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# Some Applications of Shape-Memory Alloys

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> *And the LORD said unto Moses, "What is that in your hand?" And he said, "A rod."*
>
> *Then HE said, "Cast it on the ground." And he cast it on the ground and it became a serpent: and Moses fled from it.*
>
> *And the LORD said unto Moses, "Put forth thine hand and take it by the tail." And he put forth his hand and caught it, and it became a rod in his hand.*
>
> **OLD TESTAMENT**
> **Exodus, Chapter 4:2-4**

*SUMMARY*

*Uses or potential uses of shape memory alloys fall into industrial, energy, and dental/medical categories. These various applications are considered after a brief discussion of the nature of the shape memory effect and other interesting properties in shape memory alloys. Most applications involve NiTi-type and Cu-based alloys, the latter being relatively inexpensive to produce and fabricate into numerous forms.*

## NATURE AND MECHANISTICS OF THE SHAPE MEMORY EFFECT

The shape-memory effect (SME) can be described as follows: basically, an object in the low-temperature, martensitic condition when it is deformed and the stress then removed will regain its original shape when heated. Strains typically 6–8% may be completely recovered. The process of regaining the original shape is associated with the reverse transformation of the deformed martensitic phase to the higher temperature parent phase.

Many materials are now known to exhibit the shape-memory or "marmem" (*mar*tensite *mem*ory) effect; a partial list includes the alloy systems Cu-Zn, Cu-Zn-Al, Cu-Zn-Ga, Cu-Zn-Sn, Cu-Zn-Si, Cu-Al-Ni, Cu-Au-Zn, Cu-Sn, Au-Cd, Ni-Ti, Ni-Ti-X (X = ternary element), Ni-Al, and Fe-Pt. These alloys are all ordered (both parent and martensite) and exhibit a crystallographically reversible, thermoelastic martensitic transformation.

Substantial progress has recently been made in understanding the nature of SME. As is well known, a crystal of the parent phase will transform into many orientations (plates or variants) of martensite on cooling. Ideally, a single crystal of the parent phase will form 24 orientations of martensite on cooling between the $M_s$ and $M_f$ temperatures. But when this multi-orientation configuration of martensite is deformed, a single orientation of martensite eventually results because of twinning and the movement of certain martensite interfaces. It has been shown that the twins which form in the martensite are simply other orientations (variants) of martensite; thus twinning can convert one orientation of martensite to another. The same thing happens when martensite/martensite interfaces move under stress: one orientation grows at the expense of another. In the final analysis, the single remaining orientation of martensite is the variant whose "shear" or shape deformation will permit the maximum elongation of the specimen in the direction of the tensile axis.

Although the original single crystal of the parent phase transforms into many (up to 24) orientations of martensite, the reverse does not occur. Instead, the single crystal of martensite obtained from deformation below the $M_f$ temperature transforms, on heating, to a single orientation of the parent phase. This is a consequence of the relative symmetries involved and the necessity to maintain ordering. In other words, the highly symmetric (usually cubic) parent phase has many crystallographically equivalent principal axes for the lattice change (Bain distortion) which will thus lead to the many variants of martensite which are observed. On the other hand, the relatively unsymmetric martensite (e.g., monoclinic in Cu-Zn-Al alloys) does not enjoy such a multiplicity of choices, and only a single variant of the parent is usually nucleated during the reverse martensite-to-parent transformation. In essence, the single crystal of martensite "unshears" to form a single crystal of the parent, and this "unshearing" during reverse transformation restores the specimen to its original shape. This sequence is metallographically depicted in Figure 1.

The above account appears to be generally valid, irrespective of the alloy system or martensite crystal structure.

## OTHER INTERESTING PROPERTIES OF MARMEM ALLOYS

Shape-memory alloys have interesting properties and characteristics in addition to the shape-memory effect, *per se*. As will be described later, excessively deformed (some 30% strain, and well beyond the limit of shape-memory recoverable strain) martensitic NiTi alloys have unusual elastic properties. When many of the martensitic Cu-based alloys are continually deformed beyond the single-crystal martensite stage, a new martensite phase is generated, i.e., a stress-induced martensite-to-martensite transformation occurs. This successive mode of martensite deformation allows recoverable strains of more than 17%. Shape-memory alloys are also excellent damping materials. The relative ease of movement of internal boundaries, such as martensite-martensite boundaries, under a small stress is strongly attenuating. Finally, a "two-way" shape memory can be programmed into various memory alloys by appropriate stress and/or thermal cycling. Once this conditioning has been achieved, a specimen will spontaneously "bend" when the parent transforms into martensite, and "unbend" to the initial shape during the reverse transformation.

