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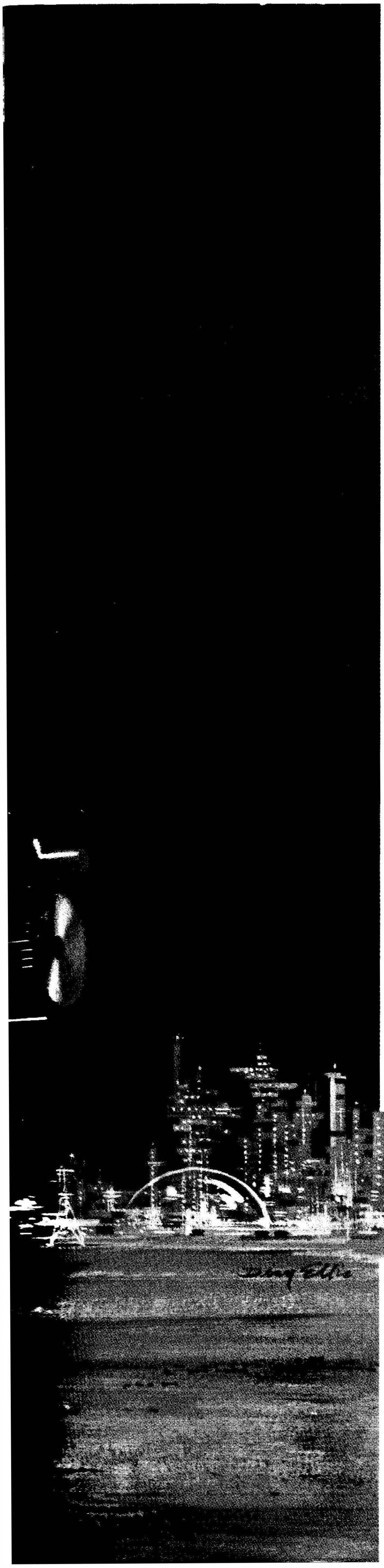


Hold a stick of this alloy in cold water and feel it soften. Next, see what happens when you dip it into hot. Only then can you understand why it is called . . .

MIRACLE METAL

BY KEVIN SANDERS

At the McDonnell Douglas Astronautics company, in Huntington Beach, California, an engine runs not on gas, oil or electricity but on warm water.

Its power element is a coiled band of Nitinol, a nickel-titanium alloy that may profoundly alter the fate of a world frantically searching for new sources of energy. The team of scientists that developed the engine calculates that Nitinol power plants may have "an overwhelming cost advantage" over oil, gas and nuclear power generation.

For nearly 20 years, unobtrusively and sometimes secretly in dozens of laboratories around the world, researchers have been probing the mysteries of Nitinol, one of the most remarkable metals ever known. Among a small but rapidly growing number of scientists it has become a subject of curiosity and controversy.

Nitinol arrived without warning. No previous work predicted its emergence; nobody knows precisely how it works. First encounters with it usually elicit amazement, shock or disbelief. At room temperature, a piece of Nitinol wire is as strong as steel. Dunk the wire in cold water and it suddenly turns soft and pliant; bend it and it stays bent. But then dip it in hot water and, suddenly coming to life in your hands, it will spring back with great force to its original shape. In short, it has a shape-memory response; it is a solid-state energy conversion system that requires only a temperature change from cool to warm to release forces as great as 55 tons per square inch.

Nitinol's amazing properties were discovered in 1958 at the U.S. Naval Ordnance Laboratory (NOL). Hence the name: Ni (nickel), Ti (titanium)—plus NOL. The discovery was an accident. When the first Nitinol ingots came out of the furnace, William Buehler, then chief metallurgist for the Navy, routinely tapped the first two finger-size bars against each other, producing a flat, leaden sound. No special surprise. But only minutes later, he found that the next two bars from the same melt rang like a bell when tapped. The only difference was the temperature: the second pair of bars was still warm from the furnace.

Not long after, at a meeting of Navy scientists, Buehler demonstrated another peculiar property of Nitinol: it can be bent repeatedly without showing signs of metal fatigue. And although Nitinol gets warm at the bend point when bent, like any other metallic alloy, it becomes cool when bent back to its original shape.

A puzzled Navy scientist who had just lit his pipe put his lighter to a piece of Nitinol wire that had buckled into a concertina shape. The metal sprang straight. "That," recalls Buehler, "was the turning point."

