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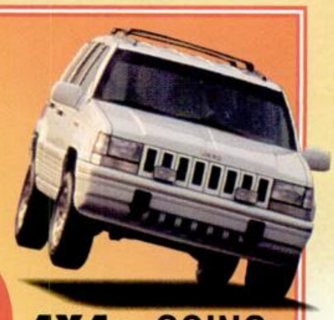

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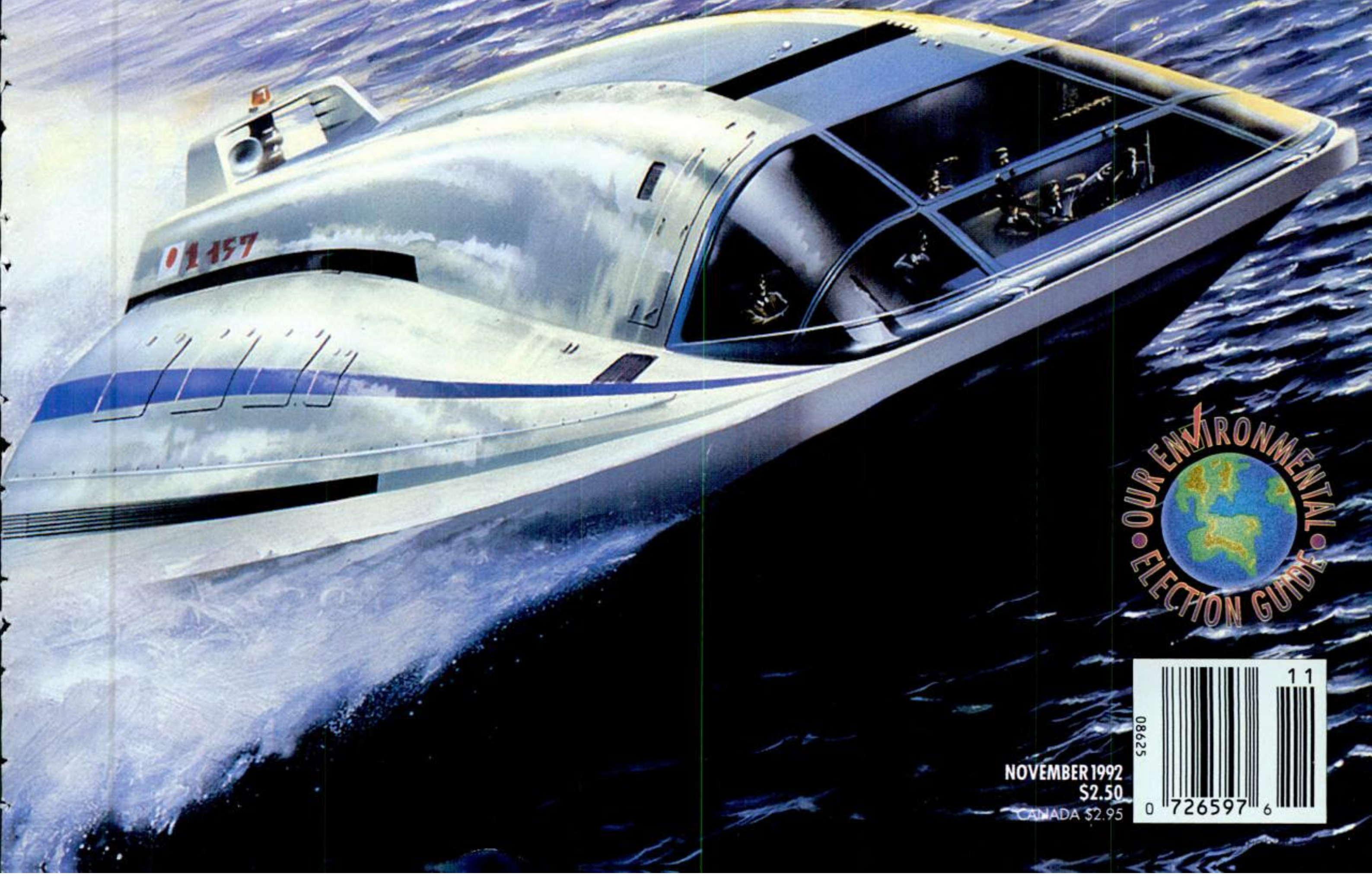
SUPERCONDUCTIVITY GOES TO SEA



