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Publication Date
1975-07-01
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July 1975

Prepared for the U. S. Energy Research and Development Administration under Contract W-7405-ENG-48

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CONTINUOUS BAND NITINOL ENGINE:
SOME MECHANICAL AND THERMODYNAMIC CONSIDERATIONS*

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Within the past two years heat engines have been developed which utilize the extraordinary properties of a nickel-titanium alloy called Nitinol to convert heat to mechanical energy. There exists the exciting possibility that these small prototype solid-state engines may evolve into practical converters of waste heat. For those of us working with these engines, the excitement is enhanced by their intellectual novelty. They are simple in concept, yet subtle in operation.

I shall discuss only the class of engines with which I have been closely associated. There are today at least a half-dozen engine designs using Nitinol as the active element, and more will surely be invented. Of these concepts, which (if any) will evolve into a practical engine is impossible to predict at this time.

The engines are made possible by the discovery, about 1960, of some remarkable properties possessed by nearly equi-atoms alloys of nickel and titanium. These alloys, which are generically named for Nickel, Titanium, and Naval Ordnance Laboratory where they were discovered, undergo an energetic crystalline phase change at ambient temperatures. During transformation, the mechanical and electrical properties are drastically altered. Nitinol also has a shape memory. The material, if plastically deformed while cool, will return to its un-deformed shape when warmed.

The idea that Nitinol may do useful work while undergoing a phase change is illustrated in Fig. 1. At a), a strip of Nitinol lies across the tops of supports. It is cooled by removing heat until it is below its transition temperature. At b), a weight $W_1$ has been added, sufficient to cause the strip to bend until $W_1$ rests on the floor. At c), a second weight $W_2$ is added, and at d) heat is added, causing the metal to stiffen and lift both weights through a distance $h$.

The thermodynamic principles underlying heat engines were established by Carnot. From conservation of mechanical energy. The derivation uses only the change in entropy of the hot and cold reservoirs, and thus is applicable to solid-state engines as well as the more conventional liquid-gas phase engines.

In Nitinol engines, the phase change is from one form of solid to another form of solid. The precise change is not well understood, but the high-temperature phase is a body-centered cubic (CsCl) crystal, while the low-temperature phase is more complex but is probably basically ortho-hombic. In this state, deformation takes place with little energy loss by migration of micro-twinning boundaries within individual crystals. Since no atomic bonds are severed in this process, it is reversible. Heating the crystal above its transition temperature causes the formation of the CsCl structure, and the atoms attempt to recover their original positions. This seems to explain the "shape memory" illustrated in the above simple engine. It does not explain that Nitinol can also be "trained" so that its shape when cold is different from its shape when hot even in the absence of external forces. In the above engine, if the strip of Nitinol is cycled a few hundred times as illustrated, then it will no longer be straight when cold but will bend to the shape shown in Fig. 1b even if the weight $W_1$ is absent. This ability to be trained constitutes a useful feature: as may be seen, eliminating the weight $W_1$ has the effect of improving the efficiency of the engine.

The amount of work which may be done per cycle and the theoretical efficiency may be estimated from stress-strain data. Figure 2 shows data from .5 mm

![Fig. 1. A conceptual cycle of the Nitinol heat engine.](image)

A Nitinol strip is transformed by the cold and deformed by weight $W_1$; additional weight $W_2$ is added. The Nitinol straightens when heated, lifting both weights.

![Fig. 2. Stress vs. strain for an untrained Nitinol wire held at a series of fixed temperatures. (6894 Pascals = 1 lb/in².)](image)
diameter wire taken at LBL. Each line represents a test with an untrained wire at a given temperature. Notice that each isotherm has a plateau: at a given temperature, there is a particular stress at which the wire yields plastically until it reaches an elongation which may be as high as 8%, depending on the temperature, and then resumes a normal stress-strain behavior. In an engine cycle, the material is deformed along one of these isotherms, then heated and allowed to contract along another isotherm as shown in Fig. 3. (Actually,

![Fig. 3. An "idealized" stress-strain diagram for Nitinol seen as a phase diagram for the alloy. Between the cubic (hot) phase and the orthorhombic (cold) phase these phases exist as a mixture. Numbers represent temperatures (°C). The two areas enclosed by arrows are possible engine cycles. Note the analogy between these cycles and that shown in Fig. 4.]

