CA-78-028

Small-Scale Appropriate-Energy-Technology Grants Program

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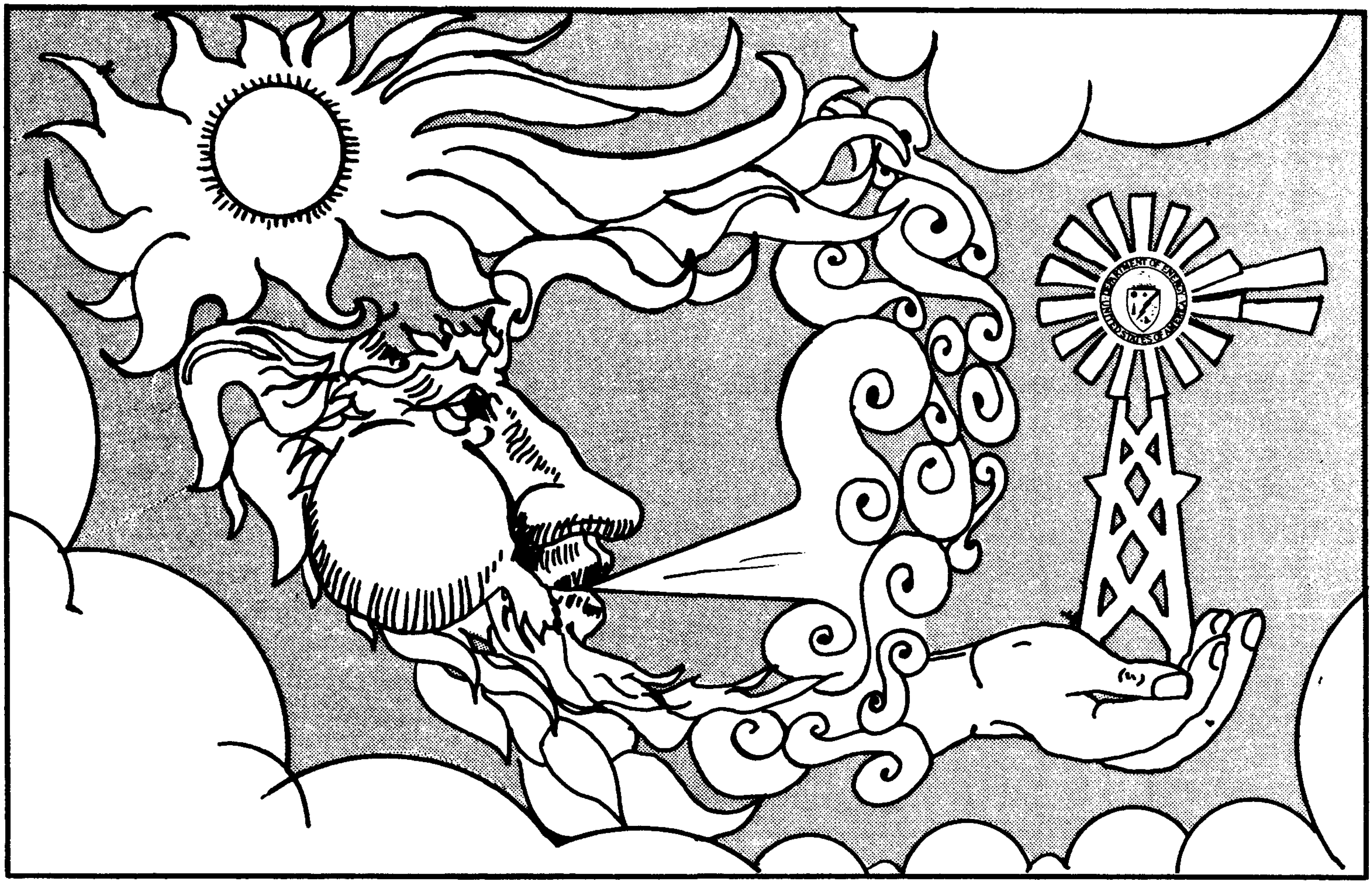

PACIFIC SOUTHWEST REGION

UNITED STATES DEPARTMENT of ENERGY

Nitinol Heat Engine

FINAL REPORT

CONTINUOUS-BAND NITINOL HEAT ENGINE

GRANT NO. EM-78-G-03-1982

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Prepared For: Small-Scale Appropriate Energy
Technology Grants Program --
Region IX
U.S. Department of Energy
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U.S. DEPARTMENT OF ENERGY

SMALL SCALE
APPROPRIATE ENERGY TECHNOLOGY GRANTS PROGRAM

REGION IX

BACKGROUND

In his energy message of 1977, President Carter stated that a balanced energy program should seek out the talents of individual inventors and small businesses and groups. Congress subsequently authorized the Energy Research and Development Administration (now the Department of Energy, DOE) to undertake a grants program in small-scale, energy-related technologies referred to as appropriate technologies because they are "Appropriate" to local needs and skills. This small grants program has come to be known as the Appropriate Energy Technology (AET) Program.

WHAT

A regional pilot program in appropriate energy technology was implemented to provide monetary grants for small-scale, energy related projects for;

- Idea development, for concepts demonstrating potential;
- Concepts testing, for projects that have gone beyond the idea-development phase and are ready for testing;
- Demonstration, to develop projects which, having been tested, now must be proven through actual use.

In terms of resources, Appropriate Energy Technology ...

- makes best use of available renewable energy sources
- conserves nonrenewable resources
- depends largely on human labor
- emphasizes use of local materials and labor skills

In scale and efficiency, Appropriate Energy Technology ...

- is efficient in its use of energy and other resources
- is simple to install, operate and maintain
- is compatible with community regulations
- may employ scaled-down industrial technology
- employs novel application of existing technologies
- emphasizes decentralized technologies

In relation to the end-user, Appropriate Energy Technology ...

- satisfies local needs
- increases community energy understanding and self-reliance
- is environmentally sound
- results in durable recyclable systems and/or products

WHERE

The Region IX program covers the states of Arizona, California, Hawaii, and Nevada, as well as American Samoa, Guam, and the Pacific Trust Territories. This program is managed by the Office of the Regional Representative, Region IX, of the U.S. Department of Energy. Similar programs are being managed through the other nine regional offices around the country.

WHO

Eligible projects can come from

- individual
- local nonprofit organizations and institutions
- state and local agencies
- American Indian tribes
- Small businesses

WHEN

Contact the regional DOE offices for the annual awards cycle

RESULTS

Over one hundred and eighty applicants in Region IX have been granted funds with which to start or continue their projects during the first three years of the Appropriate Energy Technology Program.

For additional information on this program, please contact:

Small Scale Appropriate Energy Technology
U.S. Department of Energy
333 Market Street, 7th Floor
San Francisco, California 94105

Nationally, the Small-Scale Appropriate Energy Technology Grants Program is directed by the Office of Small-Scale Technology, U.S. Department of Energy, Washington, D.C.

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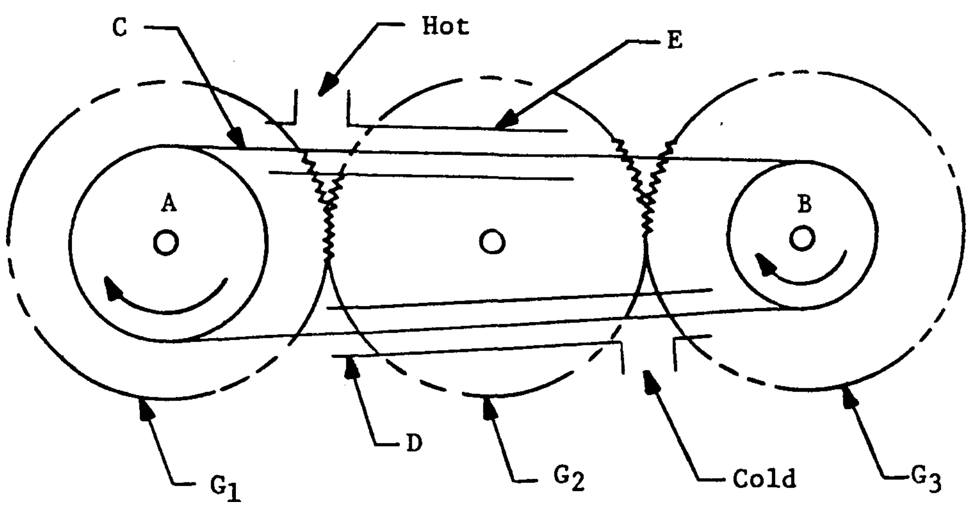
INTRODUCTION: The Nitinol Heat Engine

The Nitinol heat engine is a machine which takes advantage of the special shape-memory properties of a nickel-titanium alloy called Nitinol to convert heat to mechanical energy. Because heat can be used which is at liquid-water temperatures, it is anticipated that this class of engine may have a large commercial application in converting waste heat, geothermal water heat, and low-cost solar collector heat to useful mechanical and electrical energy. The technology of these engines is relatively new, although a number of successful small prototypes have been demonstrated. These prototypes have promising power density, limited thermodynamic efficiency, and undetermined longevity. This study concerns one class of Nitinol engine in which the alloy in the form of wire loops drive pulleys of unequal diameter. In it we attempt to determine feasibility of scale-up by use of multiple wires in parallel, and examine the relevant thermodynamic properties of Nitinol especially as these relate to fatigue lifetime.

The principles by which the continuous-band Nitinol engine functions may be understood by referring to the accompanying diagram. Two grooved pulleys, A and B, are encircled by a continuous-band of Nitinol wire, C. Three gears, G_1 through G_3, which are meshed, cause A and B to rotate with the same angular velocity. Pulley B is smaller than A so that wire going from B to A must stretch, and conversely wire going from A to B must contract if the wire is to remain taut throughout its path. Now the memory metal Nitinol has the characteristic that if it is stretched while cold it yields easily, and contracts with great force when heated. For this heating and cooling, water jackets D and E are placed around the wire between pulleys A and B, and cold water is circulated through D while hot water is circulated through E as indicated by the arrows marked HOT and COLD.



SCHEMATIC ILLUSTRATION OF

CONTINUOUS-BAND NITINOL ENGINE

Now as the wire contained in E is heated, and contracts due to the shape-memory of Nitinol, it pulls with equal force on pulleys A and B: but since A is larger, a greater torque is exerted on A than on B. This torque is transmitted through the gears G1, G2, G3 and turns pulley B. A continuous motion results, so long as the wire C does not slip on the pulleys A and B and so long as hot and cold water are supplied. Speeds up to a thousand RPM can be achieved with pulleys three to four inches in diameter. Power output may be in excess of a watt for each gram of Nitinol in the band.

The configuration shown is but one of many variants of this engine which have been built and tested. It is possible to mount pulleys A and B on a common shaft, thus eliminating the gear train, and provide idlers to switch the wire loop from one pulley to the other. These idlers can be replaced by a helical band, in which case the internal torque of the engine is reduced and the pulley diameter ratio increased. There are, of course, advantages and disadvantages to each design. The configuration chosen for this project will be one which can be scaled up for larger engines in the future.

