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HIGH OUTPUT PARAFFIN ACTUATORS:

UTILIZATION IN AEROSPACE MECHANISMS

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Introduction

The requirement for actuators and pin pullers on spacecraft is typically met by pyrotechnic actuators, electric motors, spring/silicone damper devices and non-explosive initiators. These approaches are sometimes less than optimum:

1) Pyrotechnic initiators generate shock, are limited in their stroke, raise safety concerns, cannot be fully verified before flight, and are not resetable.

2) Electric motors are heavy, complex, and costly.

3) Spring/silicone damper devices require an initiator (typically pyrotechnic), are heavy, and may require heating of the silicone damper fluid.

4) Non-explosive initiators are heavy, limited in their stroke, cannot be fully verified before flight, and are not resetable.

High Output Paraffin (HOP) thermal actuators have been developed to provide an alternative to conventional aerospace actuators: HOP actuators directly convert temperature changes to useful mechanical work. When fabricated with internal resistance heating elements they provide an electric linear motor. For applications in which slower response times (15 seconds - 20 minutes) are acceptable or preferred, HOP actuators have distinct advantages over conventional approaches.

Table 1: Capabilities of HOP Actuators

- -Resetable: Can be cycled > 10,000 times.
- -Flight hardware can be fully verified before flight.
- -Output force to 4000 N (900 lbs).
- -Stroke to 10 cm.
- -High reliability: One moving part (the actuator rod).
- -Can be fabricated magnetically clean.
- -Gentle smooth stroke.
- -Low power requirement (5-40 watts at 28 volts).
- -Non-explosive: minimal safety concerns.
- -Weighs less than 30 gms
- -Small size

The capability of HOP thermal actuators to convert temperature changes to useful mechanical work also creates a wide variety of potential future aerospace applications in thermal control systems, and systems that can utilize mechanical work from temperature changes or heat (solar) input.

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Development of the High Output Paraffin Actuator

In 1985 Maus Technologies was responsible for a development program to design a non-electronic thermal control system. A key component in the system was a device that could translate small changes in temperature into mechanical work (a thermal actuator) to drive a temperature control assembly. The application required the development of a thermal actuator to provide significant mechanical work (2.5 cm stroke, 80 N output force) from a small temperature change (10° C). Paraffin was selected to provide the motive force for the actuator. This type of actuator utilizes the 15 percent volumetric expansion of paraffin that occurs during the solid-to-liquid phase change. The resulting High Output Paraffin (HOP) actuator is similar in function to the commercial low output (1 cm stroke, 120 N output force) wax pellet actuator (Figure 1) which is well established in the thermal control industry:

