# Thermal Actuation with Shape Memory Alloys

Stoeckel

1989

# Thermal Actuation With
# Shape Memory Alloys

**Dieter Stoeckel**
***Raychem*** **Corporation**

Thermal actuators, by definition, are devices which convert thermal energy into mechanical energy. They utilize effects like the thermal expansion of solid materials, e.g. in thermostatic bimetals, or volume changes during phase transformations like solid/liquid or liquid/gaseous, e.g. in wax actuators. These devices sense changes in ambient temperature and react to these changes by bending, as in the case of thermostatic bimetals, or with the linear movement of a piston, as in the case of wax actuators. The unique property of *Tinel* alloys to remember a previous shape after being deformed offers a new perspective in actuation techniques. *Tinel* is the Raychem brand name for a family of Nickel-Titanium shape memory alloys used for thermal and electrical actuators, tube and pipe couplings, fasteners and a variety of other applications.

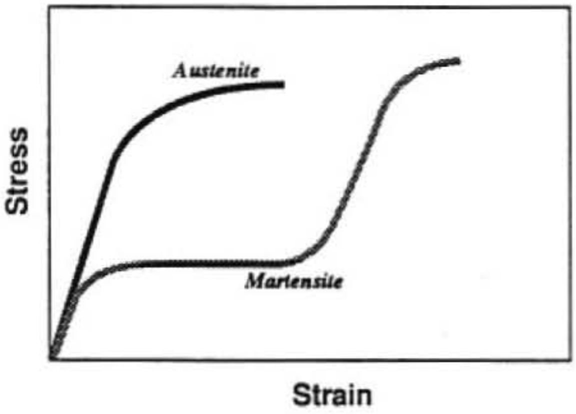


Figure 1: Tensile Behavior of Ni-Ti alloys in Austenite and Martensite

## 1. Shape Memory Effect

"Shape Memory" describes the effect of restoring the original shape of a plastically deformed sample by heating it. This phenomenon results from a crystalline phase change known as "thermoelastic martensitic transformation". The shape memory effect in Tinel alloys can be used to generate motion and/or force in actuators, fasteners and couplings. At temperatures below the transformation temperature, Tinel alloys are martensitic. In this condition they are very soft and can be deformed easily (like soft copper). Heating above the transformation temperature recovers the original shape and converts the material to its high strength, austenitic, condition (like steel).

Figure 1 shows tensile curves of Ni-Ti alloys in the martensitic and austenitic conditions. While the austenitic curve looks like that of a "normal" material, the martensitic one is quite unusual. On exceeding a first yield point, several percent strain can be accumulated with only little stress increase. After that, stress increases rapidly with further deformation. The deformation in the "plateau region" is non-conventional in nature and can be recovered thermally. Deformation exceeding the second yield point cannot be recovered. The material is plastically deformed in a conventional way. Plotting the plateau stress or the first yield point versus temperature produces a curve as shown in Figure 2. Similar curves are obtained, when the modulus is plotted versus temperature. Figure 3 shows the shear modulus of a particular Ni-Ti alloy as a function of temperature. Curves like these are basic for the design of shape memory thermal actuators, like helical compression or extension springs.