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DENNIS GRAY

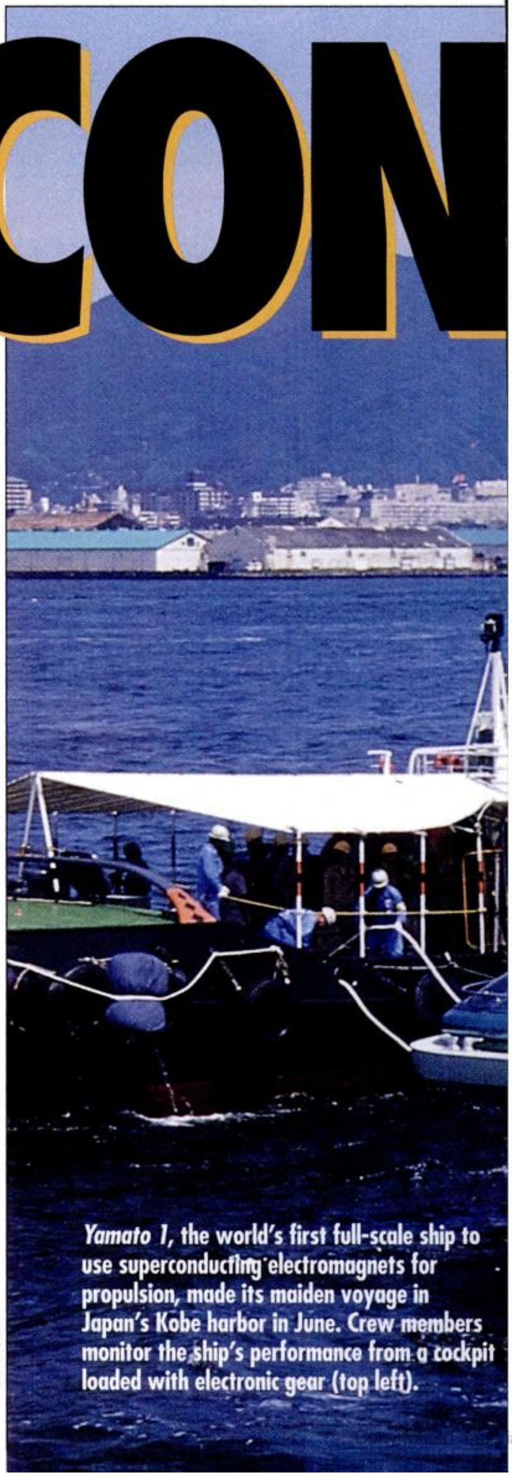
Sitting dead in the water, *Yamato 1* looks like a rocket. It doesn't take off like one, though. During its first sea trial in June, the streamlined ship didn't even move fast enough to throw a wake.

Yet that maiden voyage could become as important in marine history as the 1807 launching of Robert Fulton's steam-powered *Clermont* or the *Nautilus* submarine's first trip under nuclear power in 1955. *Yamato*'s propellerless technology may eventually move ships faster and with less noise than any propulsion system yet developed. But with *Yamato* achieving a speed of only slightly more than six knots (about seven mph) as it glided through the harbor in Kobe, Japan,

SUPERCON GOES TO SEA

With no propellers to slow them down, ships and submarines powered by superconducting electromagnets may one day cross oceans in record time.

BY DENNIS NORMILE



DENNIS GRAY

Yamato 1, the world's first full-scale ship to use superconducting electromagnets for propulsion, made its maiden voyage in Japan's Kobe harbor in June. Crew members monitor the ship's performance from a cockpit loaded with electronic gear (top left).

the technology has a long way to go. Before magnet-driven ships can become competitive with conventional watercraft, researchers will need to develop superconducting magnets that are more powerful and lightweight than any known today.

In place of a propeller or paddle wheel, *Yamato* uses jets of water produced by a magnetohydrodynamic (MHD) propulsion system. MHD technology is based on a fundamental law of electromagnetism: When a magnetic field and an electric current intersect in a liquid, their repulsive interaction propels the liquid in a direction perpendicular to both the field and the current.

In *Yamato*, the liquid is seawater, which conducts electricity because of the salt it contains. The boat's futuristic shape channels the seawater into two MHD thrusters on the bottom of the hull—one on each side.