I. Overview

Funding was sought in order to build and operate a multiple-band Nitinol heat engine, using experience gained in the past several years with single-wire engines. Fabrication of the continuous loops of Nitinol wire needed for this engine required investigation of novel techniques because welding had not proved satisfactory. Instrumentation with which to measure the engine's operating characteristics was needed, as were means of continuously supplying hot and cold water.

The goals of the research can be summarized thus: to demonstrate feasibility of increasing power output from the continuous-band Nitinol engine by installing multiple wire loops in parallel; to operate this engine in steady-state conditions so that power output could be measured; and to develop a technique for making wires which do not suffer the failure mode of previous welded wires.

Pursuit of these goals required construction of several pieces of laboratory apparatus. A heater and chiller, to serve as a continuous source and sink of several kilowatts, were installed. A feedback control system which governs the speed of the engine by means of a hysteresis brake and simultaneously measures the torque and speed of the engine was developed. Instrumentation was installed to measure the forces exerted by the Nitinol wires and to record these data along with engine torque, speed, and temperature.

A fully-instrumented "training" engine was developed for preconditioning the wires to be used in the multiple-band engine. A specialized wire-rolling mill was built with which a few continuous loops were fabricated starting with annular rings cut from Nitinol plate.

Apparatus for measuring the stress-strain-temperature characteristics of naive and trained Nitinol wire was modified to accommodate continuous loops.

A sizeable list of experimental objectives was accomplished. Torque versus speed curves were measured on the single-wire engine. Internal forces and torques were recorded as naive wires were "trained." In conjunction with state-surface measurements (stress, strain, temperature cycles), these measurements reveal how the wires adapt to certain conditions so that power output may increase or decrease as the condition of the Nitinol wire changes due to cycling, and thus change their match to the engine design.

Fatigue experiments were run on several wires. One wire was cycled approximately 80,000 cycles, expanding and contracting about 3.7% each cycle while under a stress of apprxoimately 15 kpsi. A continuous wire was cycled more than 20,000 times. This wire was of a square cross-section made by rolling a ring in a modified Turk's head wire-rolling mill. From these results -- construction of apparatus and running of experiments -- it may be seen that a majority of the original research objectives of the grant request were accomplished. Performance of a multiple-band Nitinol engine has been documented. A method of fabricating Nitinol wires (which are truly continuous throughout) has been demonstrated, and several wires made.

It remains to perfect the method of manufacture of continuous loops so that wires which have essentially unlimited lifetime, while exhibitng desirable shape-memory characteristics for use in engines, and low manufacturing cost, can be created in large numbers. When this has been accomplished, expansion to practical-sized engines can be given serious consideration.

II. Apparatus

The desire to run engines under steady-state conditions necessitated the construction of a system for delivering hot and cold water at near constant temperatures. In the system as implemented, water is heated in a modified gas hot water tank controlled by an adjustable electrical thermostat. Cooling is done by a 1-ton refrigeration unit in which the evaporator is a 50-ft coil of 1/2" copper tubing immersed in an insulated tank filled with water.

Water from the heater/chiller is pumped through a small temperature-boosting tank which is fitted with an electrical immersion heater controlled by a sensitive temperature sensor; this is controlled by a circuit to hold the exit water at constant temperature, varying only about $\pm$ 5° C. From here water is delivered to the engine, and returned to a sump. Each sump (hot and cold) is equipped with a Simer liquid level controller (Model SSS11B) which operates a pump to return water to the heater/chiller tank.

The engine used for pre-conditioning or "training" wires for the multiple-continuous band engine is shown in Fig. 1 and in Photograph A. This engine is of the "chinese-pulley" design in which hot and cold drive pulleys are a common shaft. The drive pulley assembly is mounted so that it can be moved vertically, and the total force exerted on the Nitinol wires is determined by weights, as shown in the drawing.

Forces exerted by the wire in its hot and cold states are measured by load cells formed by attaching a strain-gauge bridge to each pulley support. Signals from these bridges are amplified by a 725 operational amplifier integrated circuit and resistor network, and filtered by a capacitance-resistance pi-filter to remove rapid fluctuations before being plotted on an 8-channel Leeds and Northrop strip-chart recorder. Circuit details are given in Fig. 2a.

Speed is measured by a photo-interrupter-tachometer connected to the shaft. Twenty pulses of light per revolution are converted to electrical signals and integrated by a 9400 integrated circuit to produce an analog signal which may be read from a voltmeter dial, and which also is used as imput to an x-y recorder for speed vs. torque measurements.

This tachometer is an integral part of a torque-measurment and speed control device. The analog voltage which represents the rotational speed of the engine is compared with a preset voltage from a potentiometer. When the speed is below this threshold, no current flows in the output of this comparator circuit, but when the speed is above threshold, a current proportional to the overspeed is caused to flow through a hysteresis brake (Delevan model HYB-20-24, serial number 8FDI) which exerts a smoothly varying braking torque on the engine. The current vs. torque characteristics of this brake are fairly linear over a considerable range, so a plot of current in the brake vs. speed from the tachometer gives a first-order measure of speed vs. torque characteristic of the engine. This measurement can be improved by converting the current to torque by means of the hysteresis brake calibration curve shown in Fig. 2b .

This feedback tachometer-controller system is used to control the speed of the engine during routine long endurance runs as well as for making torque vs. speed engine characteristic measurements. It is shown in photograph B.

A circuit diagram of this tachometer-controller is presented as Figure 2c.

Temperatures in the engine heat source and sink and elsewhere are measured with iron-constantan thermocouples and recorded by means of the Leeds and Northrup 8-channel recorder. Spot measurements are made with an Amprobe "Fastemp" thermometer.

Stress-strain-temperature cycles are measured in detail in a special fixture built for this purpose. Families of isotherms, plotted by Moseley two-axis recorder, with force on the y and elongation on the x axes, reveal the shape of the state-surface boundaries as defined by Cory (Nitinol Thermodynamic State Surfaces, Journal of Energy 12, 257 1978). These surfaces are dramatically modified by training, and correlate much useful information about the behavior of Nitinol.

The stress-strain device is depicted in Figure 3. Water of a selected temperature flows through an insulated container in which the Nitinol wire loop is suspended by being attached at the lower end to a load cell and at the upper end to a lead screw. Elongation is read from the lead screw by means of a potentiometer; this is varied and recorded along with the resulting force to generate an isothermal curve.

A multiple-continuous-band engine in a 5-pulley configuration is described in a separate section.

III. Experimental

A. Training

We have learned in the past five years that the physical characteristics of Nitinol change quite dramatically as the Nitinol is thermally stress-cycled. It is not possible to avoid this conditioning; any cyclic change of stress-strain-temperature variable produces, in a naive sample of Nitinol, irreversible alterations in the thermodynamic path. Knowing that the thermodynamic path will change as an engine element is cycled, it is futile to design an engine for optimum performance using the characteristics of freshly-annealed Nitinol.

How, then, can one design machines using Nitinol to cycle many times? It has been demonstrated that certain thermodynamic cycles converage so that, after a number of cycles (of the order of 10^4) the cycle repeats within tolerable limits. One approach, then, is to run the engine element through enough cycles of stress-strain-temperature that its behavior becomes stabilized and sufficiently predictable that its known characteristics can be used in a design.

It has also been shown in limited cases that stabilization may be accelerated so that a few cycles (of the order 10 or 100) are sufficient to produce predictable behavior. For example, in work reported at the Nitinol Engine Conference at Naval Surface Weapons Center in September, 1978, we showed that a constant-force cycle with a hot-phase stress of 35 kpsi repeated 20 times converged asymptotically. When the maximum stress was reduced by 25% the cycle was repeatable within measurement precision.

In the present experiment we are interested not only in the rate at which training takes place but in the reproducibility of results of training. For this purpose, a group of wires were made up and individually run on the training engine. Four of these wires cut from a single piece of wire were later selected for use on the multiple-band engine. Fig. 4a shows the stress-strain isotherms for one of these wires after annealing and before training (traces for the other 3 are similar) and Figs. 4b-e show the equivalent isotherms for all four wires after training.

Training in this case consists of running the wires on the training engine with a nominal elongation ratio of 1.03 to 1.00 (3%) determined by the dial settings on the lathe when the grooves were cut. This ratio differs somewhat from the actual ratio seen by the wire in its cycle because, as the wire contracts during heating, it increases in cross-section such that the volume remains practically constant.

$$\frac{\delta d}{d} = -\frac{1}{2}\frac{\delta l}{l}$$

where d = wire diameter and l = length

Comparison of Figs. 4 b, c, d, e reveal a high degree of reproducibiity in the training phenomenon, and comparison of these measurements with Fig. 4a demonstrates the significance of the training process: the trained wire differs dramatically from the untrained wire.

These results are consistent with earlier results obtained in our laboratory on Nitinol wires in tension and in the form of helices. We believe there is strong evidence that wires run in the constant-force cycle of the continuous-band type engine develop stress-strain-temperature behavior characteristics which converge toward a common set of characteristics, namely, a pronounced two way shape memory (which shows up as a zero-force elongation during cooling), steeply sloping stress-strain isotherms along the curve of increasing stress, and a reduction in the thermal hysteresis from about 30°C to about 15°C. (This hysteresis is more clearly seen in cycles in which length is plotted against temperature at constant stress; these results were reported at the Nitinol Engine Conference at Naval Surface Weapons Center in September, 1978 and are published in the Proceedings.)

Most important, all wires trained by the above procedure demonstrate a "second elastic region"; this name we have applied to the region at the right-hand side of the stress-strain plots where the isotherms converge and in which the wire, in its cold phase, acts almost as if it were elastic with a modulus of elasticity about half that in the hot phase.

It is clear that such trained wires will not tolerate large deformations. This shows up as work-hardening and brittleness in trained wires, and necessitates careful handling of these wires.

As training progresses, a permanent deformation of the wire is also observed. This deformation, which may be as much as 10 or 12% elongation, apparently accommodates the change in crystal structure as a larger share is converted, per cycle, from martensite to parent phase.

The engine cycle used in the continuous-band or thermo turbine engine is approximately that shown by the dotted lines in Fig. 4f: The area enclosed in the shaded region is the work done in the cycle. The two horizontal dotted lines correspond to contraction during heating and expansion during cooling, while the two vertical dotted lines are the net effect of a complex set of free expansion thermodynamic paths followed during sudden changes in tension as the wire leaves the two drive pulleys.

The state-surface measurements shown here are used to design the engine upon which the wire is to run. For a desired pair of forces in the hot and cold legs, horizontal lines are drawn which intersect the isotherms which describe behavior at the hot and cold bath temperatures. A pair of vertical lines drawn from these intersections complete the description of the desired cycle. The horizontal distance between these vertical lines defines the elongation ratio required and therefor the required pulley diameter ratio.

It should be pointed out that this procedure is only accurate for temperatures which are well above the transition range; the correct descending isotherm for the high-temperature part of the cycle would be found by elongating the wire much more than was done, up to a strain which intersects the second elastic region described above (p. 18). To do so would destroy the wire, so instead, we choose an elongation ratio less than that found from the above procedure and experimentally determine a proper set of running conditions by varying force and elongation ratio.