Despite its unique properties, Nitinol seems to have been regarded as scarcely more than a scientific curiosity until 1973, when an important but little-noticed breakthrough was made at the Lawrence Laboratory in Berkeley, California; inventor Ridgway Banks built a working model of a Nitinol heat engine.

Banks's device is a wheel mounted flat on a central shaft. From each spoke hangs a U-shaped loop of Nitinol, each end of which is attached by a sleeve that can slide in or out along the spoke. As each loop enters the hot-water side of the bath below the wheel, it snaps open and some of the energy produced pushes the wheel around.

The small group of scientists present at the engine's inauguration felt a keen sense of the event's historic importance. Nobel laureate Edwin McMillan, then director of the Lawrence lab, grabbed a handy tis-

Illustration by Dean Ellis

sue box and scribbled some quick calculations: the engine was producing about half a watt of mechanical power. Today that box is part of an unofficial Nitinol heat engine archive.

Banks kept the machine running continuously. He watched for signs of fatigue in the Nitinol wire loops. To his astonishment, he found that after a few hundred thousand revolutions, the wheel was spinning faster. It was spinning faster because the Nitinol was developing a two-way memory. It was "learning" to resume its tight-U shape in cold water. Since less of the energy produced by the snap of the loop on the warm-water side had to be used to push the loop on the cold-water side together, more was available for pushing the wheel. Like the initial shape-memory response in warm water, this double memory is still not quite satisfactorily explained.

WHAT THEORISTS THINK

A number of theories have been advanced to explain the unusual properties of Nitinol. None is conclusive, but most theorists agree that the shape change occurs when on the atomic level the Nitinol shifts from a complex rhombic structure to a less complex cubic structure. The transformation from the cubic structure to the rhombic structure during cooling is called a martensitic transformation. If the material is bent while cold, it will remain that way as long as it is at that temperature or colder. When heated, however, the reverse transformation occurs, from rhombic back to cubic, and the material will return to its original shape.

Surprisingly little electron microscopy has been carried out on Nitinol. The most advanced work on the martensitic effect has involved brass alloys, some of which display a similar but much less powerful shape-memory response. In Belgium, Professor Luc Delaey, of the Catholic University of Louvain, has made an electron-microscope color film of the brass alloy shape change, revealing sharp mountainlike ridges that vanish and reappear as the metal is cooled and reheated. No one knows what to make of them. At a recent MIT seminar on Nitinol, a metallurgist who has spent years studying the alloy observed, "It's a gift from God. Never mind what's going on, just use it."

Nitinol research has now been reported from laboratories in Britain, Switzerland, Belgium, West Germany and Japan. In the United States, research and development of Nitinol heat engines has been done in a number of private and government research centers, supported by, among others, the Department of Defense, the Navy, NASA, Department of Energy, National Science Foundation, General Motors, Goodyear, McDonnell

Ridgway Banks sees his designs, like the original Nitinol engine, as exercises in harmony. They are machines that resonate with natural movements of their metals.

Douglas, Grumman and Lockheed. So far, 400 scientific papers have been published, and new papers are proliferating. More than 100 patents for Nitinol devices have been granted or are pending (12 are for Nitinol heat engines), and new patent applications are appearing every week.

Two publications released last year by the Naval Surface Weapons Center (formerly NOL) have generated much of the recent interest. One is a source manual of scientific and technical papers on Nitinol, the other a report on the proceedings of the world's first international conference on Nitinol heat engines.

Sponsored by the Department of Energy, the conference was held at the Nitinol Technology Center in Silver Spring, Maryland, and brought together more than 60 of the world's leading researchers in the field. They tackled a number of crucial questions concerning the thermodynamics of this unique material.

Unlike all other heat-exchange systems, Nitinol responds to temperature changes in a profoundly "unbalanced" way: the force needed to bend it when it is cold is much less than the force it releases when it goes straight again. In other words, more energy seems to come out than was put in. This is something new in thermodynamics. Notes Dr. Elizabeth Rauscher, a nuclear physicist, "There's nothing wrong with the laws of thermodynamics, it's just that they don't account for what's going on with Nitinol."

The Navy conference report concludes that Nitinol engines could convert energy more cheaply than either nuclear reactors or photovoltaic cells. Further research by the Navy suggests that a Nitinol heat engine, running 24 hours a day, could pay for itself in from 18 months to 2 years. "After that," says David Goldstein, who directs the Nitinol Technology Center, "all the energy would, in a sense, be free."