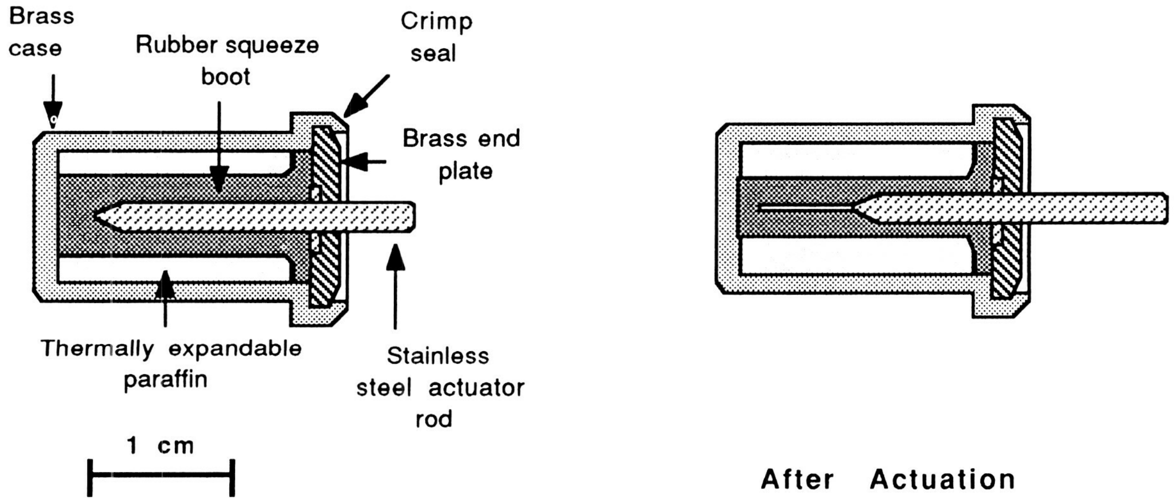

Figure 1: Commercial Wax Pellet Actuator

As the actuator is heated to the actuation temperature, the paraffin begins to melt and expand, creating hydrostatic pressure inside the actuator case. This pressure is translated through the rubber squeeze boot to the actuator rod, causing the rod to extend from the actuator. As the wax cools and solidifies, it contracts, allowing the rod to be pushed back into the actuator.

These commercial actuators are extremely reliable, being capable of cycling 50,000 times in harsh, corrosive environments. The most familiar application is the valve control mechanism utilized in automobile cooling system thermostats.

HOP actuators incorporate a modified squeeze boot design, increasing the mechanical work output, providing strokes to 10 cm and output forces to 4000 N (900 lbs) from the expanding paraffin. A typical HOP actuator is shown in Figures 2a and 2b. This actuator will extend 7.5 cm against a resisting force of 120 N (27 lbs) when heated from 35 ° C to 40 ° C.