Nitinol will traverse different isotherms on heating and cooling even without external forces. We shall ignore this "hysteresis" behavior for the present argument.) In contracting, it will readily do as much as $7 \times 10^6$ Joules per cubic meter of material. From this and other experimental data it is estimated that, at a cycle rate of one Hertz, output from Nitinol engines should be as high as one watt per gram. This is the basis of an estimate that at realistic prices (e.g. $100/kg) the cost of Nitinol wire should not be prohibitive in construction of larger engines.

Insight into the behavior of Nitinol may be gained by analogy with a liquid-gas phase diagram.** In Fig. 4 is a sketch of such a system.

As the temperature decreases below $T_c$, the isotherms develop plateaus. As a plateau is traversed from left to right, that is, as the volume is increased, the liquid is transformed to a gas. On the plateau (or rather within the region enclosed by the dotted line) the system exists as a mixture of liquid and gas. A simple heat engine cycle consists of following a path such as ABCDA. Liquid boils at temperature $T_2$ (line AB) and does work ($P\Delta V$) at constant $P$. The gas is cooled (line BC) and compressed (line CD), then its temperature is again raised from $T_1$ to $T_2$ and the cycle repeated. From the enclosed area the net work output can be calculated.

Now consider the Nitinol engine cycle depicted in Fig. 3. Assume that the region to the upper left of the curves represents the hot (cubic) phase, that to the lower right the cold (orthorhombic) phase, and the region between, having isotherms with plateaus, is a mixture of the two phases. The rectangle outlined by arrows in this diagram is closely analogous to that in Fig. 4 for a gas. A major difference is that Nitinol is farther from being "ideal" than even a relatively non-ideal gas. Still, it is possible to make some predictions based upon this model. By assuming temperatures $T_1 = 60°C$, $T_2 = 28°C$, Oleh Weres of LBL estimates a theoretical efficiency of 5% for such a cycle.:

![Fig. 4. A pressure-vs-volume phase diagram for a fluid-gas system. At temperatures below $T_L$ the liquid and gas exist as a mixture in the area within the dotted line. The path ABCD is a theoretical engine cycle.

\[
\varepsilon_c = \frac{T_1 - T_2}{T_1} \approx \frac{370 - 270}{370} \approx 0.25
\]

In reality, of course, no Nitinol engines in existence today approach these limits. No one has built engines designed to be efficient. It is interesting to speculate how improved efficiency may be achieved. I believe that reasonably efficient engines can be built taking advantage of two already existing phenomena, namely, training of the wires and incorporation of a counter-flow heat exchanger. For this purpose, I shall need to describe the existing engines.

Nitinol has an annealing temperature of about 550 to 600°C. If held in a prescribed shape while annealed, internal stresses and dislocations apparently are largely relaxed. After cooling, the metal has this new shape as its remembered state. For example, Nitinol wire may be made into a helical spring by wrapping it on a mandrel, clamping it in this shape, and baking it in an oven at 550°C. When cooled, it is then a helix of a specific pitch, diameter, and length. If the coil is compressed, it will lengthen during heating. If it is stretched, it will contract when heated.

Such a helical spring is the active element in a simple engine invented by the author in February 1974.
In this engine, two shafts are constrained to rotate at the same angular velocity by gears which synchronize them. These shafts bear pulleys of unequal diameters. Around the periphery of the two pulleys, running in grooves so that it cannot slip, is a continuous band of Nitinol helical spring. This is illustrated in Fig. 5.

Fig. 5. A simple engine using Nitinol in the form of a continuous helix. Two pulleys of unequal diameters are synchronized as they rotate. The helix is cooled and stretches as it moves to the upper pulley, then heated and contracts on its return. The greater torque on the upper pulley results in continuous motion.

Now if the pulleys rotate counter-clockwise as indicated by the arrows, the spring will be stretched on the right-hand side because of the unequal sizes of the pulleys. If this part is kept cold, the Nitinol spring will retain its stretched condition as it passes over the upper, larger pulley. Now if the portion of Nitinol spring at the left-hand side of the engine is heated, it will try to contract. In doing so, it exerts a greater torque on the larger pulley, and causes it to rotate. This rotation, coupled to the smaller pulley through the gears, transports more spring to the cold side where it is again stretched. A continuous motion results.