B. Fatigue Tests

Experiments were conducted to determine whether Nitinol wire in extension deformation might be expected to have long cycle lifetime. Three techniques were used to join the wire into the loops required for the test procedure: 1) welds; 2) ferrules; and 3) rolling continuous loops. The lifetimes of weld-joined wire were limited to a few thousand cycles due to the short lifetime of weld. Loops formed by joining the wire ends by swaged ferrules also failed at the joint after a few thousand cycles, but the break could be easily re-joined on a given wire a number of times, and thus permit fatigue tests on most of a given wire up to about 10^5 cycles. Beyond this, the time spent in removing the wire from the test engine, repairing it, and reassembling the engine, became prohibitive. Fatigue tests on rolled loops were limited to one (damaged) loop by availability. (See p. 26 below) Results are tabulated in Table I and lifetimes vs. elongation are plotted in Fig. 5. Here, for comparison we also present fatigue data obtained by other researchers. Note that we are comparing welds and ferrules with Nitinol.

The results of these tests are consistent with the interpretation that welds in Nitinol wire in tension are subject to fatigue in the heat-affected zone. While it may be possible to improve these by metallurgical treatment, at present the lifetime of 10^4 cycles is not significantly better than that of swaged ferrule connections. Ferrules, being over size compared to the bare wire, cause a variety of problems. The worst of these is that the wire at the ferrule end is subjected to strains which are significantly different from those in the bare wire, particularly at the points where the loop runs onto and off of the drive pulleys. Cushioning the ferrules by means of short plastic tubes enclosing the ferrules has increased running cycles from about 10^3 up to 10^4, and probably much longer lifetimes could be obtained with larger diameter pulleys.

1. Strain Maximum

The next factor in Nitinol cycle lifetime is the strain maximum. If the wire is deformed more than 4%, it fails according to an exponential curve when data are plotted log (number of cycles) vs. log (% deformation). Therefore it is important to limit the strains in Nitinol engine applications to less than 4% maximum even though the naive wire will recover strains up to 6% or more.

2. Handling Operations

Following maximum strain, the next important consideration is handling.

Several wires in this experiment were damaged while they were handled, in the process of measuring their properties, and during forming process.

Better technique would eliminate this loss, but it also is clearly advantageous to limit the number of handling operations which are necessary for producing a finished, trained wire.

Our data are consistent with data taken elsewhere, suggesting that Nitinol wire which is cycled such that it never experiences stresses greater than about 15 kpsi or prolonged cycling of greater than 3% strain can have practically unlimited lifetimes. The failures which were experienced in this experiment may all be traced to over-straining or to flaws such as surface imperfections and kinks introduced during handling.

These results are seen as strongly indicating further experimental work. It is essential that practically unlimited lifetimes (greater than 10^7 cycles) be demonstrated before large engines are attempted.

C. Machine Performance Tests

Questions regarding Nitinol engine performance generally fall into three categories; thermodynamic efficiency, power density, and potential for scale-up. It has been previously shown in our laboratory that simple engines such as those used in this experiment generally may be expected to achieve 1 or 2% efficiency, or about 10% of the Carnot limit which is 10 to 20% for the small delta-T at which these engines operate. (Results presented at the Naval Surface Weapons Center Conference, September, 1978.) No efficiency measurements or improvements were attempted in the present contract, although it is apparent that efficiency can be considerably improved, perhaps up to 50% of Carnot, with a regenerative cycle. The second category, power density, or output per unit mass of Nitinol, is measured in these engines in two ways; by shaft torque output and by torque exerted on the pulleys by the Nitinol wires. The shaft torque is measured by means of the hysteresis brake and a feedback loop which controls the speed as discussed in II. above of this report, and torque exerted by the wire is computed by measuring the force exerted on hot and cold legs and multiplying this difference by the difference in radius of the hot and cold drive pulleys.

A number of torque vs. speed characteristic curves were run. Table I and Fig. 6 show typical results from a single wire, run on the training engine.

In these data and others taken with the training engine, the force on the hot leg remained essentially constant with varying speed. This implies that maximum speed was not achieved; that is, the speed at which the wire has not time enough to transform while in the heating or cooling bath. We estimate that wire of diameter .030" requires about 75 m/sec. to reach thermal equilibrium. The path length for heating was approximately 14" which means that this limit allows speeds up to 900 rpm. It is clear, therefore, that dissipative losses in this engine are the speed-limiting factor. Since bearing friction and viscous drag do not scale with size, this was not taken as a serious problem.

The third category of performance, potential for scale up, was addressed in this contract period by the construction and testing of a multiple-band

Table I

PERFORMANCE EVALUATION OF SINGLE WIRE NITINOL ENGINE

Temperatures:	$T_H = 81^\circ$ C $T_C = 5^\circ$ C	
Total force (force on hot leg plus force on cold leg):	60 Newtons	
Mass of wire:	5 gm	) at room temperature
Length:	195.5 cm (77 in)	) at room temperature
Diameter:	.028 inches (TIMET V-4609)	) at room temperature
Cross Section:	.0062 in^2 (3.8×10^{-3} cm^2)	) at room temperature
Tension (in hot leg):	25 Newtons	
Tension (in cold leg):	5 Newtons	
Maximum Stress:	9 kpsi (7800 Newtons/cm^2)	

Speed	Current	From calibration wire Torque	Shaft Power*	Density	Hot leg Force/2	Power** output by Nitinol	Power Density	Mechanical Efficiency
100 rpm	70 ma	2.3 oz/in	.168 watts	.032 w/gm	25 Newtons	.31 watts	.06 w/gm	52 %
150	66	1.9	.208	.040	25	.46	.09	45
200	60	1.6	.234	.045	25	.62	.12	38
250	52	1.3	.221	.044	25	.78	.15	28
300	45	.85	.186	.035	25	.93	.18	20
350	25	.4	.102	.020	25	1.09	.21	9
400	0	.0	.0	.0	25	1.24	.24	0

* Shaft Power (watts) = Torque (oz/in) x Speed (rev/min) x (7.31×10^{-4})

** TiNi Power Output (watts) = $(F_H - F_C)$ (Newtons) x $(R_C - R_h)$ (Inches) x speed (rev/min) x (3.1×10^{-3})

engine (V. below). A geometry was selected that could obviously be scaled to any size by adding pulleys and loops.

IV. Continuous Bands

Successful operation of a continuous-band Nitinol engine with wire in tension poses a severe problem in a technique for closing the wires into loops. The juncture should be of the same material as the rest of the wire, it should have the same cross-section, it must be strong enough to withstand stresses of the order of 10 to 30 kpsi, and must cycle repeatedly around pulleys with steep-sided grooves without fatiguing. We report here briefly on three methods which have been tested in the course of this experiment.

A wire can be joined into a loop by inserting the two ends into a slightly oversize metal tube, or ferrule, and then swaging this ferrule to grip tightly onto the Nitinol wire ends. We have found that stainless steel tubing made by Unitek for securing dental arches works well. To insure a good grip on the wire, the wire near the ends is crimped before insertion into the ferrule with a pair of sharp pliers. A cushion of heat-shrink tubing, such as is used in electronics shops, placed around the ferrule and extending about one eighth inch beyond each end of the ferrule helps to prolong the life of this closure.

Ferrules of this type have been found to last for up to about 7,000 cycles in an engine, subjected to a tension of about 25 Newtons on each wire and turning through four 180-degree turns each cycle. It was by this means that we obtained most of the engine data taken in this contract period. Each time a wire fails at the end of a ferrule, the shortened wire is fitted with another ferrule and the experiment is continued.

A second method of joining wires into loops, which would appear to be highly preferable, is by welding. Flash welding results in highly inhomogeneous welds which are prone to slag, and these usually fail in a few hundred cycles. Electron-beam welding results in beautifully smooth welds which have strength adequate for use in engine applications. There is a non-homogeniety, however, at each end of the weld in the heat-affected zone where the melt of the weld interfaces with solid material.

This heat-affected zone is subject to fatigue and generally fails after a few thousand engine cycles. Homogenization of the heat-affected zone was attempted on several wires in this experiment. They were first electron-beam welded, then beaten down and cold-worked to reduce the crystal grain size. These specially-treated welds do not appear to be much superior to the untreated welds. The results are tabulated in Table I. The disappointing performance of the welded wires led to a search for other methods of making continuous wires.

A. Joining Techniques

Although earlier experiments had indicated that welding Nitinol wires--even very high quality welds in vacuum electron-beam--was not a process which resulted in long-lived loops (loops which would run many cycles), it was decided to try welding followed by "beating down" and heat treatment to homogenize the heat-affected-zone and thus remove the source of fatigue. Six wires were sent to D. Goldstein of Naval Surface Weapons Center. Two were already welded; the others were welded under his direction. All were processed metallurgically to remove the inhomogeniety caused by partial welding.

These wires were returned to our Laboratory and tested on the training engine. The conditions of running and the results are tabulated in Table II.

The most successful of these welds went approximately 12,000 cycles in a realistic engine cycle before failure. These data confirm our initial doubts as to the efficacy of welding for the purpose of making continuous wires for use in these engines.

Attempts were made to solder or braze the Nitinol wire ends together. Solder and braze are rejected by Nitinol with all of the fluxes we found available. Several attempts were made to plate Nitinol with copper and nickel, followed by soldering or brazing. Although partially successful platings were accomplished, none were mechanically strong enough to be used in engines.

Since the cause of failure of wires joined by ferrules appears to be the unusual bending stress to which the wire is subjected as the ferrule runs onto and off of the pulleys, it has been considered that a successful joining technique might result from swaging a very short coupling to each end of the wire and join these couplings with steel cable. The necessary technical work to test this method was considered to be prohibited by limited resources at this time, so it has not been tried.

A third method which has often been suggested is that a continuous loop of wire could be formed by elongating a ring. Starting with Nitinol plate, one may cut an annular ring by turning on a lathe. This ring naturally has a rectangular cross-section, which is well suited to forming in an arrangement of rollers known as a Turk's Head and sketched in Fig. 7. Such a set of rollers were fabricated in our laboratory and mounted on the ways of a milling machine to control the dimensions. This has proved to be a feasible method of making Nitinol wires which are continuous throughout.

B. Continuous Wire Manufacture

One continuous wire long enough to be used on the training engine was made from an annular ring 3.5 inches in diameter with a cross-section .025 by .120 inches. The ring was expanded in 20 steps, with annealings, to a loop 74 inches in circumference, and having a cross-section .019 by .020 inches. The elongation was by means of a set of four rollers mounted in a Turk's head configuration illustrated in Fig. 7. This rectangular cross-section was found to slip on the pulleys of the engine, so the corners were rounded by grinding and polished by running lightly over #400 emery cloth.

