The Banks Engine

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A novel heat engine utilizing macroscopic shape changes associated with a thermally-activated phase transformation in alloys of nickel and titanium has been demonstrated. Engines capable of converting small temperature differences at near-ambient temperature to mechanical work are seen as a promising technology for the recovery of thermal energy currently going to waste. Depending on future economic feasibility, such engines may be practically applied to conversion of solar, geothermal, oceanic thermal gradient or industrial thermal sources.

There are, throughout the world, abundant resources of low-grade thermal energy which are not being economically utilized at the present time. The recovery of this energy through conversion to mechanical or other useful forms has become the subject of growing interest as energy research gains importance as a matter of technological concern. In some cases conversion of low-grade heat may have positive environmental benefits as well, as in the case of industrial waste-heat and the thermal effluent from nuclear power generating facilities. Despite the limitations imposed on heat engines working at low temperatures across a small ΔT, sources of low-grade heat are so widespread and available that economical conversion of a fractional percent could have a significant impact on the world energy supply. Such resources as the oceanic thermal gradient or geothermal hot springs might become important if a suitable conversion technology for their exploitation could be demonstrated. As all systems operating under these conditions will suffer from the same thermodynamic limitations, conversion efficiency may not be the sole criterion for their competition. Simplicity of the system as a whole as well as installation and maintenance requirements will probably also be important considerations, especially in parts of the world where energy needs cannot be met by conventional sources of power. Among the small-scale applications envisioned for such engines are the operating of solar-powered refrigerating units, agricultural irrigation pumps, and auxilliary electrical power generating components.

A successful solid-state nickel-titanium heat engine was demonstrated at the Lawrence Berkeley Laboratory (LBL) in Berkeley, California, on August 8, 1973.

The engine, which runs on small temperature differences at near-ambient temperatures, utilizes the shape-memory phenomenon of the intermetallic compound Ni-Ti discovered in 1958 at the Naval Ordnance Laboratory in Silver Spring, Maryland. This alloy, known by the generic name 55 Nitinol* has the ability to repeatedly return to a previously imprinted shape when heated above a temperature threshold specific to the composition of the sample. Below the threshold, the metal is easily deformed, and the return to the higher-temperature shape is accompanied by a marked change in the elastic properties of the material (Fig. 1). This gives Nitinol the ability to perform net mechanical work in being cycled between hot and cold environments when it is deformed in the cold state and allowed to return to its "remembered" shape on heating. During this shape recovery, significant forces develop within the material, and wires of 0.5 mm diameter have been observed to exceed tensile stresses of 7000 kg/cm^2 in transition [1]. When deformed below a fiber-strain limit of approximately 6–7%, the metal may be expected to recover indefinitely without fatigue or permanent deformation.

The original prototype of the Banks Engine** (Fig. 2) is a horizontally mounted wheel, 35 cm in diameter, from which twenty 15-cm loops of 1.2-mm diameter Nitinol wire hang downwards. The wire loops are sup-

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* The metal takes its name from nickel, titanium, and Naval Ordnance Laboratory.
** The term "Banks Engine" was used by Prof. E.M. McMillan in his lecture at the Nobel Prize Winner meeting at Lindau in 1974. In the author's laboratory the machine is called the Nitinol Engine. Since the term Banks Engine has since become familiar, it is used in this article.
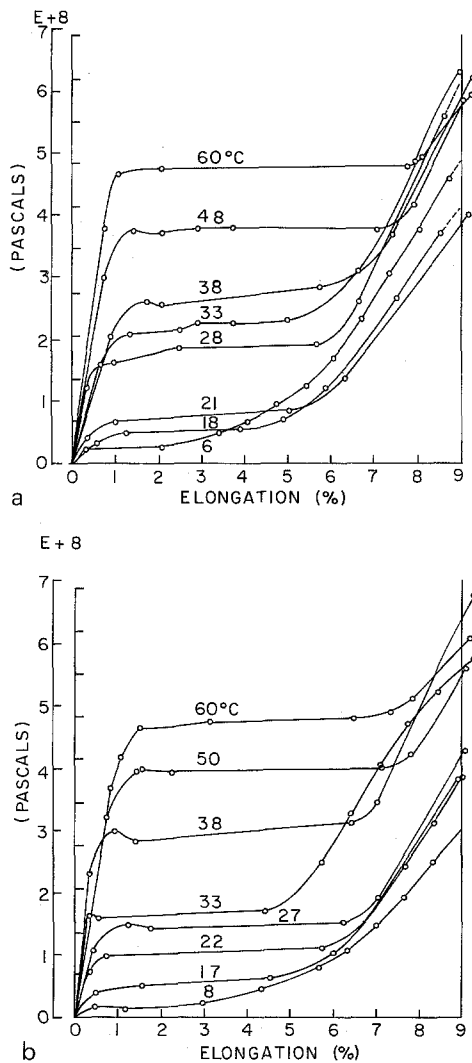
Fig. 1 a and b. Stress-elongation curves during heating (a) and cooling (b). Material 0.5 mm Nitinol wire heat number V-4609 TTR 21.1–32.2°C. Heating-cycle tests were done by heating each sample from a temperature of 2 to 4°C up to the desired test temperature, where the test was made. In the cooling-cycle tests, each sample was cooled from a starting temperature of 70°C down to the test temperature. In each case the wire sample was in an unloaded condition until the test was made. Each test was performed on a new wire sample, and each represents only one stress cycle—the first. The strain rate was 12.7 mm/min [4]

