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Unusual shape-change properties in a class of metals known as Shape Memory Alloys have been applied to the conversion of low temperature heat to mechanical work. A program for development of practical heat engines based on this phenomenon is underway at the Lawrence Berkeley Laboratory, using the nickel-titanium alloy "55-Nitinol." Details of the current prototype engine design and results of preliminary testing are discussed in light of special considerations for using Nitinol in heat engines.

Temperature-dependent changes in the elastic properties of certain Shape Memory Alloys make possible the conversion of relatively low temperature heat to mechanical work by means of 'solid-state' heat engines. Such machines show promise of having competitive conversion efficiencies and capital costs when compared to other types of engines for low-temperature conversion, as well as possible advantages in simplicity of practical installation. The current project is supported by the ERDA Division of Solar Energy and is directed towards the use of such a solid-state heat engine for driving a vapor compression air conditioner using solar-heated hot water. Other potential applications for this type of engine include the generation of mechanical power (and, in turn, electricity), from solar thermal, ocean thermal, geothermal, or industrial waste heat sources.

A prototype heat engine based on a nickel-titanium alloy known as 55 Nitinol has been in operation at the Lawrence Berkeley Laboratory since August 1973. Since that time, the mechanics of the shape memory properties of Nitinol have been studied, as have the thermodynamic properties of cycles using Nitinol wire as the working element. Several iterations in engine design have contributed to an improved understanding of the important practical considerations in Nitinol engine operation, leading to the development of an improved prototype engine.

Of the Nitinol materials commercially available the most effective have proven to be wires approximately 0.5 mm in diameter. Tests run at LBL during the last year indicate that wires of this size and shape, strained axially at 3% elongation, have an output potential of $\geq$ 1.0 watt/gram at a cycling rate of 60 cpm. It was also found that if the wires were not uniformly heated during the transformation, or if the stress developed during shape recovery were allowed to peak at a point of minimum mechanical advantage, excessive stress concentrations would develop, leading to progressive fatigue and failure. Other investigations into the details of Nitinol wire behavior under cyclic conditions revealed that the time response of the wire's shape change was quite different when being heated (rapid response) than when being cooled (slow response).

A new design has been developed, known as the Cam Track Nitinol Engine, that will accommodate these unique wire properties. It is shown in Figure 1. In this design, 0.5 mm wires are supported between