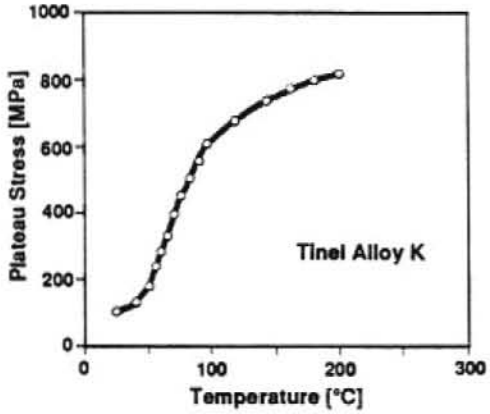


Figure 2: Influence of Temperature on the Plateau Stress of Ni-Ti

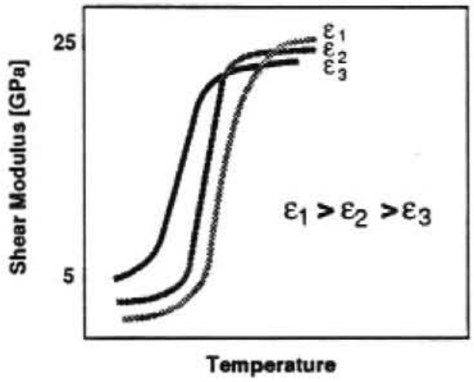


Figure 3: Influence of Temperature on the Shear Modulus of Ni-Ti

The shape memory effect can be explained in simple terms using a straight Ni-Ti tensile wire. As schematically shown in Figure 4, the wire is fixed at one end. Stretching it at room temperature generates an elongation of Δl after unloading. The wire remains in the stretched condition until it is heated above the transformation temperature of this particular alloy. It will then shrink to its original length (if no load is applied, *free recovery*). Subsequent cooling below the transformation temperature does not cause a macroscopic shape change. This effect is called *one-way effect*. On heating the transformation starts at As (*Austenite Start*) and is finished at Af (*Austenite Finish*)

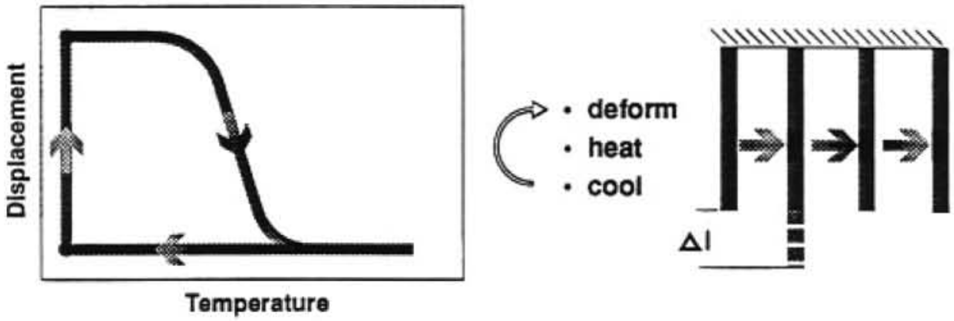


Figure 4: One-Way Effect

The one-way effect can be repeated many times. For each cycle a deforming force is necessary. If this force is applied constantly, e.g. as a constant load attached to the wire, a two-way behavior can be achieved . The applied force must be high enough to stretch the wire in the martensitic condition. On the other hand it must be sufficiently small not to cause excessive deformation of the austenite (Figure 5). This effect is called *two-way effect with external reset force* or *extrinsic two-way effect*.

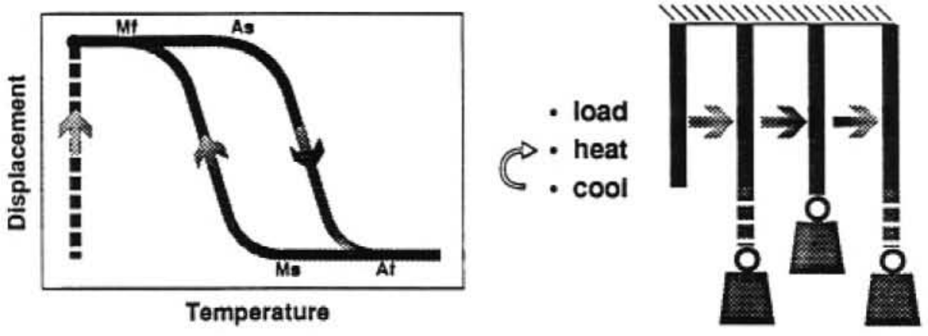


Figure 5: Extrinsic Two-Way Effect

As can be seen from Figure 5, the transformation does not occur at the same temperature on heating and cooling. An important characteristic of the effect is the temperature *hysteresis*. Standard Ni-Ti alloys show a hysteresis of 30 to 50°C. Through alloy modifications, however, it is possible to either reduce the hysteresis to about 15°C, or extend it to over 100°C. The hysteresis loop is described by the transformation temperatures As, Af and Ms, Mf (*Martensite Start, Martensite Finish*). Transformation temperatures can be varied between approximately -100°C and +100°C.

