpool of seawater occurring in what is called a vortex combustor. The rapid rotation scrapes the particles together, grinding off the inert aluminum oxide film that covers them, which initiates an intense

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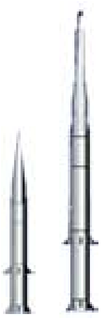
As there are NO KNOWN COUNTERMEASURES, to such a weapon, its deployment could have a significant effect on future maritime operations.

exothermic reaction as the aluminum oxidizes. High-pressure steam from this combustion process expands out a rocket nozzle or drives a turbine that turns a propeller screw.

Tests have shown that prop screws offer the potential to boost thrust by 20 percent compared with that of rockets, although in theory it may be possible for screws to double available thrust, Savchenko says. Designs for a turbo-rotor propeller system with a single supercavitating "hull propeller," or a pair of counterrotating hull props that encircle the outer surface of the craft so they can reach the gas/water boundary, have been tested. He emphasizes, however, that "considerable work remains to be done on how the propeller and cavity must interact" before real progress can be made.

## Fears for the Future

WHATEVER THE YEARS AHEAD may hold for supercavitating weapons, they have already exerted a strong influence on military and intelligence communities around the world. Indeed, they seem to have spurred some reevaluation of naval strategy.



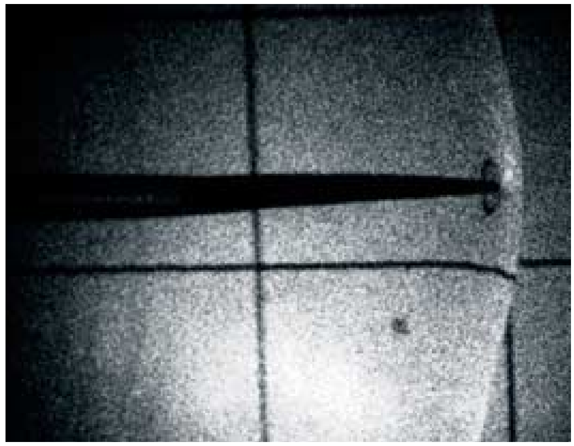
UNDERSEA MISSILES The U.S. Navy is considering design concepts for large, extended-range supercavitating weapons. On the left is a "midrange unguided engagement breaker"; on the right is a "long-range guided preemptive weapon."

For example, when news of the Shkval's existence emerged, a debate soon ensued regarding its purpose. Some Western intelligence sources say that the Shkval had been developed to allow the noisy, low-tech diesel subs of the then Soviet Union to respond if suddenly fired on by ultraquiet American submarines lurking nearby. On hearing the screws of the incoming conventional torpedo, the Shkval would be launched to force an attacker to evade and thereby perhaps to cut the incoming torpedo's guidance wire. In effect, they say, the Shkval is a sub killer, particularly if it is fitted with a tactical nuclear warhead.

Other informed sources claim that the missile is in fact an offensive weapon designed to explode a higher-yield nuclear charge amid a carrier battle group, thereby taking out the entire armada. During a nuclear war, it could even be directed at a port or coastal land target.

"As there are no known countermeasures to such a weapon," states David Miller's April 1995 article "Supercavitation: Going to War in a Bubble," in *Jane's Intelligence Review,* "its deployment could have a significant effect on future maritime operations, both surface and subsurface, and could put Western naval forces at a considerable disadvantage."

In recent years, cash-strapped Russia has openly offered the Shkval for sale at international arms shows in Abu Dhabi and Athens, a development that causes grave concern in the Pentagon. Well-placed sources say that several Shkvals have been sold to Iran, for example.



SUPERSONIC BULLET In 1997 a research team at the Naval Undersea Warfare Center Division Newport in Rhode Island demonstrated the fully submerged launch of a supercavitating projectile with a muzzle velocity of 1,549 meters per second, which exceeds the speed of sound in water.

U.S. NAVY/NUWC

Of equal worry is an August 1998 report that China purchased around 40 Shkval torpedoes from Kazakhstan, raising the possibility that Beijing could threaten American naval forces in a future confrontation in the Taiwan Strait. News from China (reportedly confirmed by U.S. Navy sources) that a Chinese submarine officer was on board the sunken *Kursk* has also raised alarms. He was there, they say, to observe the test of a new version of the Shkval.

U.S. intelligence has received several indications that the Russians were working on an advanced, much longer-range Shkval. For example, Russia's Itar-Tass news agency reported in February 1998 that tests of a "modernized" Shkval were scheduled by Russia's Pacific Fleet for that spring.

The *Kursk* incident, the Pope trial and the ambiguity surrounding both reinforce the fact that the end of the cold war has in no way halted the clandestine arms competition to secure an edge in any future conflict. Clearly, the secret storm over the Shkval rages on. SA

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