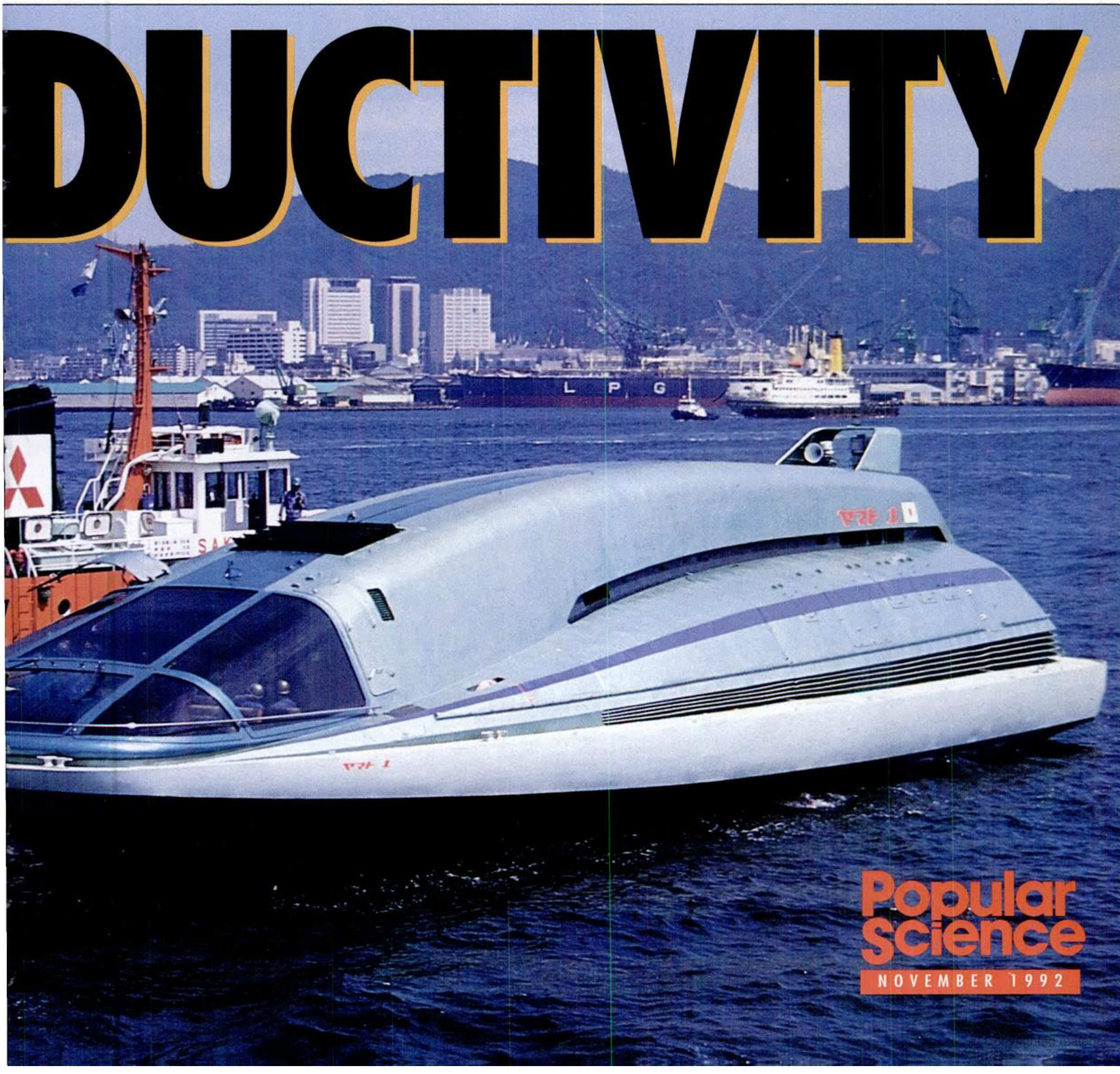
Inside each thruster, the seawater flows into six identical tubes, arranged in a circle like a cluster of rocket engines. The ten-inch-diameter tubes are individually wrapped in saddle-shaped superconducting magnetic coils made of niobium-titanium alloy filaments packed into wires with copper cores and shells. Liquid helium cools the coils to -452.13°F, just a few degrees above absolute zero, keeping them in a superconducting state in which they have almost no resistance to electricity.

Electricity flowing through the coils generates powerful magnetic fields within the thruster tubes. When an electric current is passed between a pair of electrodes inside each tube, seawater is forcefully ejected from the tubes, jetting the boat forward.