Shape memory alloys can, under certain conditions, show a true two-way effect, which makes them remember two different shapes, a low and a high temperature shape, even without external force. However, it is smaller and its cyclic behavior is not as well understood as that of the one way effect. Because there is no special treatment necessary, the cyclic use of the one-way effect with external reset force in many cases is the more economic solution.

## Designing Ni-Ti Shape Memory Actuators

The shape memory effect in Ni-Ti alloys is not limited to the linear contraction of wires. Even larger shape changes can be achieved in the bending or torsional deformation mode. Accordingly, there are many possibilities regarding the shape of the actuator. Preferred configurations are :

- straight tensile wires (high force, small motion)
- helical compression springs (large motion, less force)
- helical extension springs (large motion, less force)
- cantilever springs (bending)
- "Belleville"-type disc springs (high force, small motion)
- wave-washer springs (high force, small motion)
- torsion wires/rods
- torsion tubes
- helical torsion springs

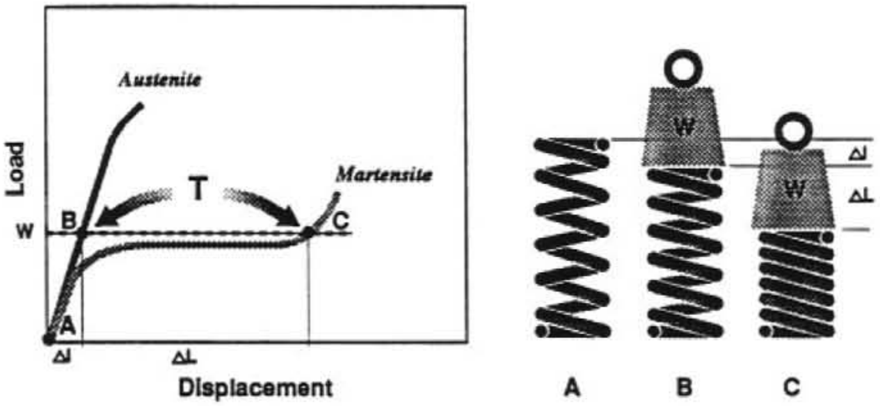


Figure 6: Work Against a Constant Load

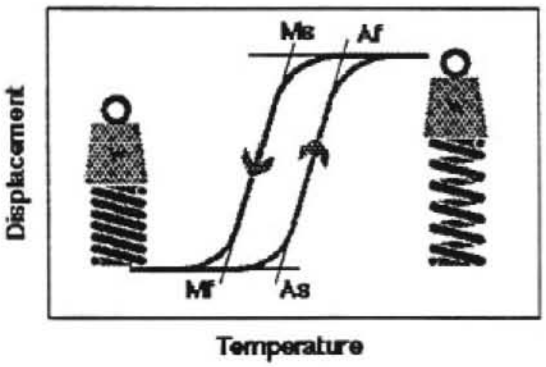


Figure 7: Extrinsic Two-Way Effect With Constant Load

The design of shape memory elements for thermal actuators is based on the different stress/strain curves of the austenite and the martensite. As an example, Figure 6 shows the force/deflection curves of a helical compression spring at high and low temperatures. The high temperature shape of the spring with no load is Lo (A). If the spring is loaded with a constant load W in the austenitic condition (at temperatures above Af) the spring is compressed along A - B with the displacement Δl (B). Upon cooling below Mf the spring converts into martensite. Now the load W compresses the spring to point C on the martensite curve with the displacement ΔL. Repeated heating/cooling cycles between points B and C. The temperature/displacement diagram for this arrangement is shown schematically in Figure 7.