Fig. 2. The original prototype of the Ni-Ti solid-state heat engine on the first day of operation: August 8, 1973

ported by spokes which radiate from a crankshaft somewhat offset from the center of rotation of the wheel and which extend outwards through its periphery. This system is similar to the configuration of an airplane engine where radially disposed pistons communicate to an eccentric crankshaft that is normally caused to rotate by forces exerted through the pistons. In the Banks Engine the force of pistons is replaced by the force of Nitinol wires straining to open from a looped U-shape to their "remembered" straight shape. The mechanical force thus generated will tend to turn the crankshaft or, equally, to turn the wheel if the crankshaft is held stationary, as is the case in the prototype. Rotation of the wheel advances the position of the wire loops which fall alternately into semi-circular baths of hot and cold water placed immediately beneath the machine.

At the time of its first demonstration, the device rotated at approximately 65 rpm when the temperature difference between the baths was ~23°C. Output was measured at approximately 0.2 watts. After a period of continuous operation ($3 \cdot 10^6$ cycles), the speed of rotation had increased to 69 rpm and the output to 0.23 watts. This improvement is probably due to the apparent development of a cold "memory" shape, which has been observed to occur in Nitinol power elements after repeated cycling in heat-engine mechanisms. Because of this phenomenon, which in the prototype manifests itself in spontaneous closure of the wire loops as they fall into the cold water-bath, energy losses anticipated in the forced closure of the loops during the cold part of the cycle do not occur.