Several variations of this configuration have been constructed. One which is particularly simple results from mounting the two driven pulleys on the same shaft so that they are constrained to rotate synchronously. Two idler pulleys transport the Nitinol wire from the larger pulley to the smaller and back: these pulleys are immersed in hot and cold baths, respectively. This arrangement is shown schematically in Fig. 6.

At the present time, only small engines have been built with no attempt at optimization. The largest of these engines developed 2.2 watts shaft output from a helix weighing 17 grams.

Efficiency of these helical-band engines is certain to be low because water is readily transported by the helix so that the hot and cold reservoirs are rapidly mixed. A gain in efficiency as well as performance is made when the helix is replaced by Nitinol wire in tension: the entire volume of the wire is deformed equally, and the wires transport much less water than does a helix. However, the wires must be prevented from slipping on the pulleys. This has been accomplished by cutting V-shaped grooves for the wire to run in. At the ends, the wire is butt-welded with no increase in diameter. Engines of this type have been in existence since October 1974. The present lifetime of welds limits these engines to a few tens of thousands of cycles. The material in the weld is different from that in the rest of the wire; it is subject to fatigue, and fails after a few hours of operation of the engine.

In this engine, the thermodynamic cycle approximates a Carnot cycle. The wire is expanded adiabatically, contracted isothermally, contracted again adiabatically and expanded isothermally. Therefore in principle this engine should approach Carnot efficiency when all precautions are taken against loss of heat. Such calorimetric experiments are inherently difficult, time consuming, and costly, and have not yet been performed.

There is an interesting improvement which may easily be made. In analogy with steam engines, a counter-flow heat exchange principle may be employed to recover a portion of the sensible heat and thus boost efficiency. In Fig. 7a such an engine is shown schematically.

Two drive pulleys, \( D_e \) and \( D_h \), are coupled mechanically so they rotate synchronously. \( D_h \) is a few per cent smaller than \( D_e \), so that the Nitinol wire, which makes a circuit around these two drive pulleys and under two idlers, \( I_e \) and \( I_h \), is stretched in going from the hot end of the engine at right to the cold end at left. The region \( x-y \) is the heat exchanger. If the pulleys are rotating as shown, cold wire from pulley \( D_e \) travels from \( x \) to \( y \) and is heated while hot wire from \( D_h \) travels the opposite direction in close proximity to the cold wire, and transfers a portion of its heat to
In addition to the cooling associated with the propagation of wave motion, the engine achieves a differential volume contraction because of the volume change accompanying the phase transitions. The volume of the wire changes as it contracts, and the resulting decrease in volume is due to the change in temperature. The volume change is given by the formula: 

\[ \Delta V = \int \left( \frac{dV}{dT} \right) dT \]

where \( \frac{dV}{dT} \) is the volume change per unit temperature change. This volume change is a function of the temperature and the material properties, and it can be calculated from the temperature-entropy diagram for the engine cycle.

The efficiency of the engine can be expressed in terms of the work done and the energy lost during the cycle. The work done by the engine is given by the area under the curve in the temperature-entropy diagram, and the energy lost is given by the area above the curve. The efficiency is then defined as the ratio of the work done to the energy lost:

\[ \eta = \frac{\text{Work done}}{\text{Energy lost}} \]

The efficiency of the engine is also dependent on the temperature difference between the hot and cold reservoirs, and it increases with the temperature difference. The maximum efficiency is achieved when the temperature difference is large, and it is given by the Carnot efficiency:

\[ \eta_{\text{Carnot}} = 1 - \frac{T_L}{T_H} \]

where \( T_L \) is the temperature of the cold reservoir and \( T_H \) is the temperature of the hot reservoir.

Therefore, the efficiency of the engine can be increased by increasing the temperature difference between the hot and cold reservoirs. This can be achieved by using a larger diameter wire, which results in a larger temperature difference between the wire and the heat exchanger. The engine can also be designed to operate at higher temperatures, which increases the temperature difference and thus the efficiency. However, the efficiency is limited by the Carnot efficiency, which is a fundamental limit on the efficiency of heat engines.