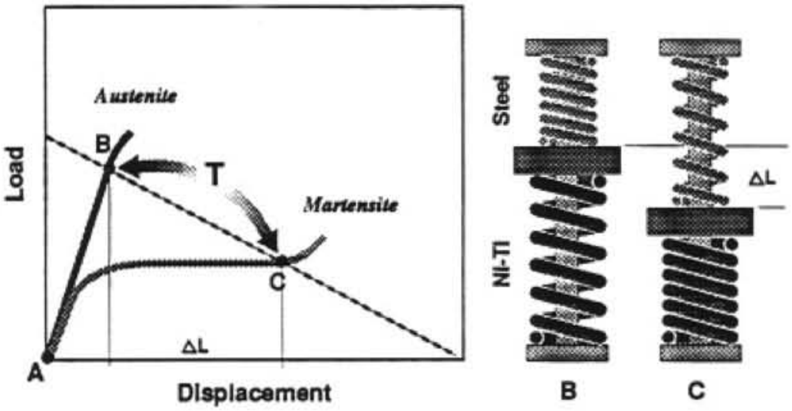


Figure 8: Work Against a Biasing Spring

If, instead of a constant load, a steel biasing spring is used, the force/deflection curve for this spring has to be superimposed to the austenitic and martensitic spring characteristics of the Ni-Ti spring. This is schematically shown in Figure 8. A Ni-Ti shape memory compression spring works against a steel biasing spring. At high temperatures (in the austenitic condition) the Ni-Ti spring is strong enough to compress the steel spring. However, at low temperatures (in the martensitic condition) the steel spring is able to compress the Ni-Ti spring. Again, repeated heating and cooling cycles between points B and C.

Under optimum conditions and no load the shape memory strain can be as high as 8%. However, for cyclic applications the usable strain is much less. The same applies for the stress; for a one-time actuation the austenitic yield strength may be used as maximum stress. Much lower values have to be expected for cyclic applications. The following numbers can be used as guidelines:

| **Number of Cycles** | **Max. Strain** | **Max. Stress** |
|---|---|---|
| 100 | 5% | 275 MPa/40 ksi |
| 10000 | 2% | 140 MPa/20 ksi |
| 100000 | 1% | 70 MPa/10 ksi |

## Design Criteria

Designing shape memory actuators is somewhat more difficult than working with conventional materials. For example, Young's and shear modulus are not linear, they are temperature dependent in a non-conventional way and depend on the strain. Moreover, there is still a lack of data concerning the torsional properties of shape memory alloys.

Thus, the use of design formula gives a first approximation only, and the final design is generally done by experimentation. With the number of applications increasing rapidly, databases are created which will facilitate future designs.

Tensile Elements (Straight Wire Actuators)

Tensile elements are stressed uniformly and, thus, the whole volume of the material is utilized. They are especially well suited for high force/ small motion applications. The applicable formulas are:

$$\sigma = \frac{F}{A} \qquad \varepsilon = \frac{\Delta l}{l_0} \qquad A = \frac{\pi d^2}{4}$$

with:
$\sigma$ = tensile stress
$\varepsilon$ = tensile strain
$A$ = cross-sectional area

Helical Compression and Extension Springs

Helical coil springs are stressed in torsion with maximum shear stress and shear strain occurring at the ID surface. The common spring formula can be applied for a first approximation with the assumption of a constant shear modulus:

$$\tau = W \frac{8\,D}{\pi\, d^3} F$$

$$\gamma = W \frac{d\, s}{n\, \pi\, D^2}$$

$$W = \frac{C + 0.5}{C - 0.5}$$

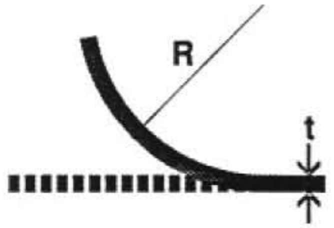
with:
$\tau$ = shear stress
$\gamma$ = shear strain

W = Wahl Correction
D = average spring diameter
d = wire diameter
F = force/load
n = number of turns
s = stroke/displacement
c = spring index D/d

Force/load and shape memory displacement are usually specified by the application, the maximum stress and strain are chosen with regard to expected lifetime (number of cycles). The value of the spring index is assumed (typically between 4 and 10). Using the stress formula gives the wire diameter and the mean coil diameter, the strain formula gives the number of active turns.