# INDUSTRIAL APPLICATIONS OF SHAPE-MEMORY ALLOYS

## Fasteners and Couplings

One of the earliest widespread applications of SME was Raychem Corporation's (Menlo Park, Calif.) introduction of tubing or pipe couplings which shrink during heating. Typical of such NiTi-type couplings are those used for connecting aircraft hydraulic lines. The couplings are expanded $\sim 4\%$ in the martensitic condition at liquid-nitrogen temperature, then placed around the tubes to be joined. During warming to room temperature, they contract, producing a tight seal. The use of such fittings avoids metallurgical degradation which can result from welding or brazing, and avoids damage to the aircraft "skin." Over 300,000 such high-performance connectors have been used in U.S. Navy aircraft, with no reported failures.

Similar NiTi-type fixtures have been used extensively for plumbing on submarines and surface ships during the past five years by the British Royal Navy, and within the past two years by the U.S. Navy for a variety of surface ships; an example is shown in Figure 2.

The size of NiTi-type fittings has been increased considerably recently, and fittings which join carbon-steel subsea pipe up to six inches in diameter have been installed successfully at depths up to 300 ft using saturation diving techniques, taking a pre-chilled fitting down in the diving chamber. For broken subsea piping, SME fittings are justified by speed and ease of installation compared with other techniques and by no necessity to rely on operator skill.

Raychem has also developed a "Cryocon" shape-memory type electrical connector particularly suited for multiconnector electrical plugs.

Extensive research and development on NiTi and NiTiX ternary alloys is also being conducted at the Brown Boveri Research Center in Baden, Switzerland.

Raychem recently introduced a new line of Cu-based alloy heat-shrinkable fittings in addition to other fasteners and devices. These devices can be provided in the field in the (deformed) martensitic condition at room temperature and applied simply by heating them with a propane torch. Figures 3-5 are examples showing a coupling, retainer, and clamp; and Figures 6 and 7 are photographs of a clamp and a seal made of a Cu-based SME alloy. Figure 8 shows a clamp and expander, demonstrating that the engineering parameters for the Cu alloys have been well worked out. Additional fasteners, clamps, plugs, rivets, etc., will undoubtedly appear in the near future, including plugs for nuclear reactors which will eliminate welding.