The performance of the engine can also be improved by using a better heat exchanger, which transfers heat more efficiently. This can be achieved by using a more effective heat exchanger material, such as a metal with a high thermal conductivity, or by using a more efficient heat exchanger design, such as a heat pipe or a heat exchanger with a microchannel geometry. The efficiency of the engine can also be improved by using a better cooling system, which removes the heat from the wire more efficiently. This can be achieved by using a more effective cooling system, such as a liquid or a gas cooling system, or by using a more efficient cooling system design, such as a heat pipe or a heat exchanger with a microchannel geometry.
it is possible to calculate $\Delta S$ for any segment of path along which $T$ is constant and for which $\Delta Q$ is measured.

To see what is going on, suppose that the lines AB and CD are horizontal in Fig. 7c (that is, the short adiabatic expansion and contraction are negligible) and that the distances BB' and DD' are made to approach zero. Then the amount of energy available to do work is $\Delta Q_{AB} - \Delta Q_{CD}$ while the total heat input is $\Delta Q_{AB}$. But

$$\Delta Q_{AB} = \int_B^A T_H dS = T_H^A - T_H^B$$

$$\Delta Q_{CD} = \int_C^D T_C dS = T_C^D - T_C^C$$

So Maximum Efficiency $\varepsilon = \frac{\Delta Q_{AB} - \Delta Q_{CD}}{\Delta Q_{AB}} = \frac{T_H^A - T_C^C}{T_H^A - T_C^C}$

which is the Carnot efficiency.

The system we have described is an approximation to this. If we take into account the segments BB' and DD', we may calculate a better approximate efficiency thus:

$$\varepsilon = \frac{\text{energy available to do work}}{\text{heat energy input}}$$

$$= \frac{\int_B^A T_H dS - \int_B^{B'} T_H dS - \int_C^D T_C dS + \int_C^{D'} T_C dS}{\int_B^A T_H dS - \int_B^{B'} T_H dS}$$

$$= \frac{\Delta Q_{AB} - \Delta Q_{BB'} - \Delta Q_{CD} - \Delta Q_{DD'}}{\Delta Q_{AB} - \Delta Q_{BB'}}$$

Note that it is necessary to measure the above $\Delta Q$'s in order to estimate an efficiency. This has never been done systematically. Using crude data which are available (and a somewhat more complicated argument) Oleh Weres has estimated that such an engine may achieve up to 80% of Carnot efficiency.

We should also try to estimate the change in temperature associated with the adiabatic changes in tension at A and C. At A, the wire is hot (fully transformed) and therefore the only heat change will be due to normal quasi-elastic deformation, i.e. the heat coefficient is a normal $C_v$. The isotherm is very steep, so that only a minor change in elongation takes place here. Hence the temperature change should not be a significant part of $T_H - T_C$.

Conversely at C, the wire is completely in its cold state and therefore has a normal $C_v$. If the wire is a trained wire so that its elongation is "automatic" and if $T_C$ is sufficiently below the transition temperature range for the (minimal) tension, then the change in elongation in going from C to D should be a small part of the total, and again the temperature change should be small compared to $T_H - T_C$.

I have outlined in this paper the development of one class of Nitinol heat engines during the period of one year. In such a short span of time it is not possible to evaluate the probability of eventual success of these or similar engines. Considerable interest has been aroused in these engines because of their simplicity, novelty, and obvious timeliness. The prospect of utilizing waste heat energy is but one of the possibilities for alleviating our almost total dependence on fossil fuels. I am convinced that there is no one energy of the future: we should plan to develop alternative and competing means of energy conversion.

Where might Nitinol engines fit into this picture? If very large engines become practical, I should like to use a saline-gradient solar pond to provide the heat source and use cold ocean bottom water as a heat sink. The converter should be an engine which can survive in very saline water, and this a natural environment for the very corrosion-resistant Nitinol alloy. I hasten to add that the economic feasibility of such a plan is very much in question. But this situation may change as fossil fuels become more dear.

Footnotes and References

*This research was supported in part by the U.S. Energy Research and Development Administration and by a grant from the National Science Foundation.

**The heuristic analogy between the Nitinol phase-change engine and conventional liquid-gas heat engines was first called to my attention by Oleh Weres of LBL in November 1974. Fig. 3 is taken from an unpublished memo by Dr. Weres.


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