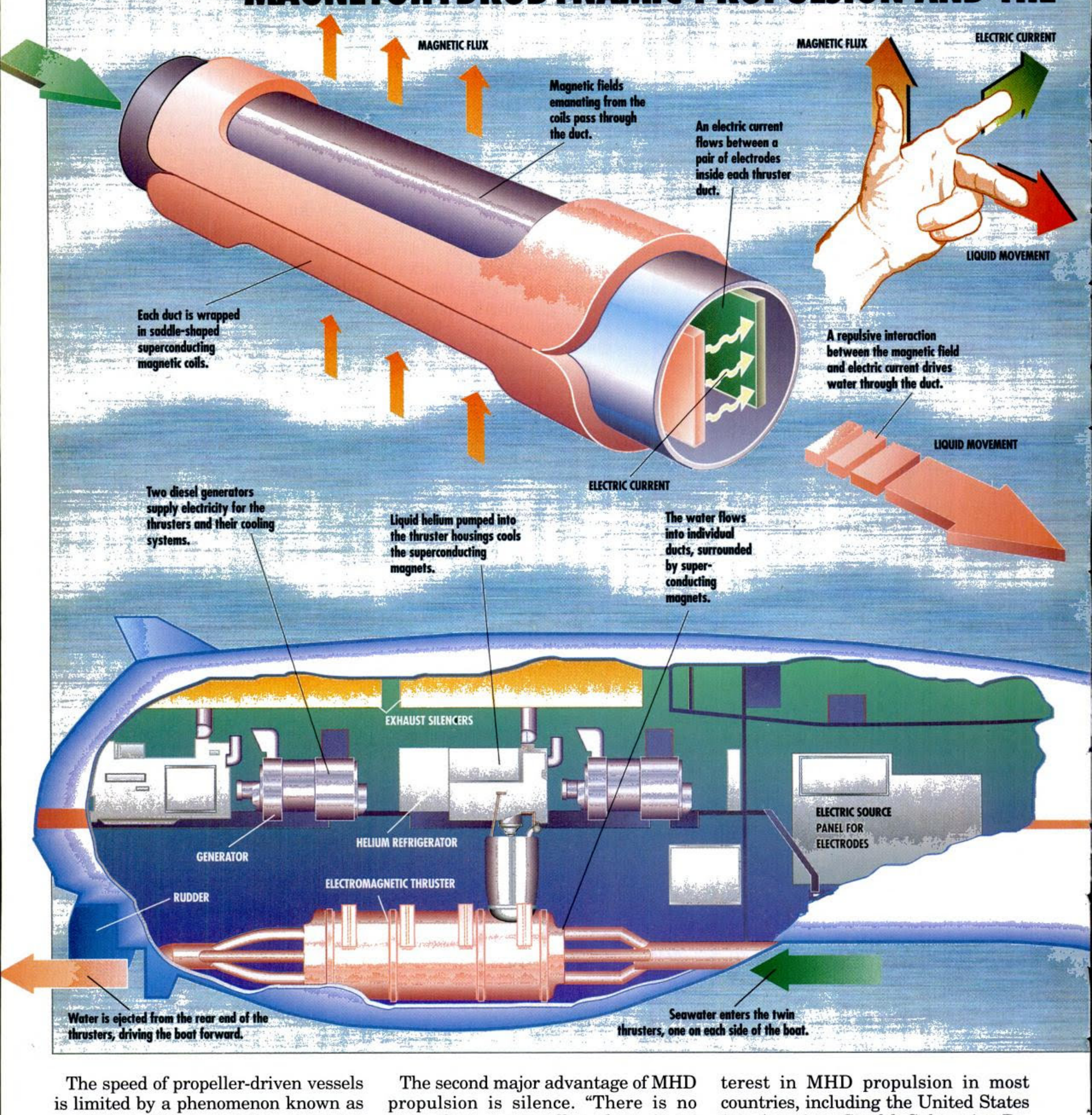
The MHD thrusters have several advantages over conventional propulsion systems. Most important, they will enable ships and submarines to travel at high speed. Visionaries anticipate speeds of up to 100 knots (about 115 mph), although researchers associated with the *Yamato* project regard that goal as extremely optimistic.

Kensaku Imaichi, professor emeritus at Osaka University in Japan and a key figure in the design of *Yamato 1*, believes the technology may have commercial ships cruising at 40 to 50 knots (46 to 58 mph) sometime in the next century. Speeds could go even higher if breakthroughs can be made in hull materials and ship stability.

DUCTIVITY



MAGNETOHYDRODYNAMIC PROPULSION AND THE



The speed of propeller-driven vessels is limited by a phenomenon known as cavitation. If the propeller turns too fast, an area of low pressure forms in front of the churning blades, causing the water to vaporize. This not only reduces a ship's efficiency, but can even destroy its propeller.

"By doing away with the propellers, we can avoid the phenomenon," says Seizo Motora, professor emeritus at the University of Tokyo and head of a scientific committee that designed *Yamato*'s hull.

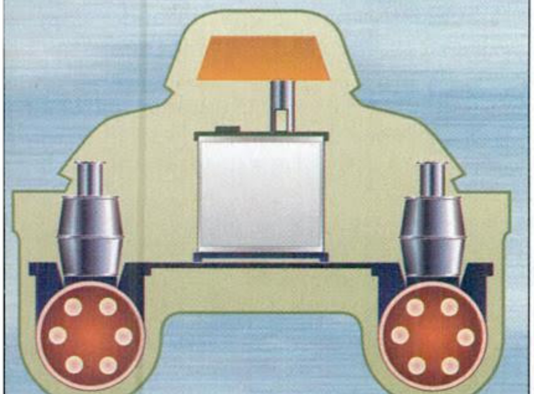
The second major advantage of MHD propulsion is silence. "There is no noise from a propeller, there is no noise from cavitation," Motora says.