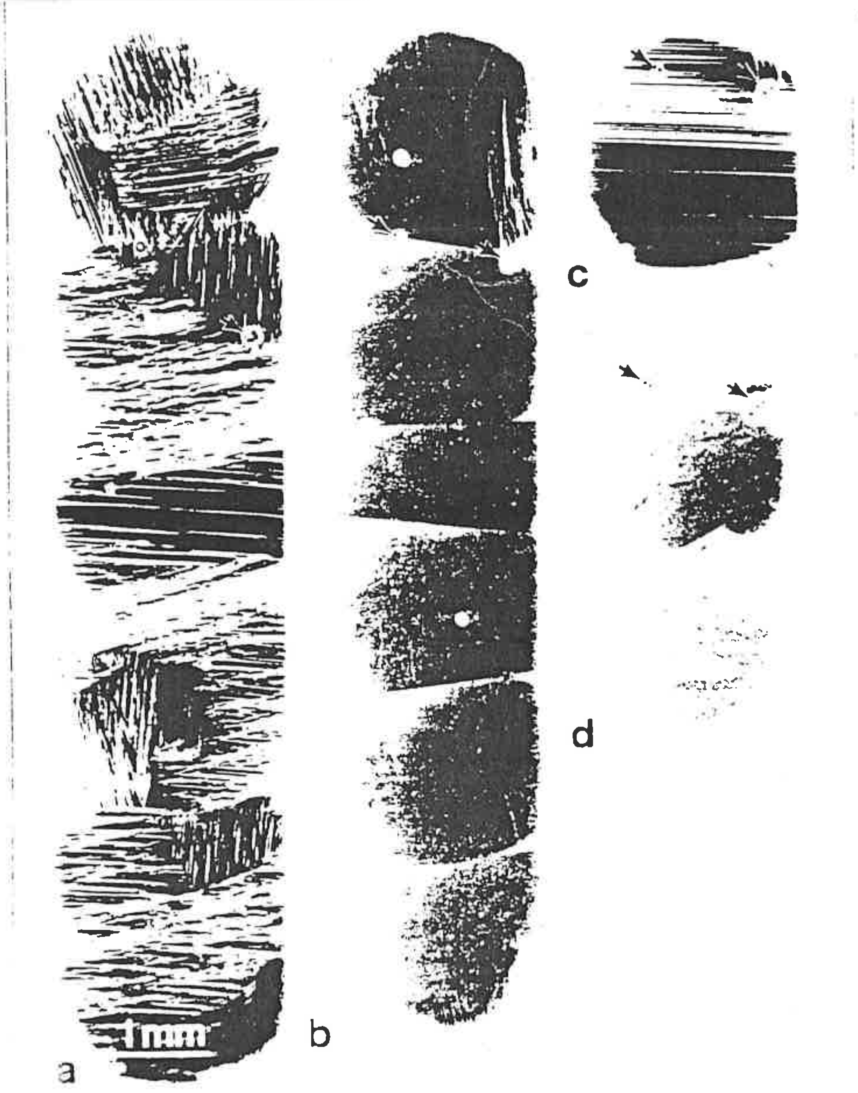

**Figure 1.** Optical micrographs showing a) numerous orientations of martensite in as-transformed Cu-Zn-Ga alloy, b) the "coalescence" of variants upon stressing, c) nucleation of only a single variant of the parent phase during heating, and d) the original single crystal of the parent phase.

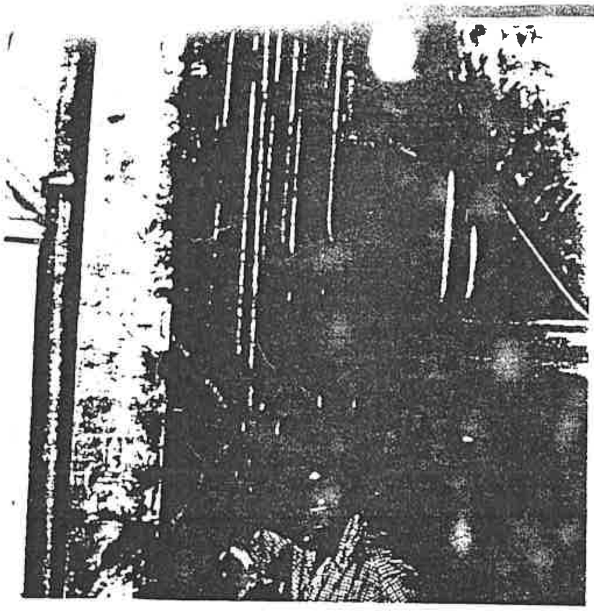

Figure 2. Bank of hydraulic piping on the USS Peleliu installed with heat-shrinkable NiTi-type couplings. (Courtesy Raychem Corp.)

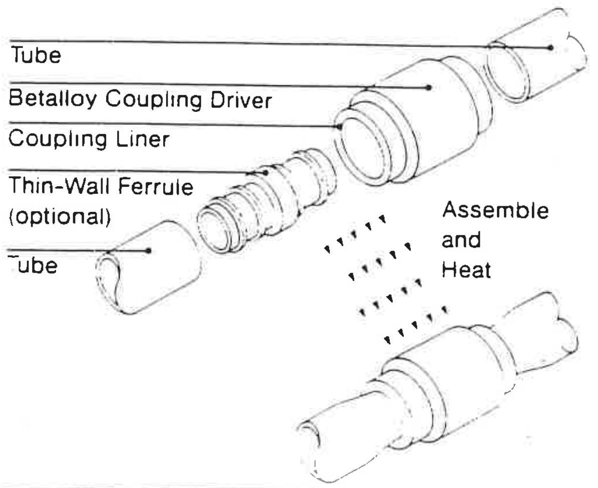

Figure 3. Tube or pipe coupling made from Cu-based shape-memory alloy. (Courtesy Raychem Corp.)