Table II

Wire Description	Symbol	Date Tested	Type of Failure	Method of Joining	Number of Cycles	Strain %*	Stress**	Comment
.024" dia. Wayman #4 weld	(4)	Sep 79	Weld	Weld	3,000		10 kpsi (40N/2 wires)	Electron beam weld.
.024" dia. Wayman	◇1	May 79	Wire	Ferrule	80,000	4.0	12 kpsi	This wire was used for testing ferrule design. Handling may have caused early failure or pieces of wire wrapped around the loop which slipped and caught in grooves.
.024" dia. Trained	◇3	Nov 79	Wire	Ferrule	7,000	3.5	12 kpsi (50N/2 wires)	Previously stressed.
.024" dia. "#9 wire"	◇2	Aug 79	Wire	Ferrule	13,000	3.5	35 kpsi (70N/2 wires)	Fastened with ferrule many times. Wire finally failed at 80,000 cycles in a place where previously it had been severely kinked during handling.
Square cross-section .020" x 63"	□1	Jan 80	Wire	None***	20,000	3.2	14 kpsi (50N/2 wires)	Turk's head; damaged during rolling Operation.
.024" dia. Goldstein	(1)	Apr 79	Weld	Weld	12,000	3.3	10 kpsi (40N/2 wires)	Election beam weld and heat treated.
.024" dia. Goldstein	(2)	Apr 79	Weld	Weld	2,000	3.3	10 kpsi (40N/2 wires)	" "
.024" dia. Goldstein	(3)	Sep 79	Weld	Weld	2,500	3.5	8 kpsi (50N/2 wires)	" "
.024" dia. Goldstein	(5)	Sep 79	Weld	Weld	300	3.3	12 kpsi (50N/2 wires)	" "

*Est. maximum cyclic elongation **Est. maximum force ***(Continuous loop)

This wire failed after approximately 20,000 engine cycles. Since other wires have been shown to have longer fatigue lives than this, (in particular, a wire fastened with ferrules which was run 80,000 cycles), and wires in other experiments have attained lifetimes of 250,000 to 1,000,000 cycles (private communication from J. S. Cory and R. M. Banks) we believe that this shortened lifetime was an artifact of the procedures used in making and testing the wire. There were several possible causes of damage to the wire. This was the first such wire produced. The rollers were not perfectly smooth or perfectly aligned. Extrusion of the wire from a ring 3.5 inches in diameter to a length of 74 inches was a severe procedure. It is quite possible that some folding and roll-up of the ring occurred at the edges, and that this resulted in inhomogenieties in the wire produced.

An accident occurred during the rolling procedure: the wire became caught in the rollers during the tenth pass, and it was severely creased when a sharp-edged roller ran off the wire. This fact was noted, and it was decided that the experiment should be completed anyway since no other material was available for starting over. Most of the groove caused by the accidental cross-rolling was removed by grinding, and the reduction was completed. After this accident, there were 10 subsequent rollings and annealings, and it was hoped that this would eliminated the damage. A visual inspection showed no evidence of damage: but it is quite likely that a notch was started which propagated during cycling.

When this wire was tested on the training engine, it was subjected to stresses as great as 35 kpsi, in an attempt to start the engine before it was determined that the square cross-section should be modified. This severe early stress may have contributed to the premature failure.

Subsequently the wire was ground by running it against a Dremel disc grinder in order to round off the corners. Visual inspection showed that rather large gouges were left on the surface after this grinding, some of which were removed by polishing by emery cloth. Since it is known that Nitinol is sensitive to surface notches, we feel that these notches may also have contributed to the failure.

There are thus several possible causes for the failure observed after 20,000 cycles: the wire was imperfectly formed or over-stressed during manufacture; it was damaged due to accidental mishandling; it was subjected to excessive stress during initial testing on the engine; and it may have had significant notches induced during grinding. All of these imperfections can be eliminated in future wires. This work will continue. Recently, two plates have been received from Naval Surface Weapons Center, and these will be used for making wire loops. More Nitinol plate has been ordered from TIMET, and when this is available we will repeat the experiments taking care not to damage the wires.

We feel that the above experiment, although it did not lead to a completely successful result, shows feasibility of making continuous loops by this process. The wire created showed all of the characteristics which we associate with drawn and annealed wire, and trained as expected on the engine. (See Fig. 8) We are convinced that a refinement of the techniques used will result in wires which will last a much larger number of cycles.

V. Multiple Band Engine

A number of possible machine configurations were considered as the prototype multiple-continuous band engine. The design selected is the 5-pulley arrangement illustrated in Fig. 9 and Photograph C. This engine design had been operated previously with a single wire and with two wires in parallel, and hence is not a radical departure from machines with which we have had experience. It can be arranged so that heating and cooling take place in immersion tanks so that water flow requirements are minimized. The design may be scaled up by adding more sheaves on the drive pulley and more wires. Finally, it is relatively easy to instrument so that forces, torques, and temperatures are recorded.

The engine consists of a central drive pulley and four idler pulleys about which multiple continuous Nitinol wires run in parallel grooves. Each wire runs once over the top of the drive pulley, under an idler and over a second idler, then under the bottom of the drive pulley, over the top of a third idler, under a fourth, and returns to the top of the drive pulley. Alternating deep and shallow steep-sided Vee-grooves are formed in the central drive pulley, and the wire runs in a shallow groove as it passes over the pulley and a deeper groove when it passes underneath. Thus, if the wire expands while it travels around one idler pair and contracts as it travels about the other, a net torque is set up and the arrangement runs as an engine.

Expansion and contraction take place because of cooling and heating of the Nitinol wires as they pass through tanks in which the lower two idlers are immersed. Tension in the wires is maintained by long springs which control the vertical position of the upper idler pair. These springs may be adjusted so that forces are balanced when the engine is in a running condition, with significantly less force on the cold leg of the engine than on the hot.

Tensions in the wires in the hot and cold legs are measured by strain gauge bridges attached to the beams which support the lower idler pulley shafts. Signals from the strain gauge bridges are amplified, filtered and recorded as described in II. above.

Forces in the hot and cold legs may also conveniently be measured by stacking weights on the sliding pulley supports which are acted on by the springs; when the wires become slack, the weight equals the force exerted by the spring.

Temperatures are recorded in the heat-source and heat-sink tanks which contain the lower idlers. It is particularly interesting to measure the equilibrium temperature of the drive pulley, because this is intermediate between the heat-sink and heat-source temperatures. If this temperature is such that the wire changes shape as it reeves about the pulley, this may result in a loss of work output. Measurements made on a running engine by placing small thermocouples down into the deep and shallow grooves of the drive pulley indicate that these grooves are at nearly the same temperature, which is about halfway between the heat-source and heat-sink temperatures.

The drive pulley is constructed of multiple discs with edges tapered

6 degrees on each side. Deeper grooves are formed by placing shims between the discs. It was found that this arrangement allows for reasonably fast experimental determination of a proper shim thickness to give optimum performance. It should be noted that, because of the steepness of the sides of the grooves (which is necessary so that the wire becomes captured and held without slipping at the intermediate temperature of the drive pulley) even a few thousandths of an inch makes a several percent change in elongation. The design limits imposed by the state-surface isotherms are very stringent: variation of .2% elongation may be the difference between a vigorously running engine and one which will not start at all.

The engine was run first with a single wire, and the engine characteristic curves measured. These are shown in Fig. 10.

The proposed plan was to have continuous wires fabricated and to test these on the multiple-wire engine. However, since the wires which were fabricated at Naval Surface Weapons Center did not have long lifetimes, and the alternative method of extruding wires by means of the Turk's head roller arrangement was not successful until near the end of the contract, we elected to test the 5-pulley multiple-wire engine with wires which were fastened together by swaged ferrules.

The engine was tested using 2, 3, and 4 wires in parallel, each wire being fastened by a ferrule as already described. The rather surprising result was that the power output by each wire diminishes as the number of wires increases, and with four wires in parallel the engine does not produce enough torque to overcome friction.

We have tried to isolate the causes of this difficulty. The wire loops were carefully measured while hot, and ferrules fitted such that they were all within .1 mm of being the same length. The drive pulley was carefully shimmed so that the variation in elongation ratio was less than 6 parts in 100 from a mean of 1.6%. The mean value of 1.6% (that is, one pulley is 3 inches radius, the other 3.048 inches radius) was found experimentally to be a suitable elongation ratio in which any one of the four wires operates well by itself. With these adjustments, the four wires in parallel remained taut throughout their paths as the total force was gradually increased up to 200 Newtons (four times the force used with a single wire, as on the training engine.) There was approximate sharing of this force among the wires on the hot side of the drive pulley.

This model approaches, as closely as we are able to achieve, a situation in which each wire goes through a thermodynamic cycle which, when operated singly, results in a net power output. One would expect that the output from the four wires in parallel should be about four times that for a single wire. Instead, the power output is diminished. What accounts for this change?

We believe that the answer lies in a combination of several subtle mechanical interferences between the wires. The most important of these is associated with the passage of the ferrules over the drive pulley.

When the engine operates with a single wire, the machine length is free to vary such that the tension in the wire, working against a spring, remains nearly constant as the effective length of the wire changes. When there is a sudden change in effective pulley ratio as the ferrule rides up onto the groove, this is transmitted as a sudden change in tension on the wire. In the case of a single wire, this change in tension is quickly accommodated by a small motion of the spring such that the wire remains in a condition where it can do positive work. In the multiple-band mode, the total force is much greater, and the individual wire takes a larger fraction of this force without moving the spring. At this point, the other three wires become nearly slack, so that they are not doing work. As rotation continues, the wire which is under high tension transfers mass less rapidly than the others so that the tension gradually becomes equalized among the four wires; but the transient effect of a ferrule passing onto and off of the drive pulley results in a substantial loss of work output for each of the wires for an entire cycle. If this transient occurs too frequently, as it does with four wires, the net power output goes to zero.

To look at this phenomenon in a different way, one may observe that the addition of multiple wires changes a constant-force cycle into a nearly constant-length cycle for each wire individually. The tolerances on length, pulley ratio and speed for a fixed-length engine are extremely critical; therefore, it is not altogether surprising that the transients set up by the ferrules are enough to prevent successful operation.

These problems illustrate the most troublesome aspects of dealing with Nitinol wire in tension, namely that here we must deal with large forces operating over small distances. Mechanical tolerances become critical, and friction must be minimized. In the 5-pulley design, the drive pulleys being at intermediate temperature makes it necessary to reduce the elongation ratio from 3 to 1.6% elongation which substantially reduces the available work output as estimated from the isothermal state-surface traces, while at the same time aggravating the the problem of mechanical tolerances.

Friction is not negligible, either, in this configuration. The drive pulley grooves must be very steep, or slippage results; and the wire tends to become stuck in these grooves so that work is expended in pulling the wire free as it leaves the pulley. Measurements show that this could account for the failure of the engine to operate, when coupled with the increased tensions in the wires which result from ferrules entering the drive pulley. This condition would be ameliorated if the wire and pulley cone surface were highly polished. At this time we have not been able to study operation of a multiple-wire engine in which the loops are truly continuous wires. It seems clear that another series of experiments are in order when we have succeeded in fabricating multiple continuous loops which are of very nearly the same length, diameter, and stress-strain response characteristics. To manufacture such wires will be our next effort.

Lack of successful operation of the 5-pulley multiple-wire engine must be seen in perspective as an experiment in which we had no reliable way to predict the result and from which we have had the opportunity to learn about the interplay of forces between components in this class of engine. We believe that this knowledge is valuable, and will aid in eventual scale up of Nitinol engines.