The construction of the Banks Engine was an outgrowth of interest in the conversion of low-temperature solar thermal energy into mechanical work. A similar engine utilizing bimetallic spring elements was investigated but abandoned because of the extremely low expected conversion efficiency. Among the tests made on the prototype during the first few months of its operation was the generation of electricity with solar-heated water (Fig. 3). This experiment was made at LBL during November 1973. The solar collector employed on this occasion was a quite primitive device consisting of a wooden box insulated on the inside with 7.6 cm of polyurethane foam and lined with a sheet of black vinyl. Surface-heat losses were reduced by floating two layers of glass tubing intended for use in fluorescent-light manufacture. These clear glass tubes (with rubber corks in either end) are a relatively strong and remarkably inexpensive form of glass, and are the subject of current experimentation in the field of flatplate solar collectors. The day on which the test took place was cool and overcast until noon, and by three o'clock the temperature of the water had reached approximately 50°C. Water was cycled through the engine by means of an electric pump, and with a small DC generator driven by the engine, a miniature light bulb was lit. While one would prefer not to speculate on the overall conversion efficiency of this arrangement, it was quite probably the first
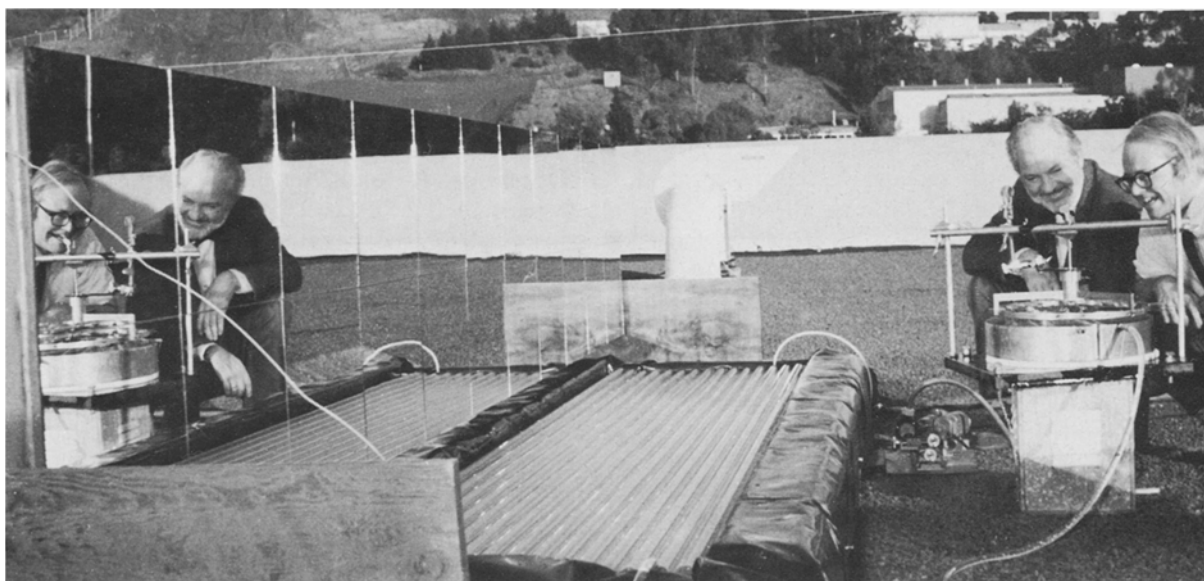
Fig. 3. Conversion of solar heat to electricity by means of the thermomechanical Ni-Ti principle was first accomplished (on a rather small scale) during November 1973

time that sunlight had been converted to electricity by means of a solid-state hot-water engine.

At the present time Nitinol is understood to belong to a small group of alloys known to undergo macroscopic change of shape related to a solid-state phase transformation at certain critical temperatures. While the phase-transformation phenomenon is common to many alloys and pure metals (it is best known in steel) only a few alloys, including Nitinol, are sufficiently ductile for the shape memory to manifest itself in macroscopic changes. Of these alloys probably the best known is a Au-Cd alloy exhibited in Brussels at the 1958 World's Fair. In Ni-Ti the critical threshold may exist over quite a wide temperature range (-150 to $+150°C$) dependent on the proportions of Ni and Ti in the alloy's composition. Increasing the relative amount of Ni has the effect of lowering the temperature threshold for the transformation, and extremely low critical temperatures may be achieved by atomic substitution of Co for Ni.

The transformation is characterized as a "martensitic" transformation with reference to a similar phenomenon observed in the cooling of certain steels from elevated temperatures. In the steels, such cooling produces lamellar substructures along the crystal lattices (martensites) that resemble analogous formations seen to nucleate in the Ni-Ti cold phase. The two phases in Ni-Ti are therefore referred to as martensitic or austenitic, the martensitic phase being below the thermal threshold and the austenitic phase being above. This nomenclature, while technically misleading, has by now become fairly well established. It is generally convenient to refer to two specific temperatures in speaking of the characteristics of a given specimen, since the temperature to which the material must be heated to initiate the austenitic phase (austenitic start

temperature A_s) is somewhat higher than the temperature to which it must be cooled to initiate the martensitic phase (martensitic start temperature M_s). In practice, one may observe changes in a sample over a gradient of a very few degrees; and it is therefore possible to interpret the range of approximately 20°C that separates M_s and A_s as the gradient through which the material changes from being predominantly in one phase to being predominantly in the other phase. Shape imprinting of the austenitic phase is accomplished by heating a sample to temperatures of 500–600°C for a period of a few minutes. During this treatment the specimen must be constrained in the shape that is being imprinted, and it is this shape to which it will return when subsequently heated above the much lower transition threshold.