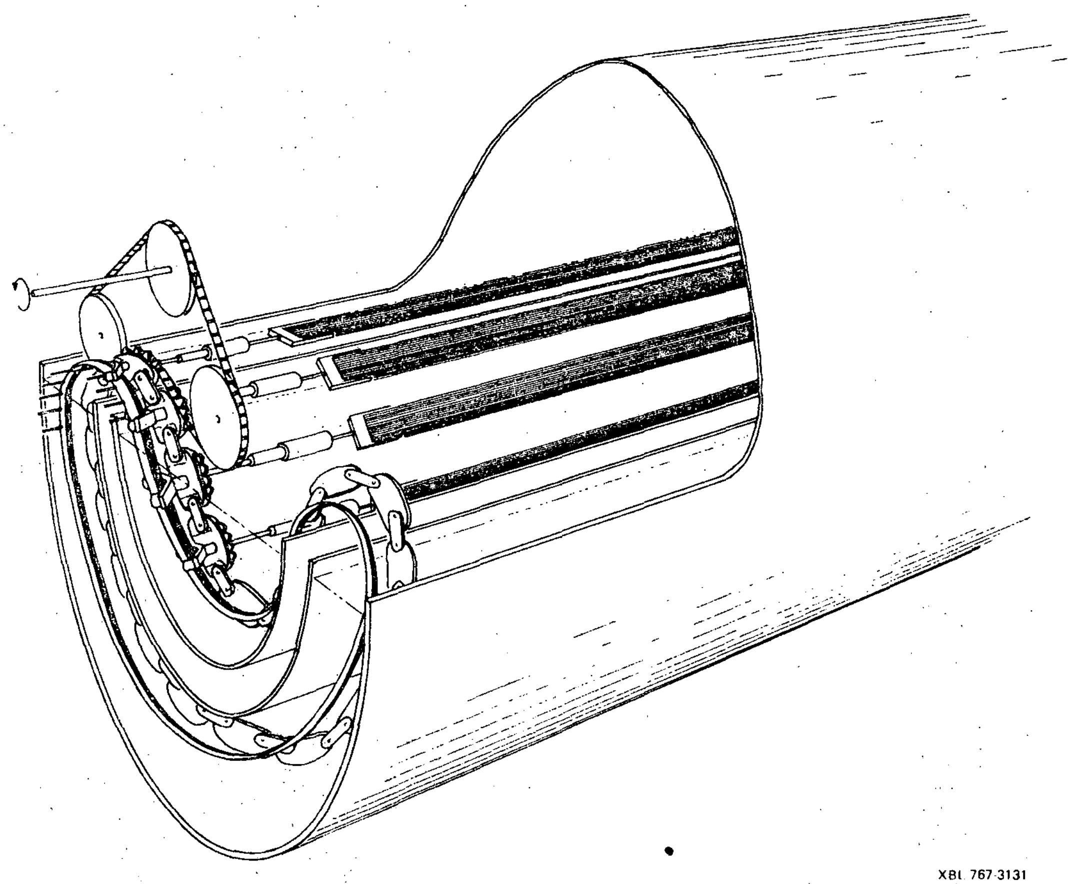

Fig. 1: Cutaway view of Cam-Track Nitinol engine concept. One end of the tank is shown, with concentric water baths, typical power elements, one of the pair of cam-tracks, and power take-off.

two movable trolleys mounted on continuous tracks. The tracks are supported by a multiplicity of standoffs from the ends of a cylindrical tank. While the ends of the tank are parallel, the lengths of the standoffs differ, so that the distance between the tracks may be varied. In practice, the tracks converge along approximately 20% of their complete length, diverge during approximately 50% and run parallel for the balance of their length.

During the part of the cycle in which the tracks diverge (outer diameter in Figure 1) the wires are immersed in cold water and, because of the divergence of the tracks, are elongated by approximately 3%. Following this part of the cycle the tracks run parallel as the direction of the travel is reversed to approach the concentric hot water bath (inner diameter). Immediately at the point where the wires enter the hot water, the tracks begin to converge, and recovery stresses in the Nitinol wires are relieved as shortening of the wires drives the trolleys forward along the track. Following this part of the cycle (the power stroke) the tracks again run parallel as the wires leave the hot bath and re-enter the cold bath.

Each of the twenty working elements of the engine contains 240 feet of Nitinol wire. These elements are linked together by a continuous chain, in which are incorporated sprocket teeth to engage a flexible chain leading to the power take-off. The full load of Nitinol wire in the prototype will be 4800 feet, and, at an elongation of $\sim$ 3%, with anticipated cycling rate of $\geq$ 60 cpm and parasitic (frictional) losses of $\sim$ 50%, output is expected to be in the neighborhood of 0.5 horsepower.

Preliminary tests on a hand-cycled apparatus, simulating the mechanical cycle of the Cam-Track design, have indicated that wires may be reproducibly elongated to $\geq$ 3.0% without fatigue or non-recoverable strain. The critical part of the cycle has proven to be the mechanics of unloading the stresses developed on heating. In the first tests, recovery loads were so extreme that the ball bearings of the trolley mechanism failed. Following these first tests, pairs of compression springs were introduced between the trolleys and the Nitinol wires. During the next series of tests it was found that the test element containing 240 feet of Nitinol wire fully compressed the springs, readily developing a net increase in force of approximately 350 pounds as measured by a strain gage.

As solid-state working elements lack the flow and compression characteristics of normal working fluids in conventional engines, dynamic stress effects are likely to have an important effect on the working lifetime of the material. With the springs in place, 1000 cycles were made on this apparatus, with no detectable permanent elongation of the wire. Since progressive elongation is normally detectable well below 100 cycles, this test established a conservative lower limit for reproducibility. In this configuration, however, the output of the engine would be essentially limited to the energy output of the springs. Therefore it was decided to direct this testing towards increasingly "hard" mechanical cycles. After a series of iterations, during which the springs were replaced with Bellville washers and the track was redesigned, a satisfactory cycle was achieved, possessing high torque characteristics and minimal displacement lost in mechanical compliance. One thousand cycles have been successfully completed with this system.

Summarizing, the conditions which the new engine cycle provide are: 1) independent rates of dimensional change on heating and cooling of the working elements; 2) uniform unloading of stresses developed on heating; and 3) thermal uniformity in the working elements when work is being done by them or on them. The prototype model of this design will have an estimated power output of approximately 0.5 Hp, with the possibility of scaling up to $\geq$ 1.0 Hp by addition of more Nitinol wire, but without additional moving parts.

Tests made on this device will determine the practical conversion efficiency of this type of engine, within the limitations of commercially-available Nitinol wire. The current status of this project will be reported at the conference.

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