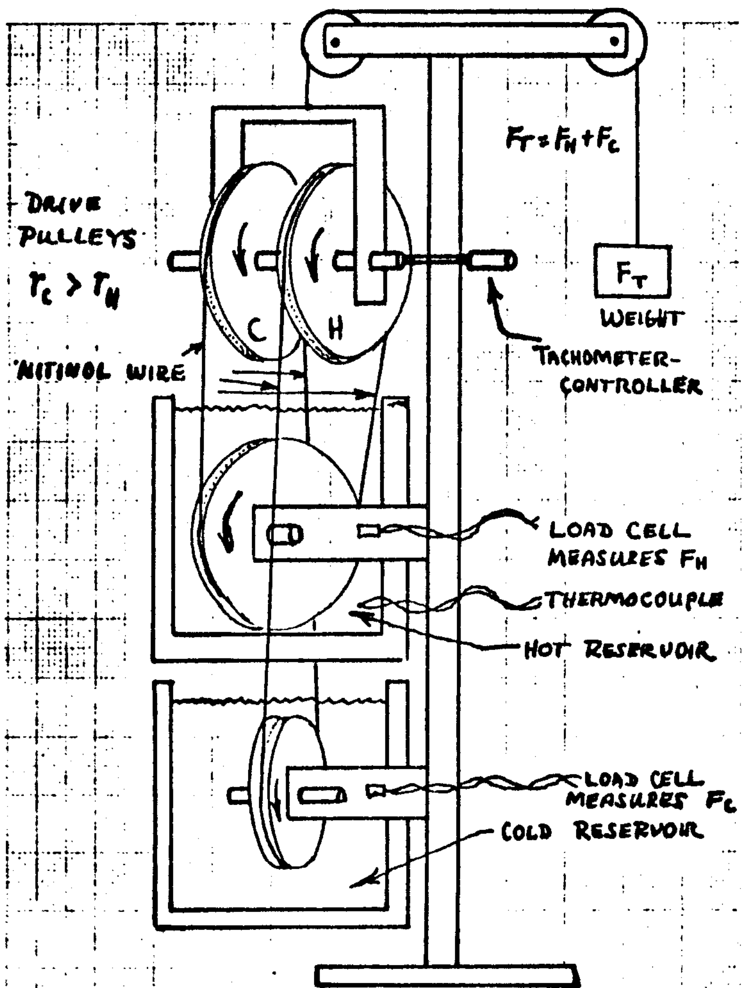


FIGURE 1
CONTINUOUS-BAND NITINOL HEAT ENGINE USED FOR TRAINING STUDIES

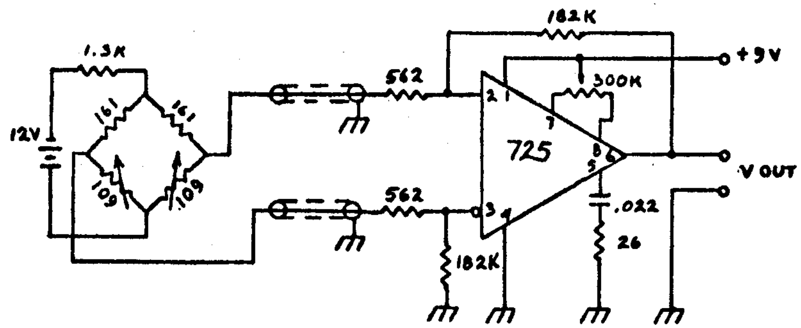


FIGURE 2a. INSTRUMENTATION AMPLIFIER

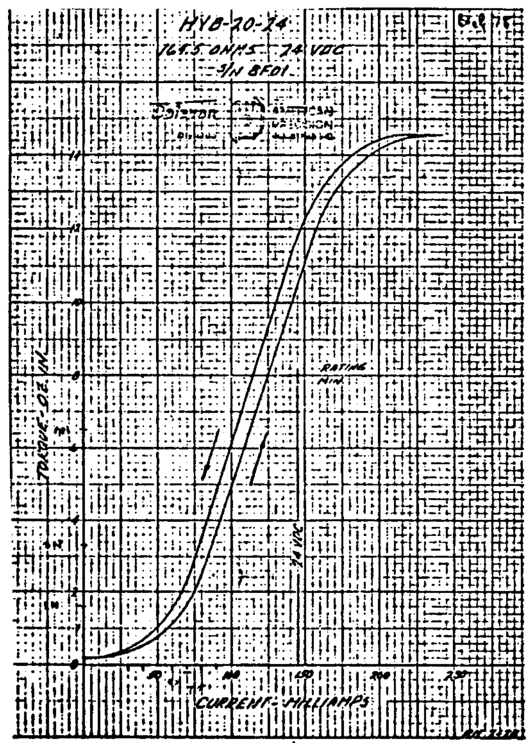


FIGURE 2b. HYSTERESIS BRAKE CALIBRATION CURVE

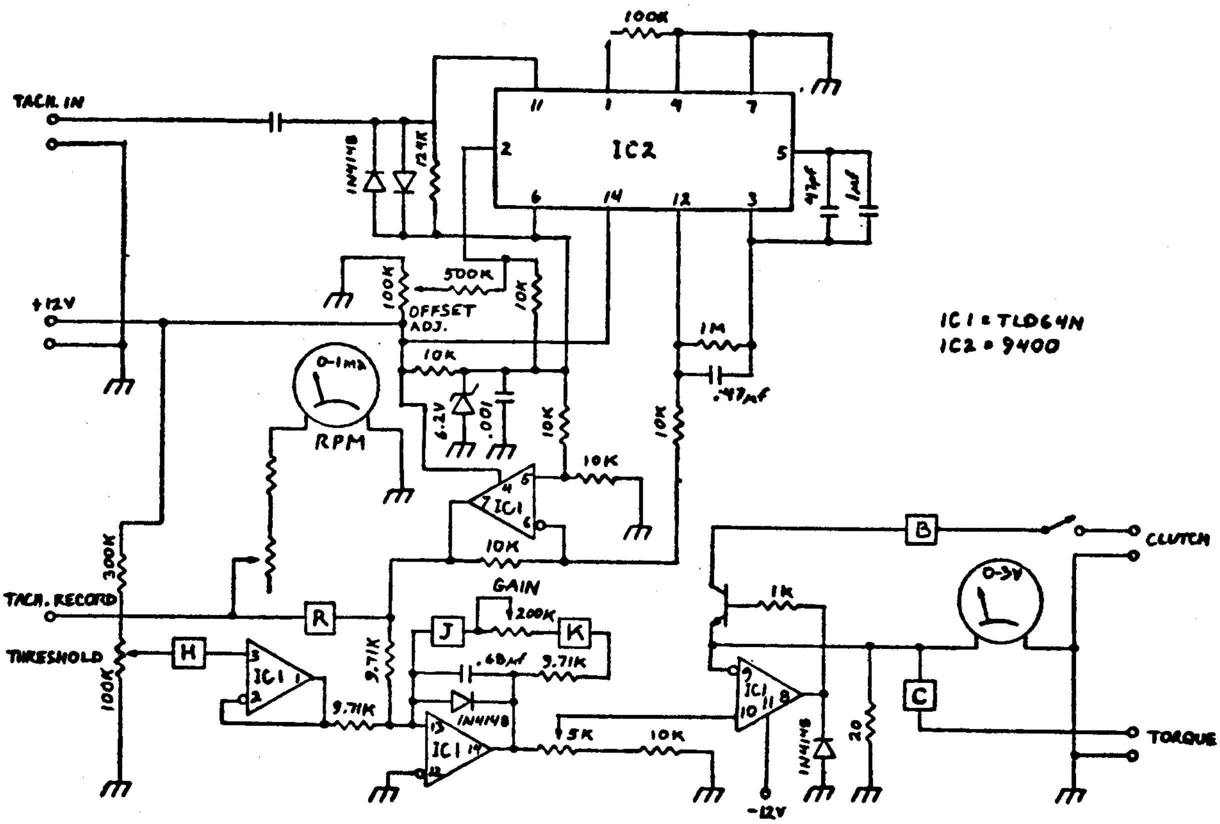


FIGURE 2 2. TACHOMETER-CONTROLLER CIRCUIT

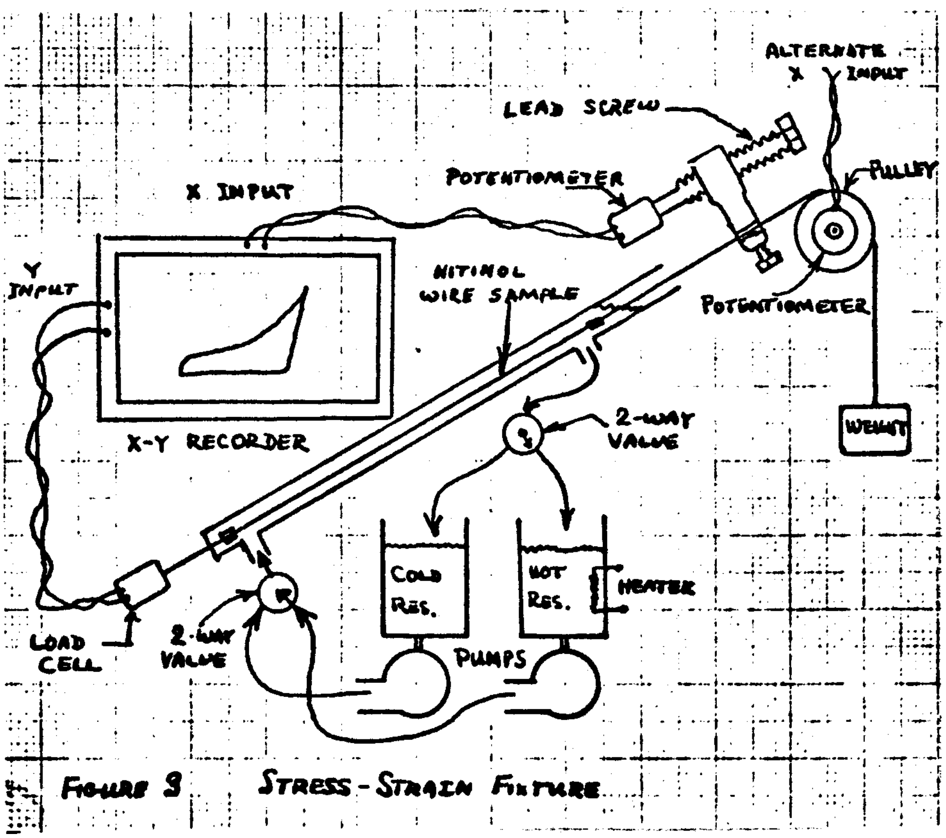


FIGURE 3 STRESS-STRAIN FIXTURE

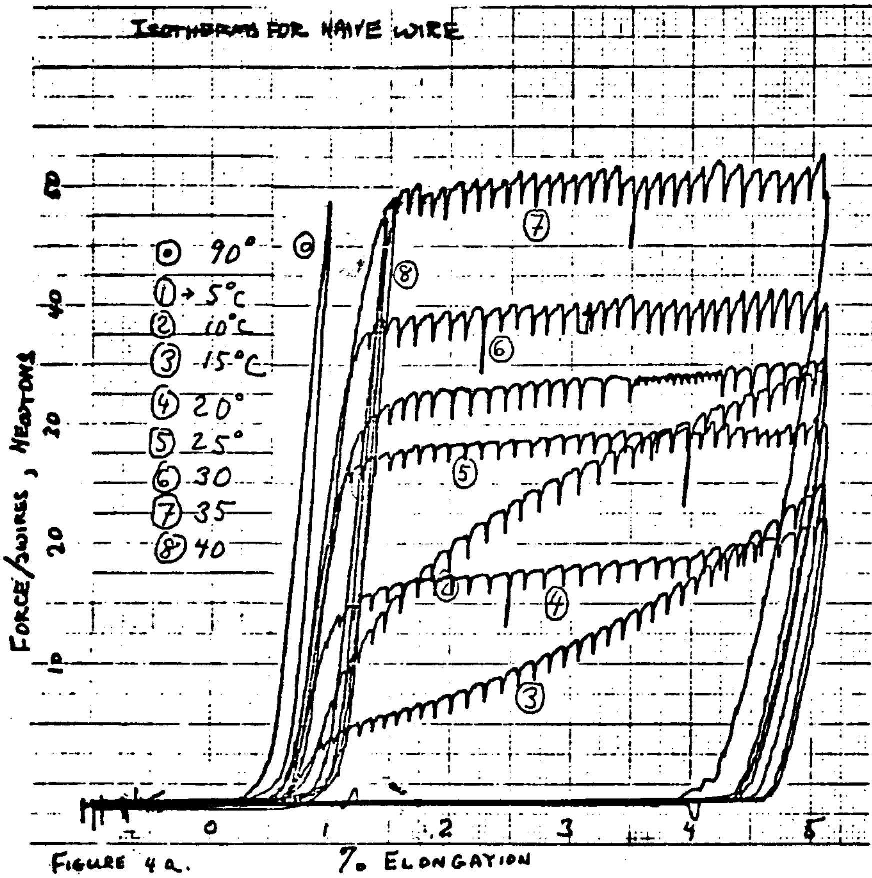