Already, several applications for the Nitinol heat engine have been proposed. Because the characteristic shape-memory transformation can be activated by temperature differences of as little as 9 degrees centigrade, simple solar collectors or geothermal springs could provide a continuous supply of warm water for fractional horsepower Nitinol heat engines to drive irrigation pumps in areas not served by conventional power sources. Such small, self-contained heat engines would be ideal for much of the underdeveloped Third World.

In more advanced nations, low-level-waste heat, which draws off more than two-thirds of all the energy consumed by industrial plants, could be scavenged by Nitinol heat engines and converted to useful mechanical work. And since changes in the ratio of nickel to titanium alter the temperature at which the shape-memory effect occurs, Nitinol engines could be designed to operate at a wide variety of temperatures. Within a very wide temperature range, Nitinol reacts less to the exact temperatures of the hot and cold sides of its bath than it does to the difference between them. If composed of 55 percent nickel and 45 percent titanium, it will give its shape-memory response at differences in the room-temperature range. Given a slight increase in the proportion of titanium, however, it will perform at temperatures as high as 120 degrees centigrade. Thus it can be used, for example, to power automatic fire-fighting equipment.

Engineers are now considering the possibility of combining a series of Nitinol engines designed to respond at progressively lower temperatures along the flow of hot water emitted by industrial plants. Since this water is the cause of much of the thermal pollution of streams, rivers and oceans, Nitinol heat engines that absorb waste heat could provide an important ecological bonus.

HYDROELECTRIC POWER

In the long run, the biggest sources of thermal energy for Nitinol heat engines are likely to be oceans, natural lakes and the lakes that form behind hydroelectric dams, which are, in a sense, huge solar collectors and heat storage systems. The temperature differences of around 20 degrees centigrade between the ocean's warm surface water and deeper cold water is close to the optimum for Nitinol heat engines. Researchers calculate that engines operating at only 3 percent efficiency could draw enough energy from

Photograph courtesy of Lawrence Berkeley Laboratory the Gulf Stream to power the entire eastern seaboard of the United States. Hydroelectric sites have the additional advantage of already possessing power-transmission lines. Some scientists are predicting that Nitinol heat engines could double the output of existing hydroelectric facilities.

Nitinol has been around for more than 20 years. Why isn't the world running on solid-state shape-memory heat engines?

In the words of the *Whole Earth Catalog*'s editor Stewart Brand, who first drew attention to the possibilities of Banks's engine in his magazine *CoEvolution Quarterly,* "There are some things that are so original that it takes time for the social mind-set to catch up with them." Even so, Brand thinks support should be redirected from some of the more conventional energy projects into research and development of heat engines.

The successful development of commercial heat engines would challenge at least three competing energy systems in which considerable money and effort have long been invested: photovoltaic cells, solar-power towers and organic-fluid Rankine turbines. All three systems could be rendered obsolete by Nitinol heat engines. According to the latest Navy figures, a Nitinol heat engine could convert energy for a mere 6 percent of the current cost of photovoltaic conversion. And while photovoltaic cells are fragile, Nitinol is tough, and it gets tougher. "Nitinol never wears out," says McMillan. "It just keeps getting better and better."

Solar-power towers, with vast arrays of mirrors focusing the sun's rays on a central boiler to produce steam for turbines, can operate only during daylight hours. Nitinol engines operating on waste heat can run around the clock.

Rankine cycle turbines using ammonia are currently considered by the government to be the heat-conversion system best suited for ocean thermal-energy conversion (OTEC). But researchers have noted a number of advantages that Nitinol seems to have over the organic-fluid system. Nitinol is resistant to corrosion and can come in direct contact with ocean water without polluting. Nitinol engines are much simpler than the Rankine devices, and Navy calculations of the comparative cost per kilowatt-hour suggest that while turbine power is still slightly cheaper, the difference is narrowing.