Cantilever Elements

Cantilever elements are stressed in bending with a non-uniform stress distribution over the cross-section. Maximum tension and compression occurs at the outer fibers of the element. The following approximate formula can be applied:



$$\sigma = \frac{6LF}{w t^2}$$

$$\varepsilon = \frac{t}{2R}$$

with $\sigma$ = bending stress
$\varepsilon$ = bending strain
$L$ = length
$F$ = bending force
$w$ = width
$t$ = thickness
$R$ = bending radius

**Applications of Thermal Shape Memory Actuators**

The use of Ni-Ti shape memory alloys for thermal actuators offers a variety of benefits including:

- high forces
- large movements
- small size
- different actuation modes
  - linear
  - bending
  - torsion
  - combinations thereof
- high work per unit volume and weight
- motion completed in narrow temperature range

Shape memory thermal actuators combine large motion, rather high forces and small size, thus providing high work output. They usually consist of only a single piece of metal, e.g. a helical spring, and do not require sophisticated mechanical systems. They, therefore, often fit into tight spaces in given designs, where thermostatic bimetals or wax actuators would require a major redesign of the product. In flow-control or oil pressure control valves, for example, helical springs can be placed in the fluid path, without restricting the flow (Figure 9). Thus, they provide fast response to changes in temperature.

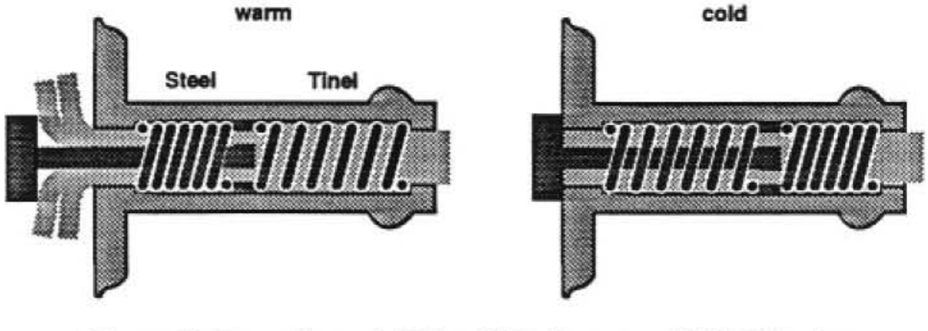


Figure 9: Flow Control Valve With Integrated Ni-Ti Spring

As shape memory actuators generate the motion and/or force in a narrow temperature range, which can be predetermined by the alloy composition, work output can be more than 100 times higher than with thermostatic bimetals. In Figure 10 the temperature/deflection curves of a shape memory cantilever beam and a thermostatic bimetal strip are plotted.

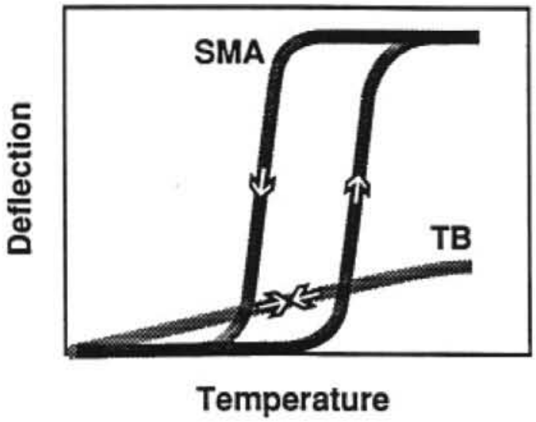


Figure 10: Comparison of Thermostatic Bimetal And Shape Characteristics

Shape memory actuators have been used successfully in the areas of thermal compensation, thermal actuation and thermal protection.

Thermal Compensation

Many material properties are temperature dependent. Oil, for example, is much more viscous at low temperatures than at high temperatures. Almost all materials increase in volume with increasing temperature. Viscosity and thermal expansion are material properties, which are characteristic for a particular material. Thus, they change at quite different rates for different materials.