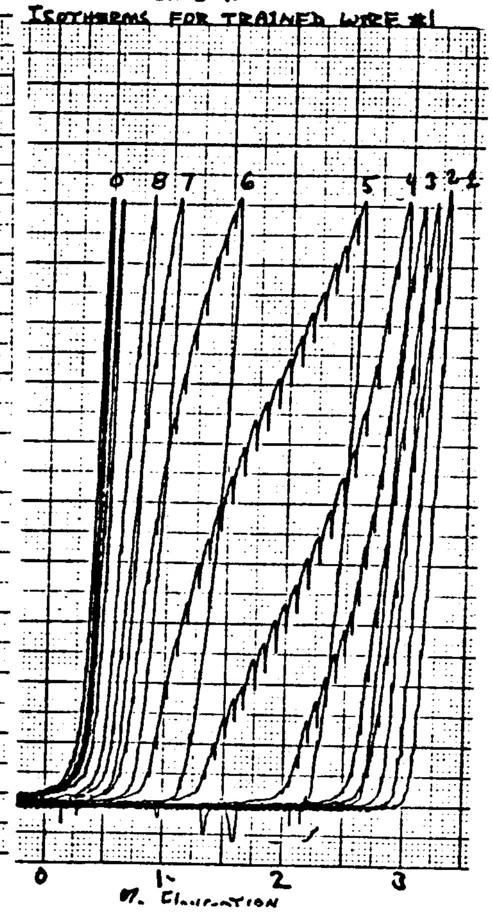


FIGURE 4a.

FIGURE 4B



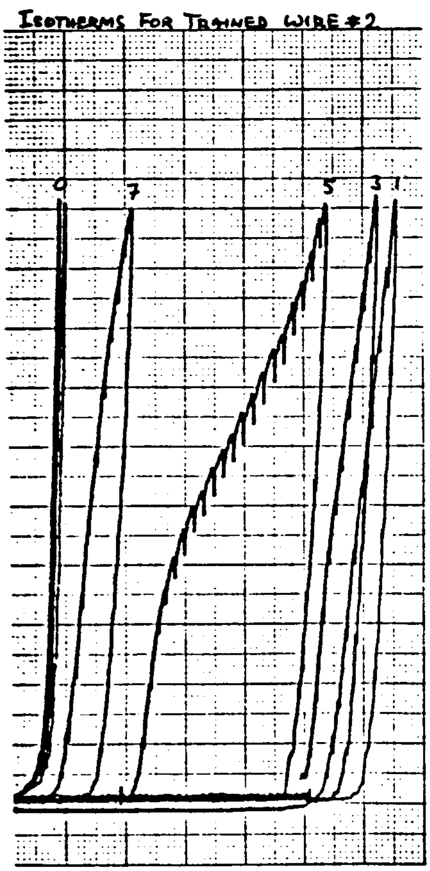


FIGURE 4C

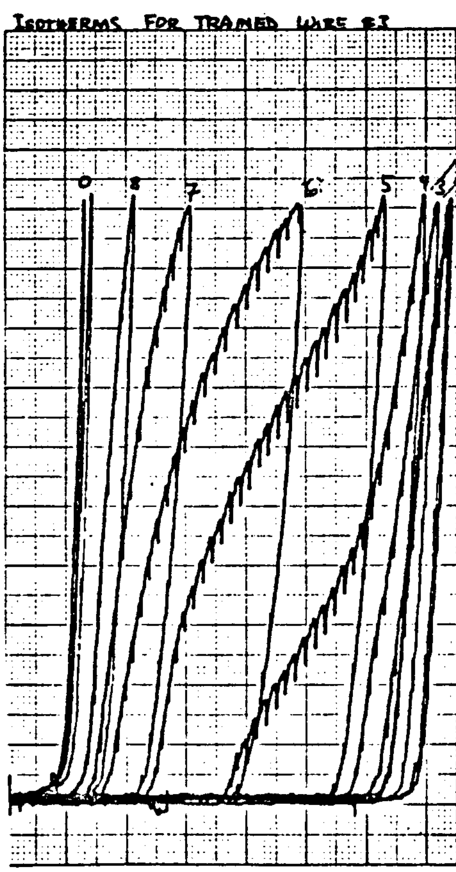


FIGURE 4D

FIGURE 4E

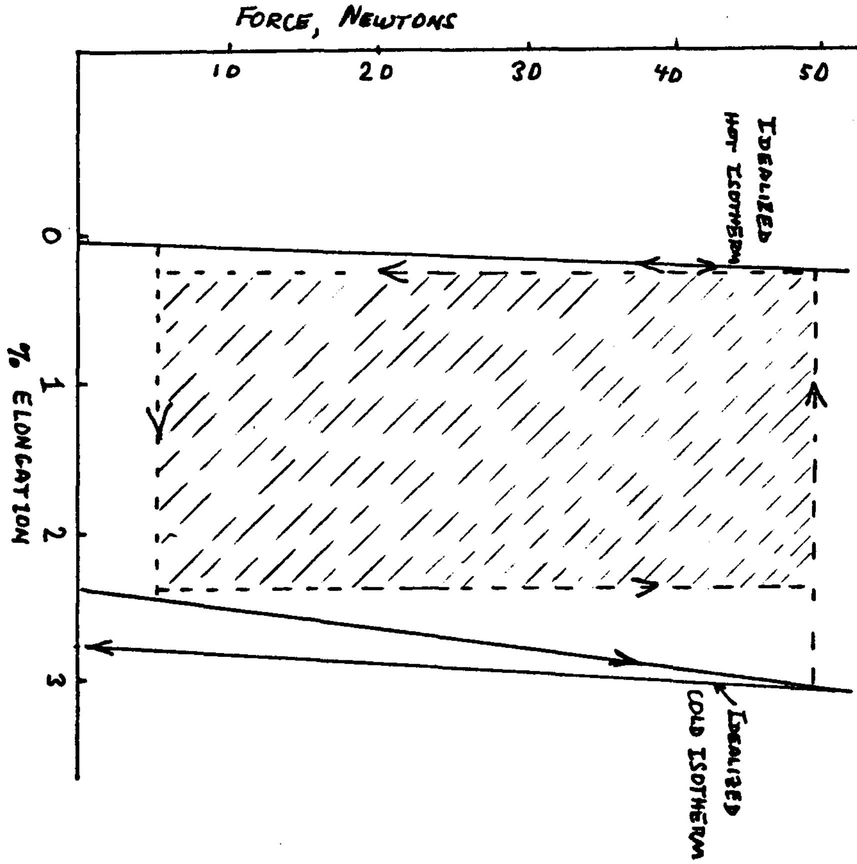


FIG. 4F THERMAL-STRESS CYCLE

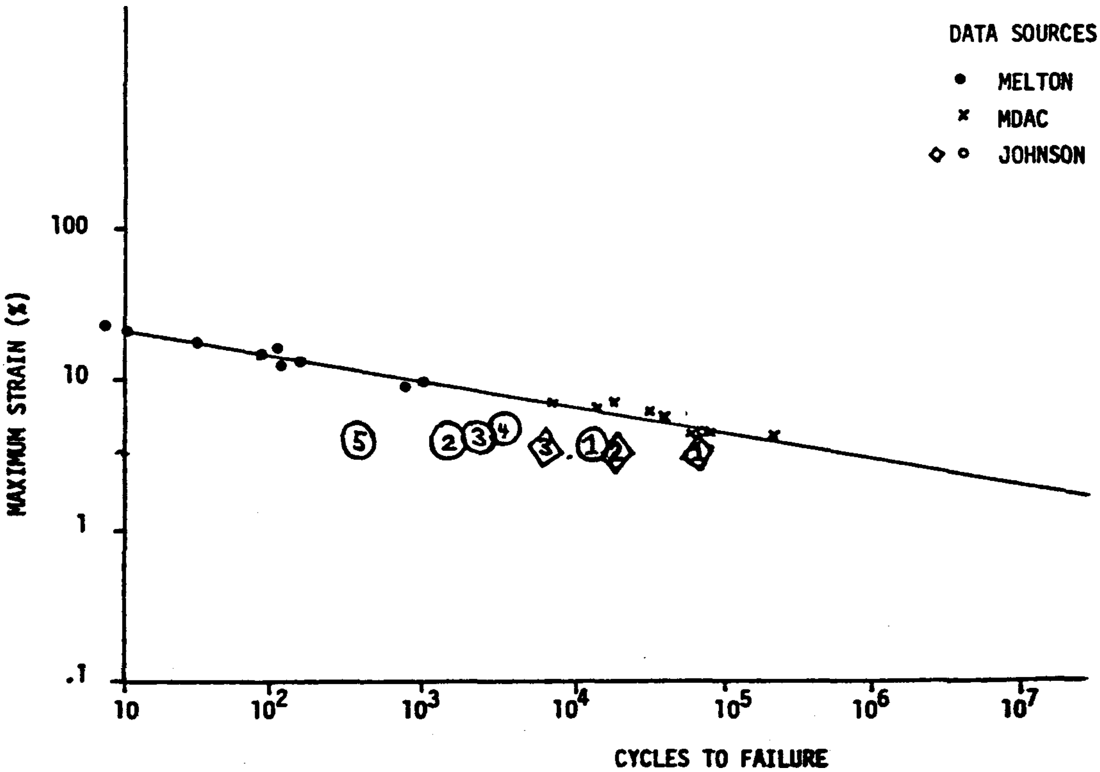


Figure 5 Maximum Cycling Strain Versus Cycles to Failure for Nitinol. Comparison of our experimental results on joining with published data on Fatigue in Nitinol. Refer to TABLE I for meaning of Symbols