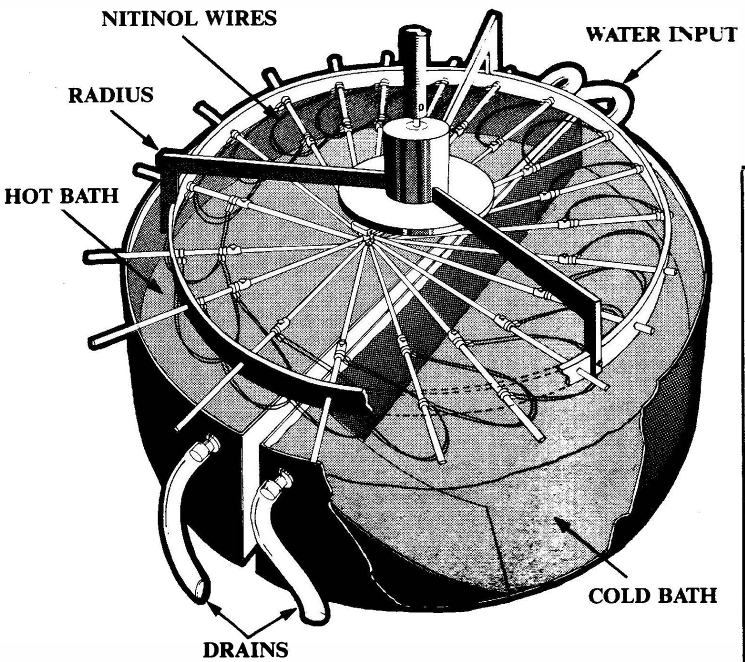
Bundles of Nitinol that expand and contract just like our muscles may be a good substitute for a diseased heart.

Nitinol is still in an early, even primitive stage of development. If the material is strained beyond certain broad limits, it can be permanently deformed or develop fatigue. It is also expensive, about $200 a pound, and tricky to make. To achieve a desired transition temperature, the proportions of nickel and titanium must be accurate to one part per thousand; production requires a vacuum furnace and sophisticated support equipment to ensure purity. Some researchers say that all the material produced so far is crude and that properly refined Nitinol could be vastly more powerful, able perhaps to respond to temperature differentials as low as 3 or 4 degrees centigrade.

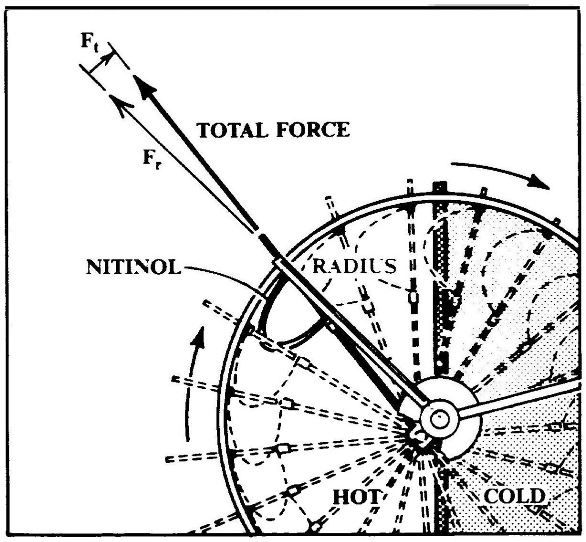
Recent metallurgical advances are making possible new levels of precision, purity and consistency. Near Utica, New York, the Special Metals Corp. is about to go into the production of commercial quantities of Nitinol. Some other works in progress:

Ridgway Banks, the father of the Nitinol heat engine, is now working on a new model that takes advantage of the theoretical 8 percent contraction that occurs in Nitinol when it is raised above the transition temperature. Banks believes this is probably the most efficient way to use Nitinol since the force of the change occurs uniformly throughout the entire cross section of the power element. At his new laboratory in Berkeley, he has been getting a flow of about 20 watts of power

Suspended from spokes attached off-center, each U-shaped Nitinol loop springs apart in hot water, creating a radial force (F_r) that pushes outward along the wheel's radius and a tangential force (F_t), perpendicular to the radius, that spins the wheel.



THE BANKS ENGINE



Left illustration by Carol Kramer; right illustration by Ian Worpole from a prototype model. "This is the first engine I've had anything to do with," says Banks, "that could be upgraded to kilowatts or conceivably megawatts of power."

Another San Francisco inventor, Bob Trupin, also formerly of the Lawrence Berkeley Laboratory, has assembled what is probably the biggest single-element Nitinol heat engine. It consists of a long water bath divided by a wide strip of Nitinol plate into a hot side and a cool side. The bath rocks on an axis, shifting the work element into contact first with the water on one side, then with the other. Trupin calculates that he will eventually get a 100-watt output of energy from his machine after he solves a mechanical problem: his Nitinol element consists of short segments clamped together, and the "punch" of the Nitinol stroke is so sudden and powerful that the clamps fail to hold the strips of Nitinol together. Trupin thinks a single seamless strip of Nitinol might solve the problem.