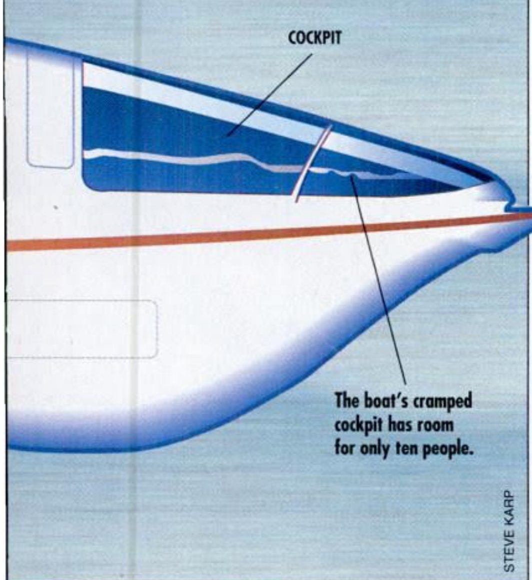
Silence is a central part of the plot of Tom Clancy's novel *The Hunt for Red October*, in which a Soviet submarine's noiseless propulsion system renders the vessel virtually undetectable by sonar. Clancy says that his fictional submarine propulsion system, dubbed the caterpillar drive, is not based on MHD technology. But the quest for stealthy submarines is what fuels interest in MHD propulsion in most countries, including the United States (see American Stealth-Submarine Research on Hold).

Because MHD thrusters have no moving parts, they are not only quiet and vibration-free, but are also expected to have lower maintenance requirements than conventional propulsion systems. And with no need for a drive shaft to link the power source to the propulsion system, shipbuilders could experiment with new ship designs. Among the possibilities: cargo sub-

"LEFT-HAND RULE"

The "left-hand rule" is a simple method for calculating the interaction between a magnetic field and an electric current in a liquid. If you hold your left hand in the position shown in the drawing at left, you can use three of your fingers to represent the three forces at work. With your thumb pointed in the direction of magnetic flux, and your index finger pointed in the direction the electric current flows, your middle finger will indicate the direction in which the liquid will move as a result of the repulsive interaction between the magnetic field and electric current. You can test this rule on the drawing at far left, which shows one of Yamato's thruster ducts. Six of these ducts are arranged in a circle within each of Yamato's two thruster pods (below). Diesel generators and cooling systems fill most of the remaining space inside the boat (bottom).





STEVE KARP

marines shaped like jet airplanes and catamaran-style ocean liners.

A primary goal of the consortium that built *Yamato 1* was to revitalize the stagnant Japanese shipbuilding industry. The Ship and Ocean Foundation, a private organization that sponsored the $40 million project, received research and manufacturing support from Japanese giants such as Toshiba, Kobe Steel, and Sumitomo Electric. Mitsubishi Heavy Industries supervised the construction of *Yamato 1* at its shipyard in Kobe.

The Japanese researchers aim to develop fast, fuel-efficient commercial ships that could eventually ferry California oranges to Japan in less than a week, a trip that currently takes about two weeks. The technology might even be used to construct large cargo submarines, which could dive below the ocean surface to avoid storms. MHD propulsion might also be used in submarine ferries that would transport passengers between Japan's numerous islands.

If the Ship and Ocean Foundation has its way, MHD technology will never be used for military gain. "We will restrict the use [of the technology] to peaceful purposes," vows Yohei Sasakawa, director of the foundation and chairman of the steering committee for the *Yamato* project.

Like many technologies now being developed in Japan, MHD propulsion was first proposed by American scientists. Several researchers published papers on the subject in the early 1960s. A few years after the first papers appeared, Stewart Way, a Westinghouse Research Center consultant who collaborated with an engineer at the University of California at Santa Barbara, used an MHD thruster to propel a small model submarine. But Way used ordinary magnets rather than superconducting ones, and scientists concluded that the technology would have to await more efficient methods of generating strong magnetic fields.

In 1968, a report on Way's research reached Yoshiro Saji, who had recently joined the faculty of Kobe Mercantile Marine University. Saji had been looking for some way to apply his specialty— cryogenics—to ships.

Saji had worked with liquid helium and knew of its role in superconductivity. With a boiling point of 4.2°K (-452.13°F), liquid helium is used to cool superconducting alloys down to their critical temperature—the temperature at which electrical resistance disappears.

Saji realized that the strong magnetic field required to boost the efficiency of MHD propulsion could be generated by a superconducting coil. He spent five years on theoretical work and started actual experiments in 1973. In 1978, Saji and a group of colleagues succeeded in propelling a superconducting MHD model ship through a tank of seawater. There was only one problem: The miniature ship wouldn't go straight.

"No matter what we did, it always turned. I thought it was really strange," Saji says.

The model was 4.5 feet long, with the superconducting coil and electrodes in a fin sticking straight down from the bottom of the boat. The coil was a simple oval immersed in a liquid helium bath, and the electrodes were placed above and below the coil. In this arrangement, called an external-field system, the electromagnet does not surround a water-filled duct. Instead, the magnetic field is projected into the open water below the boat. That was the problem.