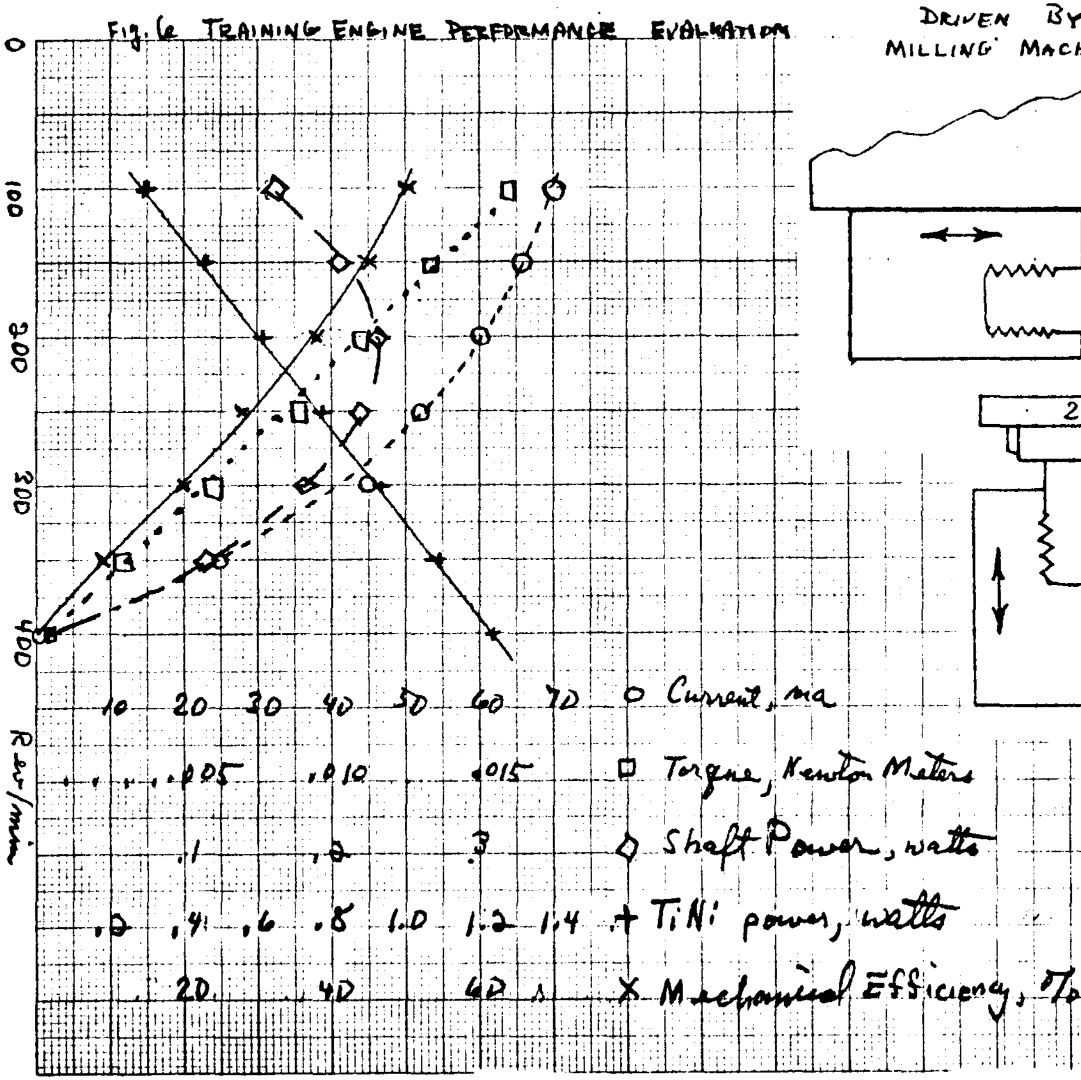
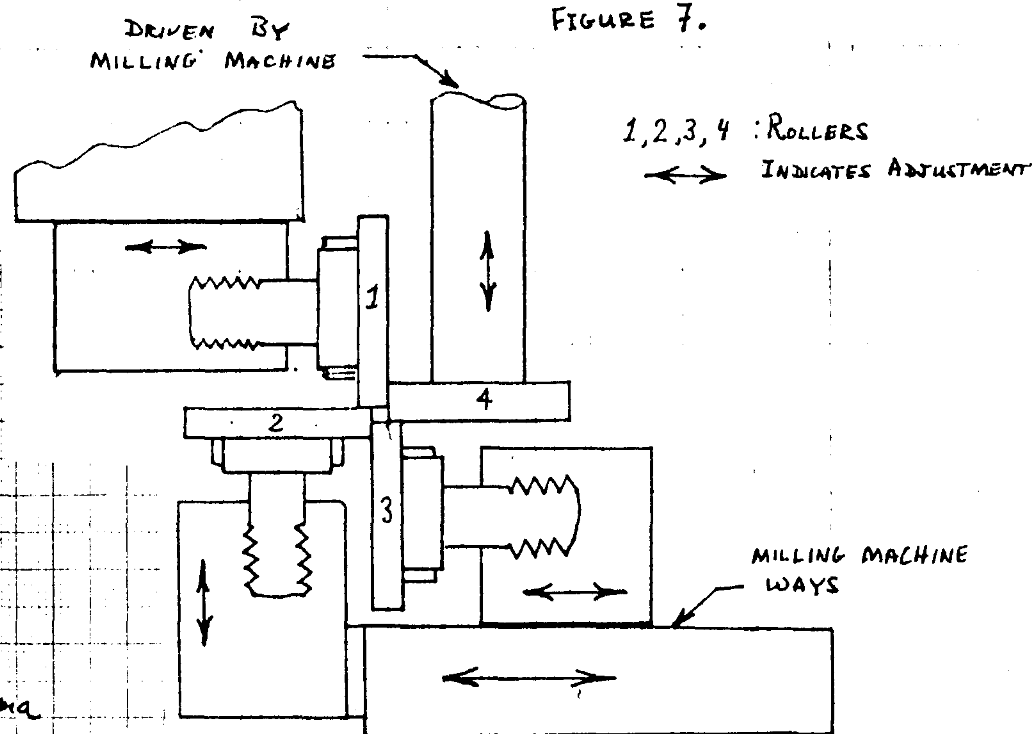


FIGURE 7.