In Belgium, work is being done on a heat engine using the cheaper but less powerful brass alloys. A low-power prototype brass alloy engine has been developed by Delta Materials in England. The company recently introduced to the United States the first commercial brass shape-memory device: a spring activator for greenhouse windows that opens them when the weather is warm and closes them when it gets cold.

Recent reports indicate that the Chinese may be at work on a Nitinol heat engine, probably for irrigation. In Washington early this year, a delegation of scientists from Peking requested copies of all available material on Nitinol.

Engineers at Battelle's Columbus Laboratories in Ohio have been working for more than 10 years on a wide range of military and industrial applications. Some of the research is sponsored by the U.S. military and remains classified. Other projects include a fire-sprinkler system in which the Nitinol element in the sprinkler head would give a faster response than present types.

BIOMEDICAL APPLICATIONS

Since Nitinol is not only lightweight and nonmagnetic but also uncommonly inert even after prolonged contact with the body, it is being tested on lab animals in a number of biomedical applications. These include orthodontic braces for the teeth, bone plates for the compression-setting of fractures, surgical probes for hard-to-reach areas of the body, and internal support structures such as devices to keep arteries open. Perhaps the most ambitious biomedical project is a heart pump using Nitinol wire designed to expand and contract like a muscle.

Preliminary studies by the Department of Energy and the World Bank on the global distribution of nickel and titanium show that both elements are abundant and cheap (about $10 a pound) and are fairly evenly dispersed around the planet. No Nitinol OPECs lurk.

And so, sometime before the end of the century, there will be a Nitinol technology, a Nitinol industry, perhaps, in some parts of the world, a local Nitinol economy. The crash and roar of the fossil-fuel age may be replaced by the quiet splash of countless wires, levers, loops, pulleys, springs, fans, fins, belts and wheels on millions of engines, cycling continuously between warm and cold water, drawing out a flow of clean, safe, endlessly renewable energy through whatever mysterious force vibrates along the crystal lattice of a metal that remembers . . . and forgets . . . and remembers . . . and forgets . . . and remembers. . . . ■

HOMEMADE ENGINE

The splashing triumph of a young and inquisitive inventor.

Long before he ever got his hands on Nitinol, 17-year-old David Mitzi had spent 1,000 hours of his spare time designing an engine using the exotic alloy. By the time he made his engine spin last winter, he had logged another 1,000 hours, mostly in the family basement in Stamford, Connecticut, building with parts from a scrapyard, always tinkering and adjusting, since his first versions failed to spin.

The final product is held together, he admits, chiefly with epoxy glue. But the clicking and splashing Nitinol heat engine has brought him great recognition: awards from the Department of Energy, the Navy, the Army and General Motors that have included trips to Hawaii, London and Tokyo to talk with scientists and other inventive youths.

Mitzi got the idea of building a Nitinol engine during his junior year in high school after encountering an article on shape-memory alloys.

His device uses Nitinol wires suspended from extendable arms that radiate outward from a hub like the spokes of a wheel. The small levers by which the Nitinol makes the arms extend are a special innovation.

The wires travel around in an oval tank and alternately splash into hot or cold water. As they encounter hot water, the wires straighten (the shape-memory effect) and cause the levers to force the extendable arms outward. The arms, which have small rollers on their ends, press against the tank wall, pushing the wheel around the oval. The two quadrants in which the oval narrows contain cold water, and as Nitinol wires rotate into them the wires bend again.

The young inventor is already mulling the design for his next Nitinol engine, glad to have access to the libraries of Princeton University, which he entered this fall as a freshman. He'll study physics and engineering, continuing a fascination with science that he says was first stirred by an excellent teacher in eighth grade.

–George Sweetnam

FREE NITINOL

In cold water, Nitinol is easily bent, yet in warm water it snaps back to its original shape. If you would like a free stick of Nitinol, send a creative idea for its use and a self-addressed, stamped envelope to:
***Science Digest* Nitinol**
P.O. Box 1575
Radio City Station
New York, NY 10019
Offer ends October 30, 1981. The Nitinol sticks are courtesy of the Special Metals Corporation, a subsidiary of Allegheny International.

Photograph by Joseph Kugielsky