Earth's magnetism increased the strength of the magnetic field on one side of the fin and decreased it on the other, generating more propulsion on one side of the model. When Saji had the water tank reoriented along a line from magnetic north to south, the boat went straight.

To avoid the influence of Earth's magnetic field, the superconducting coil and the electrodes were

MATSUHIRO WADA / GAMMA LIAISON

Hoisting *Yamato 1* from the water exposes its unique hull design. This view shows the boat's thruster outlets.

laid horizontally on the flat hull of Saji's next model. In 1983, this 1.1-ton, 11.5-foot-long model achieved a speed of 2.5 feet per second.

Saji's work attracted the attention of Sasakawa, scion of a wealthy philanthropic family with longstanding ties to Japan's shipbuilding industry. Sasakawa asked for Saji's cooperation in taking the work under the aegis of the family-dominated Japan Foundation for Shipbuilding Advancement, now known as the Ship and Ocean Foundation. The foundation recruited scientists from industry, government, and academia to take part in the design of *Yamato 1*—the ship's name comes from one of the earliest civilizations on the Japanese islands. *Yamato* was also the name of a massive World War II battleship sunk by Allied planes in 1945 as it headed toward Okinawa.

Scientific committees assigned to tackle various aspects of the ship's design began their work in 1985. The committee designing the thrusters soon decided to adopt an internal-field system. The researchers were worried that the uncontrolled magnetic fields emanating from an external-field system might affect other boats and the marine environment.

The committee built a small internal-field thruster, loaded it in a model, and successfully sailed it through a tank of water. The thruster had a superconducting coil wrapped around a single water duct.

For the actual ship, however, the thruster committee decided to arrange six ducts in a circle. The committee members claimed this would virtually eliminate magnetic radiation leakage, because the stray flux emanating from one coil would be drawn into its neighbor. (The effects of magnetic fields on the human body are unknown ["Electromagnetic Fields: In Search of the Truth," Dec. '91].)

While models demonstrated the MHD technology, scaling it up proved troublesome. The first sea trial, two years behind schedule, was cut short when "quench" warning signals lit up in the ship's cockpit. Quench is the phenomenon in which a superconducting coil slips out of the superconducting state.

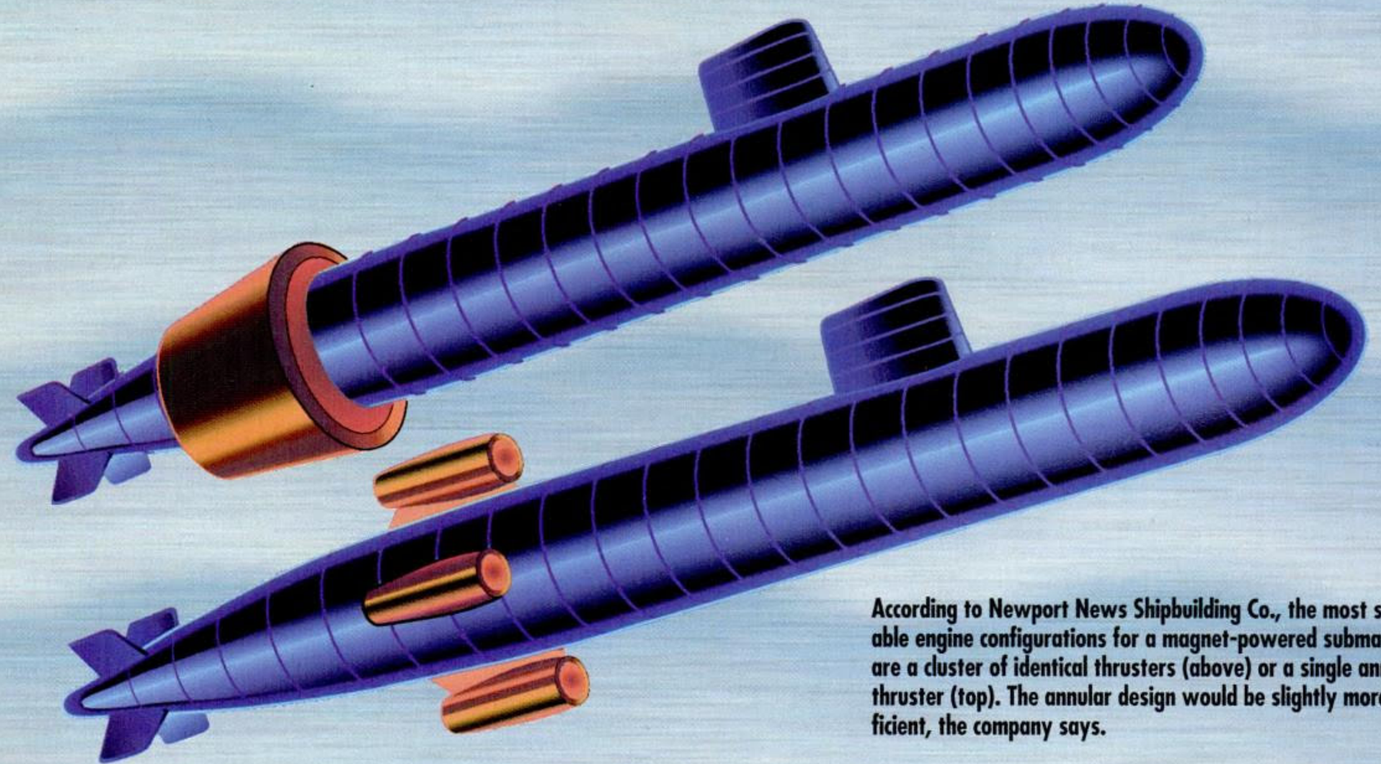
"Even if an unimaginably small portion of the coil slips into ordinary conducting mode, it generates an enormous amount of heat, which propagates throughout the system," explains Imaichi, who heads the thruster committee.