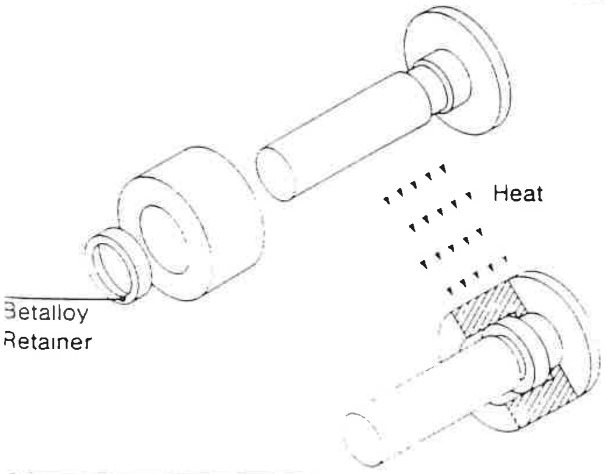

Figure 4. Retainer made from Cu-based shape-memory alloy.

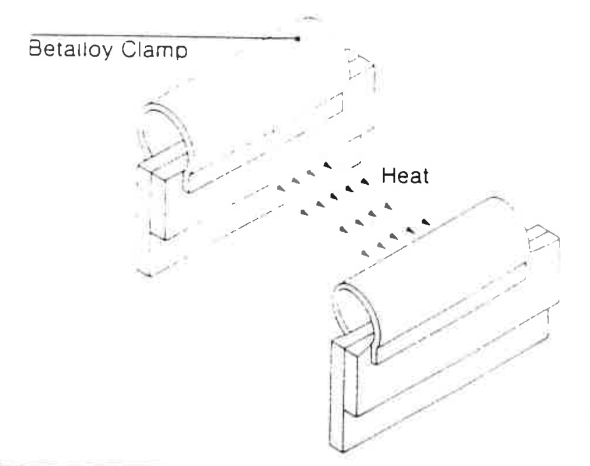

Figure 5. Clamp or crimp made from Cu-based shape-memory alloy. (Courtesy Raychem Corp.)

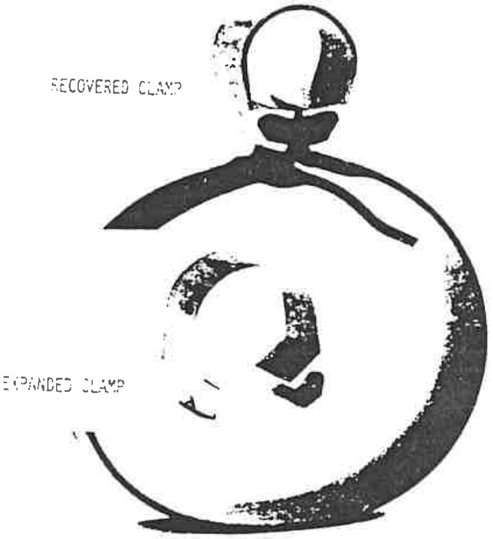

Figure 6. Clamp made from Cu-based shape-memory alloy. (Courtesy Raychem Corp.)

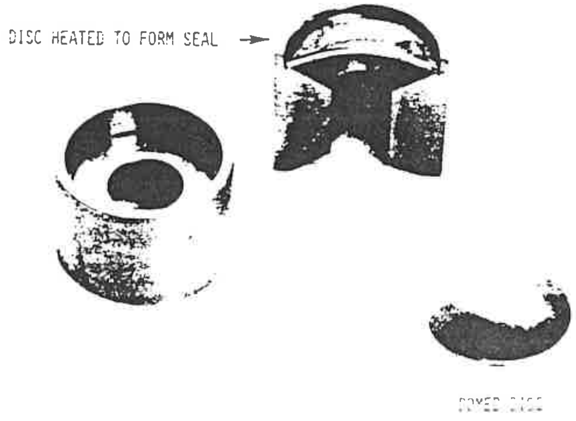

Figure 7. Disc seal made from Cu-based shape-memory alloy.