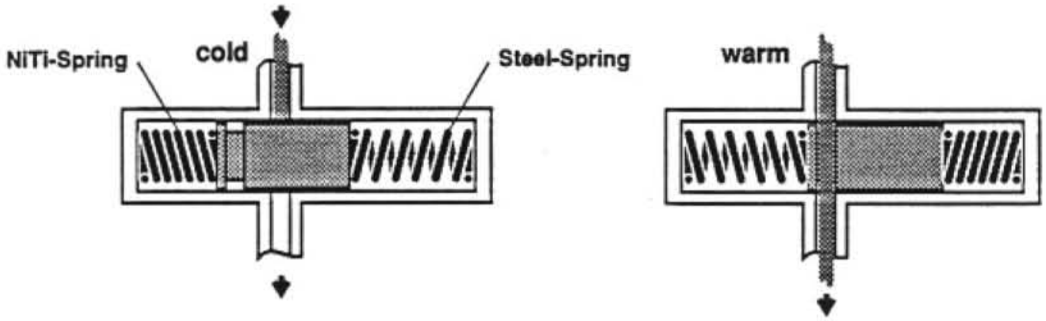
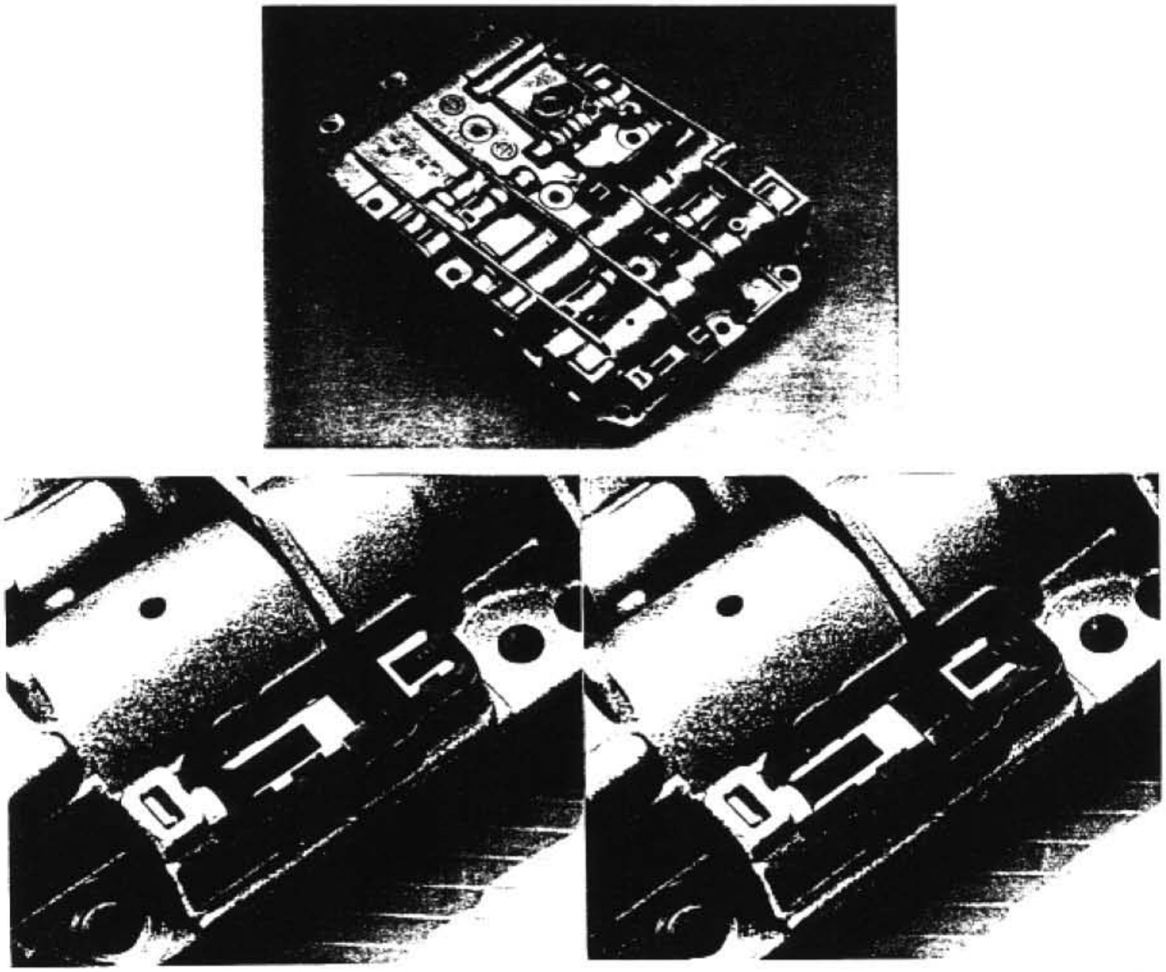