The Nitinol phase transformation is accompanied by marked changes in many of the material's physical characteristics. Most important in its application as a thermo-mechanical transducer is a change in internal crystal structure from an orthorhombic type in the cold phase to a CsCl type in the hot phase. The precise significance of these distinct crystal types and the function of heat in their formation are still under study, but it has been pointed out that the theoretical geometries of the orthorhombic structures show a significantly linear arrangement of Ni and Ti atoms. The flexibility of martensitic Ni-Ti is attributed to a diffusionless shear mechanism that may be likened to the shear that takes place between the individual pages of a book when the book as a whole is bent. While the overall deformation of the book may be great, actual dislocations of one page relative to the neighboring page will be comparatively small. In Nitinol, gross deformation of the specimen is seen as involving individual atomic dislocations of less than one interatomic

distance each. Thus, the "slippage" along martensitic lattice boundaries involves no internal friction when kept within permissible limits of deformation.

During the phase transformation, changes may be observed in other properties of Nitinol. Electrical resistivity, heat capacity, magnetic susceptibility, and acoustic transmission are all influenced by the transformation. When Nitinol is isothermally deformed, it also exhibits an exothermic and endothermic reaction, which leads to speculation about the possibility of using it as the thermal element in a solid-state heat pump. This phenomenon is closely related to the latent heat associated with the transformation during thermal cycling.

Prior to its application in heat engines Nitinol has been used in a variety of space-related devices such as self-erecting antennae, extendable booms, and sun-tracking mechanisms [2]. It is also the basis for thermally-activated relays and a variety of coupling devices, both electrical and mechanical. Uses of the material have been under investigation in medical and orthodontic fields. Until recently the properties of the material were relatively unknown, so the wide variety of potential applications for it is still in the early stages of exploration.

The research that has been done on Nitinol to the present time does not give a reliable basis for prediction as to its ultimate feasibility in energy conversion. Published data have often been conflicting, largely owing to inconsistencies in the samples studied by individual researchers, and to their often insufficient metallurgical characterization. While published thermo-mechanical conversion efficiencies have been as high as 25% [3], much work remains to be done before the actual efficiencies of practical engines can be evaluated.

Another important factor in the growth of this technology will be the economic competitiveness of Nitinol heat engines. Neither nickel nor titanium is particularly rare or expensive, but improved processes for their combination in acceptably uncontaminated alloys are still being evolved and therefore subject to the costs of developmental research. Titanium is well known to be extremely active in its combination with other elements, and the production of the alloy must be done under vacuum. The proportions of Ni and Ti governing the transition-temperature threshold are exacting to $<0.1\%$ by weight, and current production techniques cannot always assure that a threshold predicted a priori will in fact be achieved, nor that the

product of a single melt will be homogeneous throughout. At the time of construction of the prototype, Ni-Ti materials cost approximately $150/kg, with a decrease in that price by a factor of two expected under conditions of volume production. During the intervening year, however, production in the United States has decreased while the cost per kg has increased. It is still quite likely that with the proper economic stimulus both production quality and cost of Nitinol will be significantly improved.

While it is too early to evaluate the ultimate scope or importance of this energy-conversion technology, it is possible to see applications where it would be of use at the present time. The possibility of a solar-powered agricultural pump has been mentioned, and is typical of a machine for which there is a current worldwide need. The requirements for such a device would be simplicity, durability, and ease of installation and maintenance in remote rural areas; here the qualifications of the Banks Engine seem extremely promising. Combined with the simplest sort of stationary solar collector for the hot side, the engine itself would constantly re-supply the cold side with the water being pumped. Such a system, moreover, would be automatically self-regulating in response to changing thermal conditions throughout the day.

Should low-cost electrical power or synthetic fuels become widely available in the future—particularly in the industrialized nations—it is quite likely that alternative systems, however efficient in their conversion of low-grade heat, will not be widely exploited. There is, however, a present worldwide market for fractional-horsepower units in regions where conventional energy sources are either not available or prohibitively expensive. This need is likely to become more urgent in the future as the full exploitation of world natural and agricultural resources becomes a growing common priority.

1. Buehler, W., Cross, W.: Wire J. 1, 41 (1969)
2. Schuerch, H.U.: Certain Physical Properties and Applications of Nitinol. NASA CR-1232 (1968)
3. Jackson, C.M., et al.: 55 Nitinol—The Alloy with a Memory. NASA SP-5110 (1972)
4. LBL Engineering Note M-4778, UCID 3699 (1974)