Numerous patents have also been filed for various SME devices not yet been marketed, such as mechanisms for platform motion, pumps for fluids, and thermal warning devices which can be attached to containers used for shipping refrigerated biological materials such as human blood.

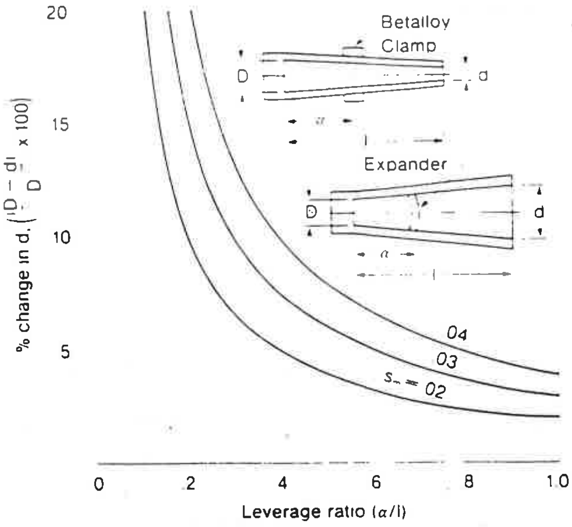

Figure 8. Clamp and expander made from Cu-based shape-memory alloy. (Courtesy Raychem Corp.)

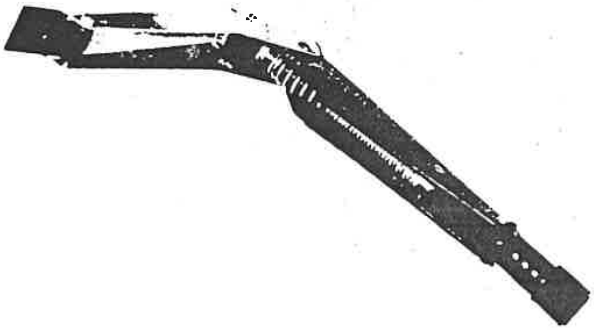

Figure 9. Greenhouse window control incorporating a Cu-based shape-memory alloy. (Courtesy Delta Memory Metal Co.)

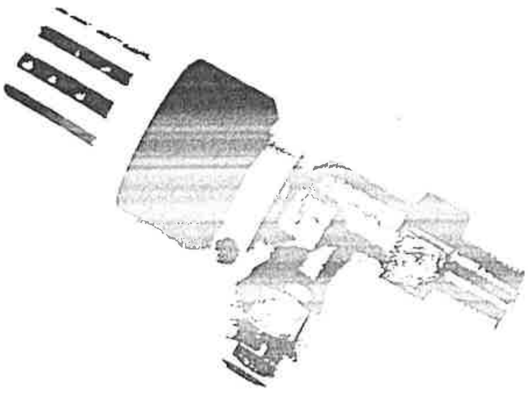

Figure 10. Thermostatic radiator valve incorporating Cu-based

## Thermomechanical and Thermostatic Devices

Substantial efforts in developing Cu-based shape-mem ory alloys have been made by the Delta Memory Meta Company (Suffolk, England). They have developed a range of Cu-Zn-Al SME alloys with emphasis on thermostats, controls for heating and cooling equipment, automotive control devices, and actuators for equipment ranging from greenhouse windows to fire doors. Many of these prototypes have been cycled a half-million times or so with no observable fatigue, "creep," or change in deflection characteristics.

Figure 9 shows an actuator for greenhouse windows, basically a spring-loaded hinge containing a bias spring and a SME spring. Below 18°C, the SME spring is in the co tracted (martensitic) condition and the window is closed. When the temperature rises, the shape-memory spring overcomes the restraining bias spring, and at 25°C the window is fully opened. The window is automatically pulled shut when the temperature falls. As expected, the hysteresis of an unloaded actuator is some 10–15°C, but this can be compensated for by forcing the actuator to work against a bias spring. Delta has proposed similar devices to open fire doors, actuate ventilators in factories, open radiator vents in diesel trucks, and control vents in warm-air heating systems.