TURKS HEAD ROLLER ARRANGEMENT

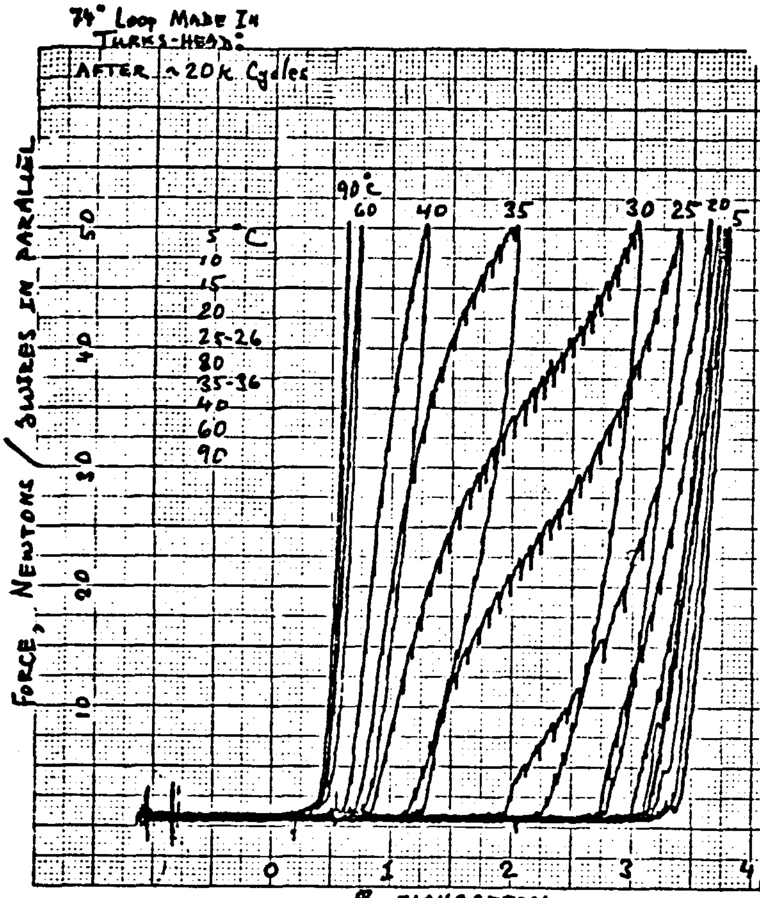


FIGURE 8 % ELONGATION

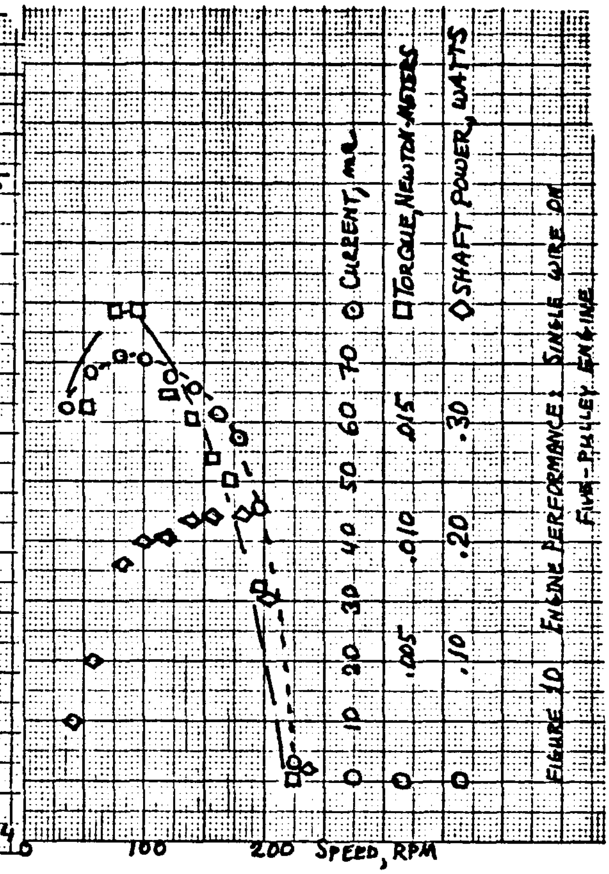


FIGURE 10 ENGINE PERFORMANCE: SINGLE WIRE ON FIVE-PULLEY ENGINE

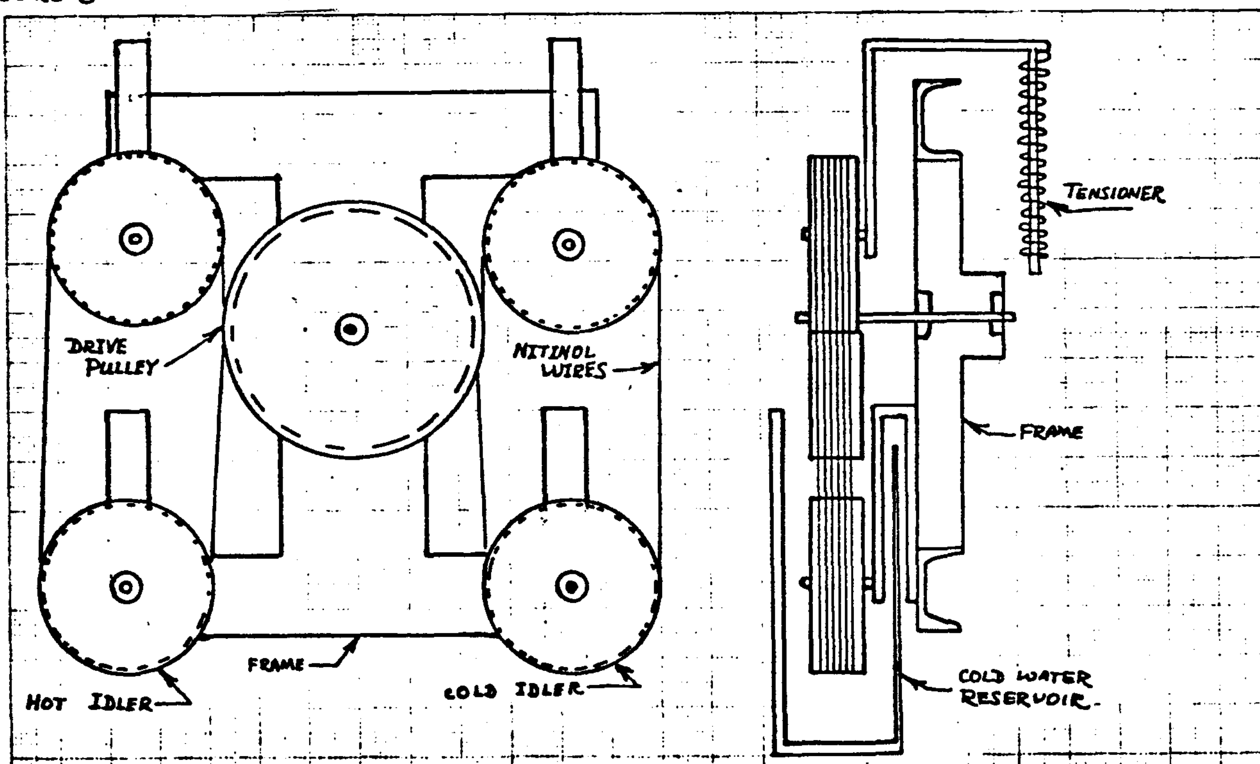
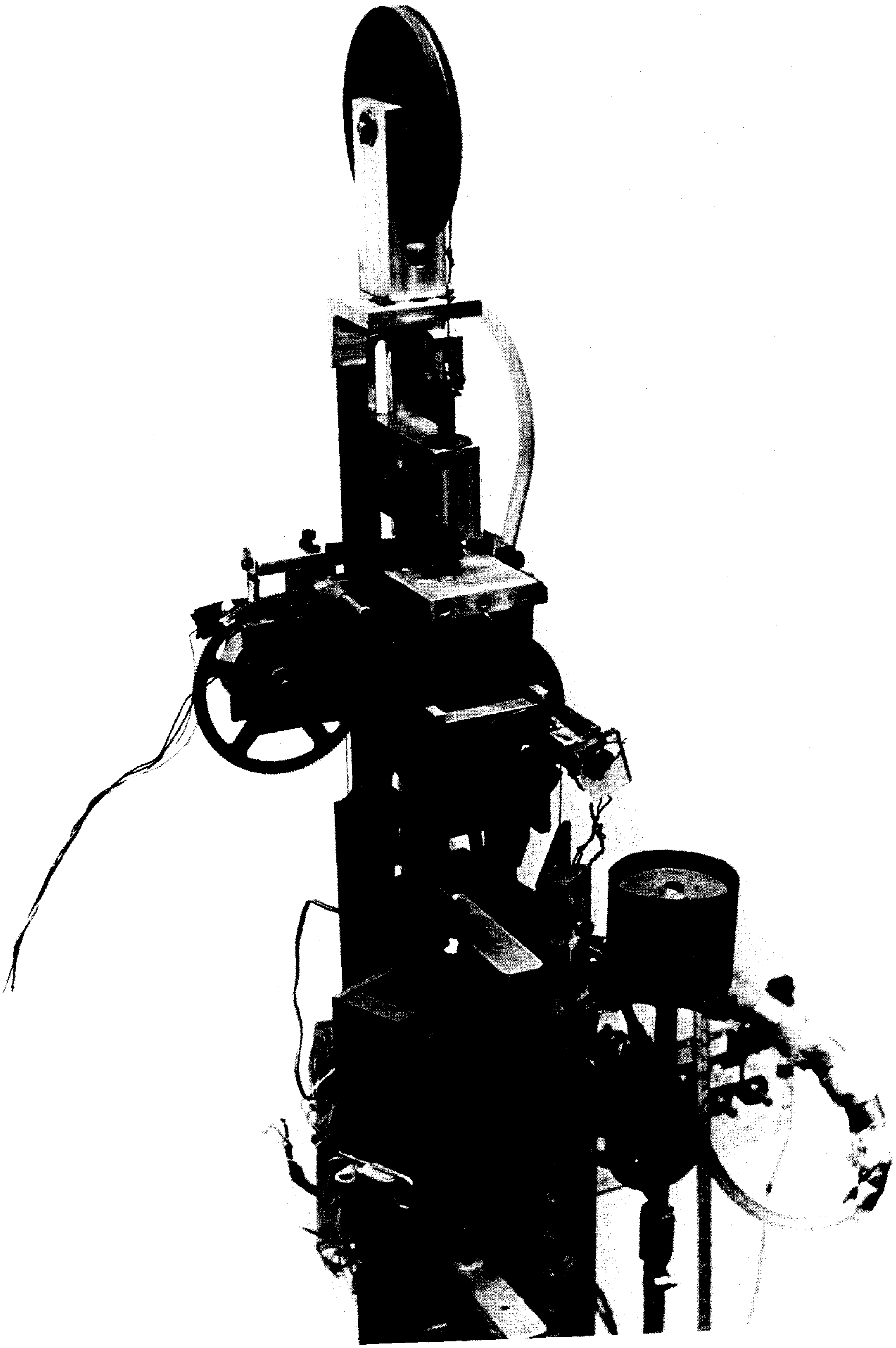
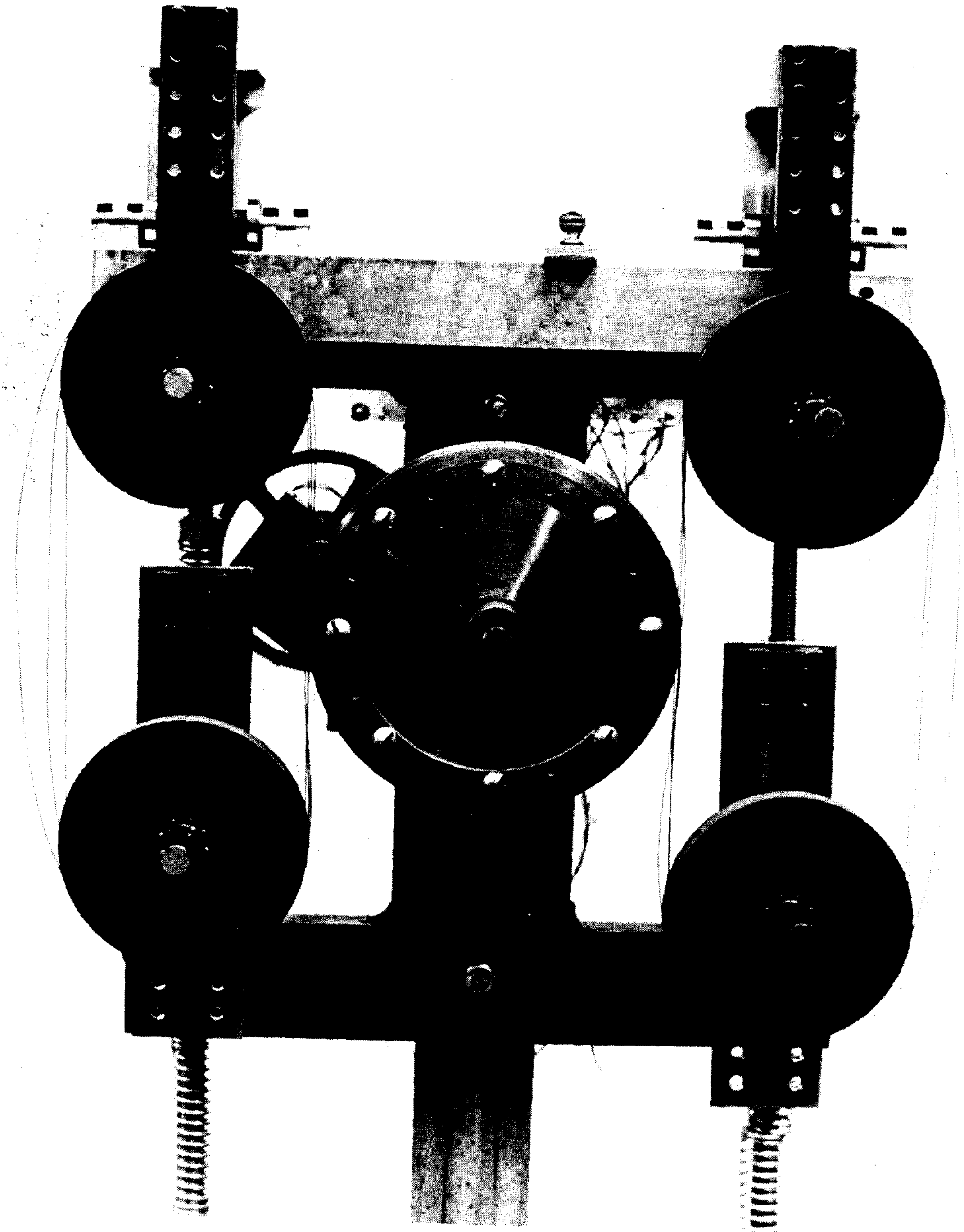


FIG. 9 FIVE-PULLEY ENGINE

Photograph A. NITINOL Engine



Photograph B. Multiple-Wire NITINOL Engine



Photograph C. Hysteresis Brake Tach-Controller