Figure 11: Governor Valve With Ni-Ti Spring

Because of changing oil viscosity, the performance of hydraulic systems can be strongly temperature dependent. This is one reason for the rough shifting of automatic transmissions during cold weather, particularly in Diesel powered cars. The problem can be eliminated by reducing the shifting pressure until the engine and all other systems warm up to operating temperature. Incorporating Ni-Ti shape memory springs into governor valves of automatic transmissions makes these valves thermally reactive.

As described earlier, Ni-Ti springs exert very different forces at high and low temperatures. In the valves they respond automatically to changes in transmission fluid temperature. When the engine temperature is low, the shape memory spring is soft, allowing a biasing steel spring which is stiffer at this temperature to move a piston that reduces pressure and helps reduce rough shifting. At high temperatures the same spring becomes stronger than the steel one. It pushes the piston in the opposite direction, optimizing shifting pressure (Figure 11)

This new concept, a joint development of Mercedes-Benz of West-Germany and Raychem in California, was recently introduced in model year '89 Mercedes cars. Figure 12 shows the valve plate with two thermally reactive valves (cut away sections) and Figure 13 a close-up view of one of the valves at high and low temperature.



**cold** **warm**

Figure 12 and 13: Valve Plate of Automatic Transmission With Shape Memory Valves

Since conventional shock absorbers tend to be too hard at very low temperatures, they don't provide comfortable driving. Again, this is caused by the high viscosity of the oil in the shock absorber, which usually is balanced for the temperature range of 0°C to 100°C. A shape memory washer in the shock absorber's valve (Figure 14), which changes the pressure at low temperatures, can compensate for the oil viscosity.

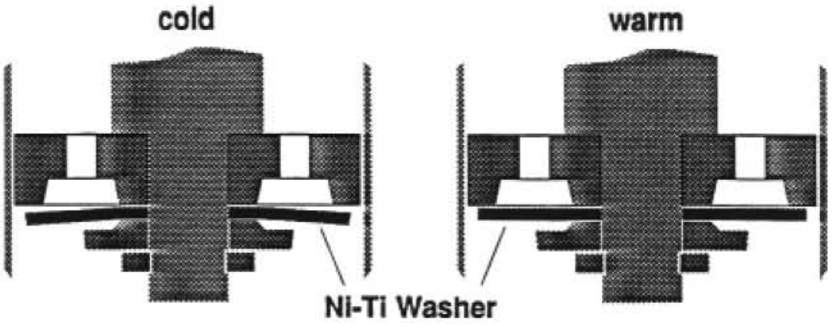


Figure 14: Shock Absorber Valve With Shape Memory Washer

Oil filters for jet engines have to be monitored for clogging. The indicators usually respond to the increased oil pressure when the filter is clogged. However, increased oil pressure can also be caused by high oil viscosity during very cold weather. In this case, a clogged condition of the filter is simulated and the indicator responds accordingly. These false alarms can be avoided by the use of shape memory compensating valves.

Ni-Ti washers can be used when high forces and small motion is required, e.g. to compensate for different thermal expansion of dissimilar materials. In gearboxes with steel shafts and aluminum cases, for example, rattling noise is caused by the decrease in preload of the assembly with increasing temperature. Ni-Ti Belleville-type or wave washers can generate in excess of 1000 N with a deflection of approximately 0.5 mm, and, therefore, restore the preload in the gearbox, when it reaches operating temperature. Figure 15 represents this situation schematically. A similar configuration is used by Toyota of Japan in their Sprinter/Carib cars.