A sudden rise in temperature could destroy the coil, so *Yamato 1* is wired with sensors that constantly check for anomalies that might presage quench. "If the sensors are too sensitive, that interferes with ordinary operation," Imaichi says.

That seems to have been the case on the maiden voyage. Apparently, heat leaking through a gap around some electrical lead cables set off the warning signals.

The signal glitch was a minor detraction from the day's success. In just seven years, the Japanese team had

AMERICAN STEALTH-SUBMARINE RESEARCH ON HOLD



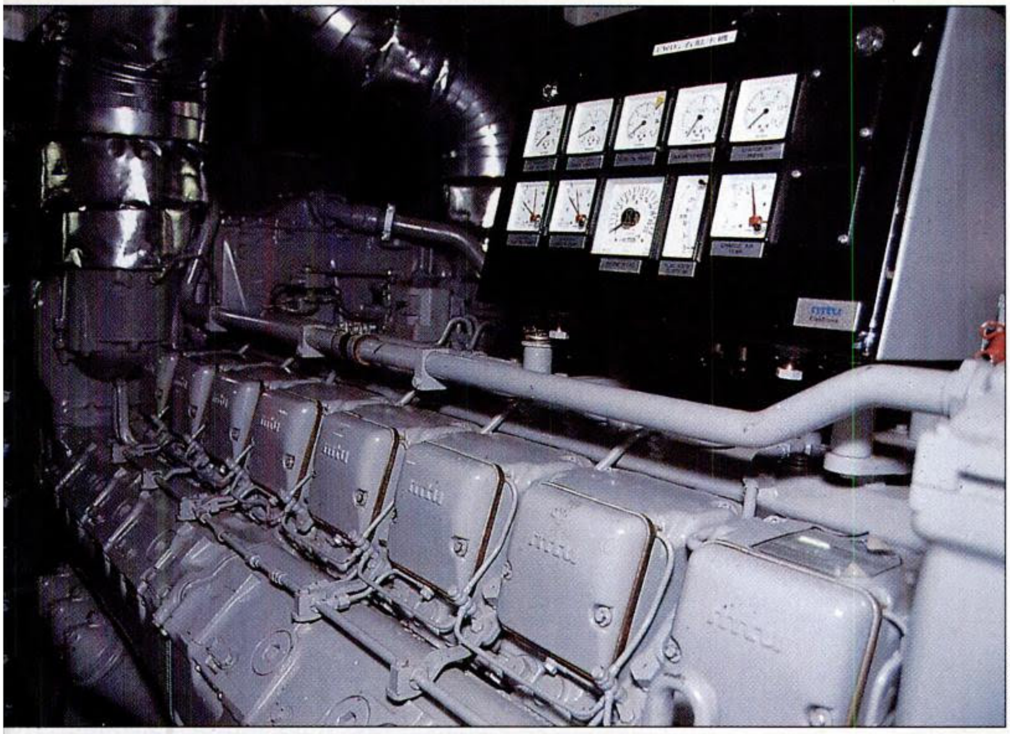
According to Newport News Shipbuilding Co., the most suitable engine configurations for a magnet-powered submarine are a cluster of identical thrusters (above) or a single annular thruster (top). The annular design would be slightly more efficient, the company says.

Although the United States pioneered the development of magnet-powered ships in the early 1960s, the current American research effort in this area can be summed up in one word: negligible.

No U.S. government agency has serious plans for building a ship or submarine with magnetohydrodynamic (MHD) propulsion. A few groups, however, have built MHD "thrusters" in the laboratory. In the largest project, researchers at Argonne National Laboratory in Illinois used a 21-foot-long superconducting magnet—30,000 times stronger than Earth's magnetic field—to propel water through an 18-inch-wide duct, simulating the action of an MHD jet in the open ocean.