Another SME spring-actuator/bias-spring device is thermostatic radiator valve for residential hot-water heating systems (Figure 10). As the temperature in a room increases, the actuator expands, overcomes the force of the bias spring, and closes the port of the valve on the hot water line of the radiator system. The temperature can be adjusted by rotating the top head assembly, which alters the compression of the bias spring. Such regulators are comparatively inexpensive and have a much faster system response time. With a proper bias spring, thermal hysteresis can be held to 1.2C°. There is a remote-control version of these valves.

Another Delta device, an automotive clutch fan (Figure 11), uses an SME actuator in the form of a helical spri which is biased against a set of four steel leaf springs. The SME actuator coil engages a clutch which turns an automotive engine fan when the "air-off" temperature exceeds a certain value, typically 53°C; the actuator closes the clutch plate until the temperature is under control. At low temperatures, the fan idles at ~250 rpm. At higher temperatures, the clutch fan speeds up sufficiently to cool the engine assembly. If this speed is less than engine speed, the clutch fan will slip. Thus the fan does only as much work as required and, accordingly, saves energy. Such a device has been road tested for 20,000 miles, and indications are that it would operate an additional 60,000 miles. The clutch fan was proposed in order to reduce engine noise (at idling) and fuel consumption (because it removes the energy loss from the fan when it is not required to cool the engine).

Another automotive application of Cu-type SME alloys concerns the carburetor. In this case, atmospheric pollution is minimized and fuel consumption optimized by compensating for fuel viscosity. A simple jet made of a Cu-Zn-Al SME alloy is inserted in a Stromberg-type carburetor. As the fuel warms, an orifice reduces in size and thus meters the correc fuel volume. Figure 12 shows the performance of such a Note particularly the reduction in CO emission at lo fuel temperatures.

A further automotive application, also concerning th carburetor, is to use a Cu-type SME actuator to close a "cold start" choke at a predetermined time after an engine has started. The SME actuator is energized by heat from an electrical source, causing the actuator to close the choke.

Figure 13 shows a room-temperature thermostat control designed by Delta. This control consists of an SME actuator spring and bias spring mounted to a standard microswitch, with a simple adjustment for temperature. A similar therm boils. If the kettle boils dry or is not filled, the SME element is heated, switching off the kettle.

Other examples of Cu-Zn-Al SME devices are the tubular and coil-type torsion actuators shown in Figures 14 and 15 in the "closed" and "open" positions. A somewhat similar line of Cu-Zn-Al SME devices is being developed by N.V. Bekaert in Zwevegen, Belgium, but they have not yet been introduced in the U.S.

The above discussion emphasizes many existing thermomechanical and thermostatic applications of Cu-based SME alloys. More will surely follow, considering the inexpensiveness of such brasses and their ease of fabrication. However, such alloys are subject to aging effects and cannot cyclically operate indefinitely when the "upper" temperature is ~150°C or more. The nature of the aging effects which cause deterioration of the shape memory remains to be determined. Higher operating temperatures are expected in the future through alloy development.

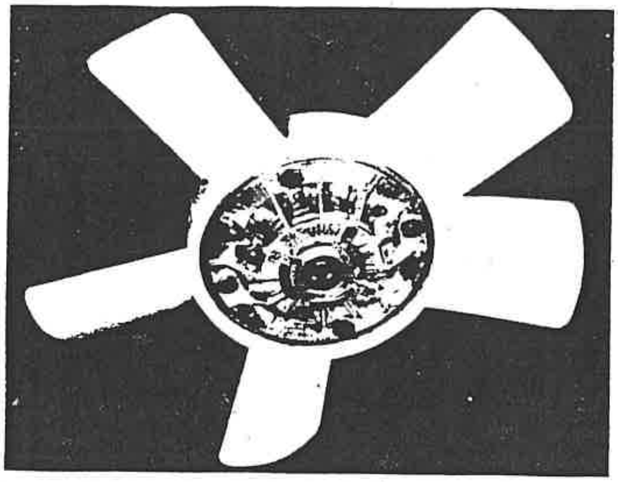

**Figure 11. Automotive clutch fan with heat-energized actuator made from a Cu-based shape-memory alloy. (Courtesy Delta Memory Metal Co.)**