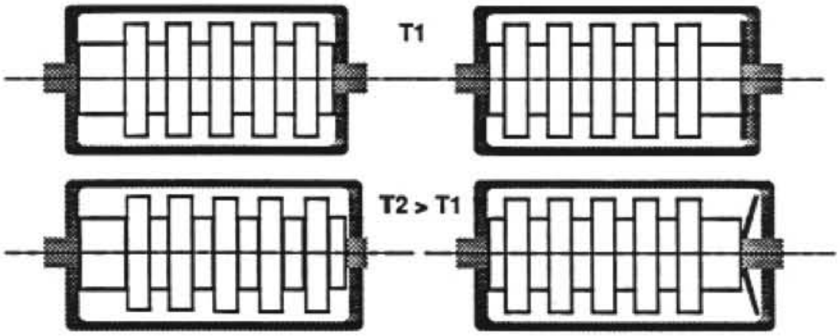


Figure 15: Compensation For Thermal Expansion of Dissimilar Materials

Thermal Actuation

Shape memory actuators can be used to automatically perform a task when a specific temperature is reached. Perhaps the first thermal actuator of note was the greenhouse window opener which used a Cu-Zn-Al spring to open windows when the inside temperature became too warm for optimum plant care, and would close the windows when the temperature dropped. Although not a huge commercial success, it neatly demonstrated thermal actuator concepts. Other examples of thermal actuator applications are air conditioning louvers, which are used to deflect air up or down depending on the temperature or brewing temperature control valves for coffee makers.

To improve fuel efficiency and the efficiency of the catalytic converter, the engine, transmission and other components of a car should reach operating temperature as quickly as possible. This can be achieved in a very cost effective way by using yet another shape memory governor valve in the automatic transmission to control the shifting RPM. At low temperatures shifting takes place at increased RPM to achieve rapid warm-up. As soon as operating temperature is reached, the shape memory governor valve reduces the shifting RPM back to normal.

Thermal Protection

Thermal protection or over-temperature protection is another area where shape memory actuators can provide significant benefits over alternative methods. In many cases thermal protection is a single action when the temperature of a device exceeds a predetermined value, as in fire prevention and detection. In these one-time applications, the shape memory effect can be utilized to its limits, e.g. up to 8% recoverable strain and up to 600 MPa operating stress.

The capability of shape memory elements to change shape in many different ways allows interesting configurations designed to fit in tight spaces of existing devices, e.g. for the purpose of retrofitting to provide a fail-safe feature.

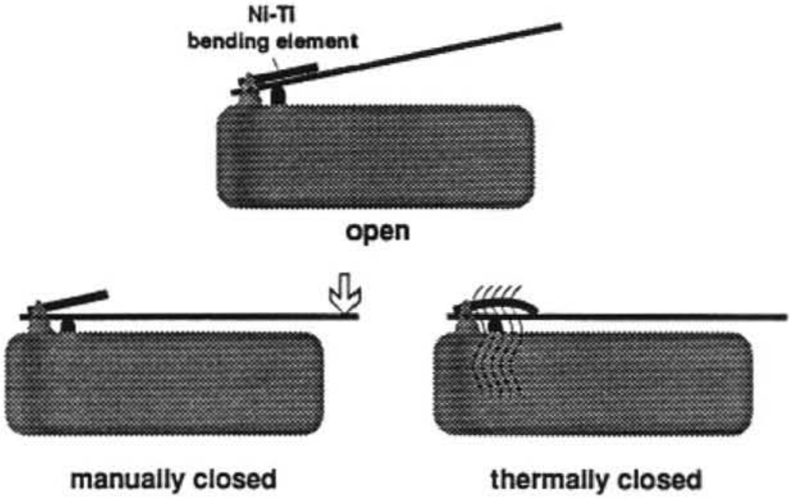


Figure 17: Microswitch With Thermal Actuation

A thermal protection device that uses a shape memory actuator and is presently marketed in the U.S. is an anti-scald valve which automatically shuts off the water flow when the water becomes too hot.