Researchers at Newport News Shipbuilding Co. in Virginia and the Naval Underwater Systems Center in Newport, R.I., have conducted similar experiments, smaller in scale.

The conclusion from these studies? "There's no showstopper" that will make magnetic propulsion impractical, argues Michae[l] Petrick, who led the Argonne team. The key to building an MHD-powered vessel, he says is designing lighter and more efficient magnets. Although the Argonne experimental thruster was several times more efficient than those in Japan's *Yamato 1*, it nevertheless wasted about 60 percent of the force gener-



DENNIS GRAY

MATSUHIRO WADA / GAMMA LIAISON

Electronic sensors monitor the temperature of superconducting magnets and other conditions inside the thruster compartment (above). Each thruster contains six individual water ducts (right).

ated by the magnet. Furthermore, the stainless steel magnet weighed 180 tons—far too heavy for a ship.

Another limitation of the technology is that MHD ships will not work in areas with significant amounts of fresh water, which does not conduct electricity as well as salt water. Thus it might be difficult for an MHD ship to dock at many major ports, says Mike Superczynski, an expert on superconducting magnets at the David Taylor Research Center in Annapolis, Md. Also, salt water would quickly corrode the electrodes in the thrusters, Superczynski argues.

Both the Argonne and Newport News Shipbuilding projects are now on hold, pending more government funding. "We've gone as far as we can go in the laboratory," says Newport News Shipbuilding's Rich Ranellone. "Our next step should be a demonstration at sea." Ranellone proposes installing a magnetic thruster on an existing research submarine.

He shouldn't get his hopes up. The Defense Advanced Research Projects Agency, which funds this type of work, doesn't have the money to keep MHD research afloat. "We've finished our program," says Captain Ted Rice, an undersea warfare expert at the agency. "There are too many other things we need to attack."

Navy brass aren't excited about MHD propulsion either, agree experts close to the service. "The Navy is not even vaguely enthused about the idea," says Alan Berman, a staff member at the Center for Naval Analyses in Alexandria, Va. The biggest potential drawback: The huge magnetic fields emanating from an MHD-powered submarine would make it easy for enemies to detect, even if it made no sound. An MHD-powered sub would also leave a trail of chlorine, created by the electrolysis of seawater. For now, it looks like the international race to build a magnet-powered ship has exactly one contender.—*Robert Langreth*

STEVE KARP

turned a laboratory curiosity into a full-scale moving boat.

Making it practical, however, is a bigger challenge. *Yamato*'s thrusters, refrigeration systems, and twin 2,000-kilowatt diesel generators virtually fill the 98-foot ship, leaving room for a crew of only ten in a cramped cockpit. The equipment weighs 143 tons, or about 70 percent of the total vessel displacement of 204 tons. By comparison, the propulsion systems of current oceangoing freighters typically account for less than 10 percent of the total displacement.

The maximum efficiency expected from *Yamato 1* is less than 4 percent. The efficiency of current commercial ships ranges from around 22 percent for hydrofoils to 60 percent for cargo ships. And a first-rate sculler can propel himself along faster than *Yamato 1*, which has a top speed of only eight knots (9.2 mph).

For MHD propulsion to become practical, researchers will have to develop magnets that are much lighter and more powerful than current ones. *Yamato*'s coils now generate a maximum magnetic field of four tesla. Imaichi thinks the magnetic field can be raised to 30 tesla within the next two decades, and that this improvement will result in an overall efficiency of between 22 and 23 percent. This, he says, is comparable to the current efficiency of hydrofoils. "An MHD ship can be competitive with that kind of ship," Imaichi says. But to date, the maximum steady-state magnetic field achieved using superconductors has been about 20 tesla.

Incremental improvements will come from using superfluid helium, which can cool the superconducting coil down to 1.8°K (-456.45°F), allowing increased current and thus a stronger magnetic field. Superconducting niobium-tin alloy filaments will also provide stronger fields, but the material is much harder to form into wires than the niobium-titanium alloy used in the present coils.

A leap forward could come with the refinement of new ceramic superconducting materials, which weigh as little as one-third as much as metal superconductors currently available. More important, with critical temperatures above 77°K (-321.09°F), the ceramics are "high-temperature" superconductors. This means they can be cooled with liquid nitrogen, which is less expensive and easier to use than liquid helium.

Taking these possible advances into account, Imaichi and other researchers have concluded that the ultimate efficiency of the technology will be somewhere around 50 percent, equivalent to the efficiency of current cargo ships. Hoping for the technological breakthroughs that will make MHD propulsion competitive with conventional ships, Sasakawa and his colleagues intend to build a second-generation MHD ship.

"It took 130 years for Watt's steam engine to be put to practical use on a ship," Sasakawa explains. "If you don't have dreams, you can't make progress." PS