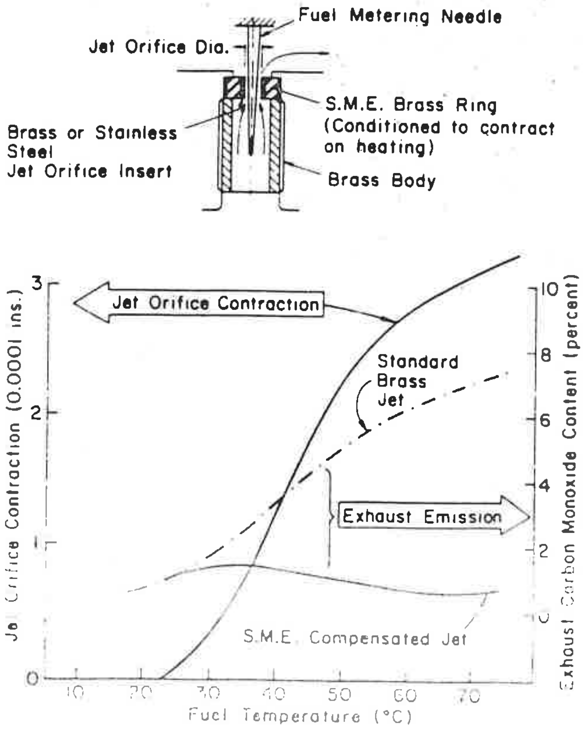

**Figure 12. Carburetor jet assembly with variable orifice controlled by a Cu-based shape-memory alloy. Note the reduction of CO emission by using the SME compensated jet. (Courtesy Delta Memory Metal Co.)**

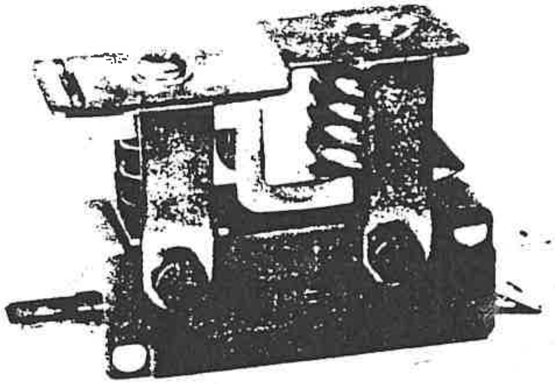

**Figure 13. Room-temperature thermostat control using a Cu-based shape-memory alloy spring. (Courtesy Delta Memory Metal Co.)**

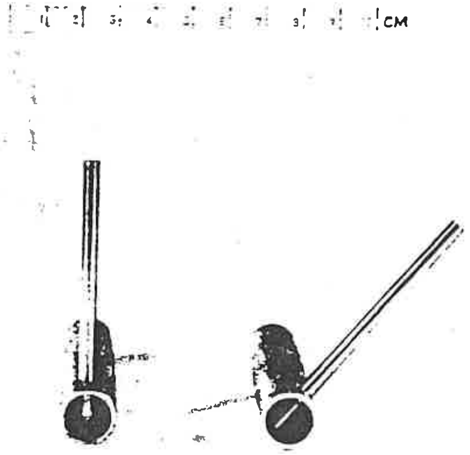

**Figure 14. Tubular torsion actuator made from Cu-based shape-memory alloy. (Courtesy Delta Memory Metal Co.)**

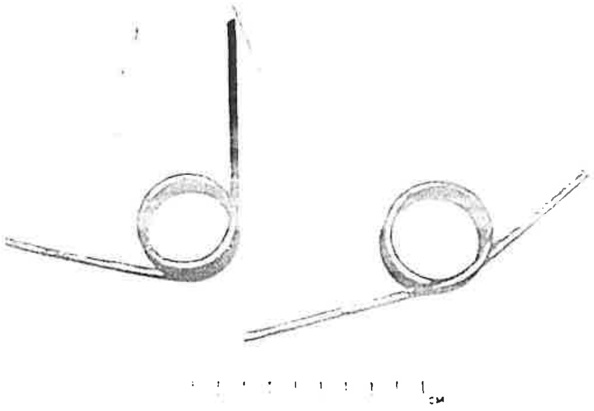

**Figure 15. Coil-type torsion actuator made from Cu-based**

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