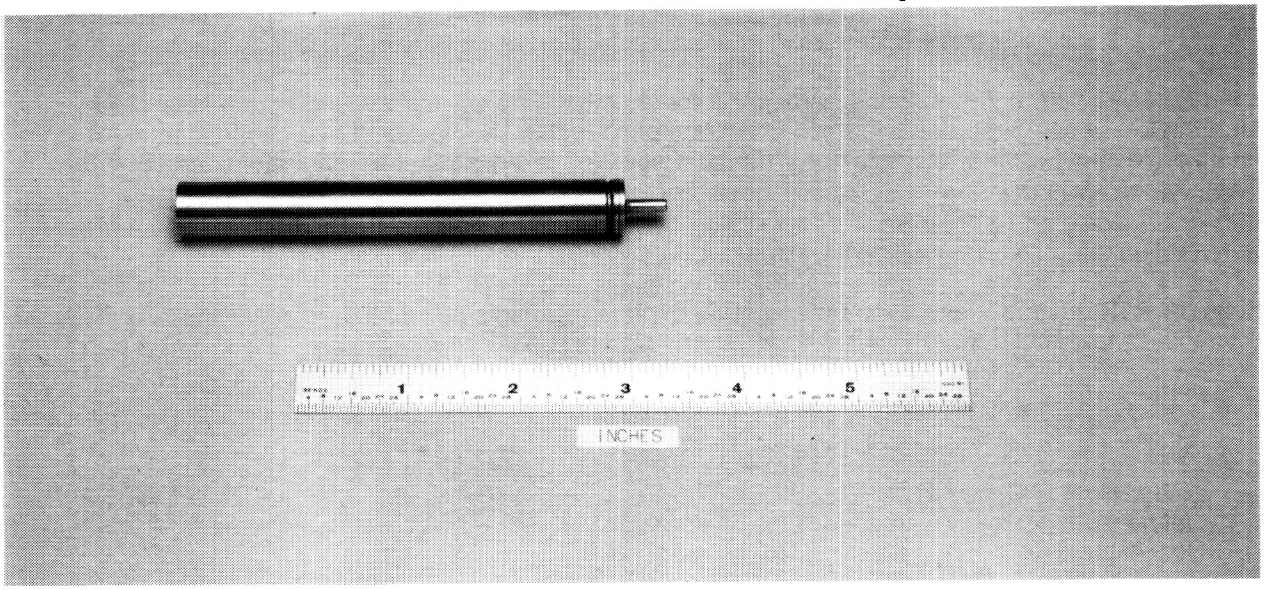

Figure 2a: HOP Actuator Prior to Actuation

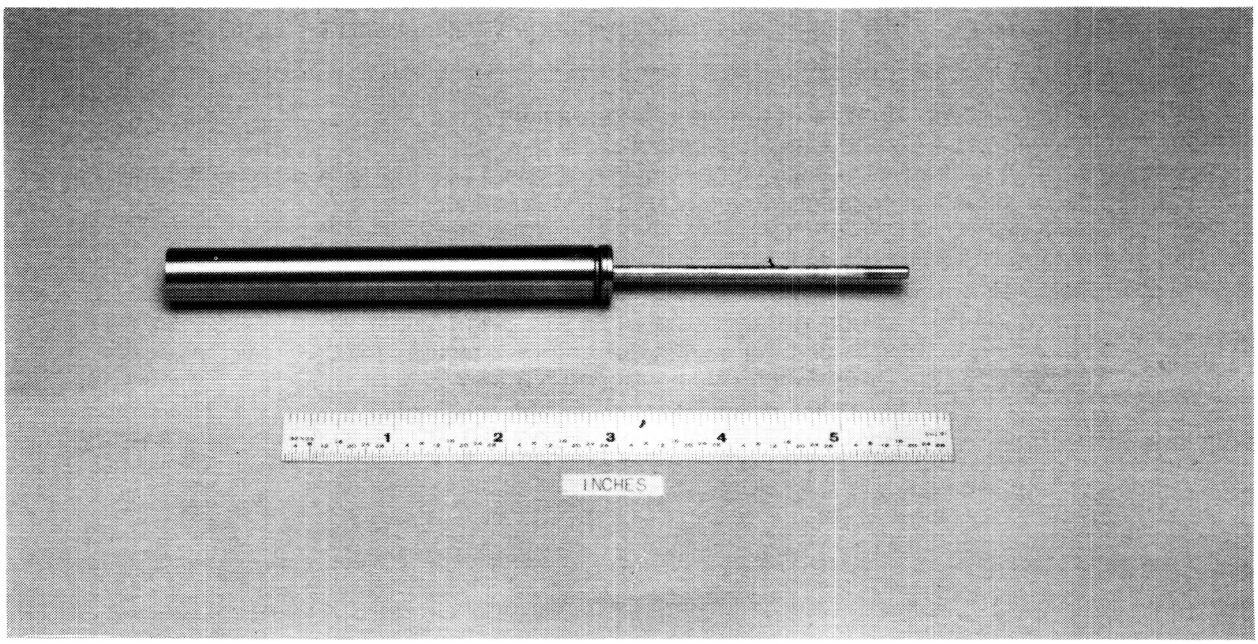

Figure 2b: HOP Actuator After Actuation

The capability of these types of actuators to generate significant mechanical work from small changes in temperature is well suited to aerospace mechanisms, where light weight, simplicity and reliability are prime concerns. As a result, the HOP actuator technology was adapted to the specific requirements of the aerospace industry.

Development of the Aerospace HOP Actuator.

Paraffin actuators are not new to the aerospace community. Mechanisms utilizing commercial wax pellet actuators have been designed and flown on spacecraft. The devices have used external resistance elements to heat the actuator. The most notable example is the magnetometer flipper on the Voyager spacecraft[1]. These mechanisms will be included on future flights (Galileo and the Mars Observer Mission), and the NASA Jet Propulsion Laboratory has an ongoing program to develop a generic launch latch utilizing wax pellet actuators.

Paraffin driven actuators have been utilized in aerospace mechanisms because of inherent characteristics that make them well suited for space applications:

Table 2: Characteristics of Commercial Wax Pellet Actuators

- -Low weight
- -Gentle stroke
- -Non-explosive
- -Non-magnetic
- -Reliable
- -Resetable for up to 50 K cycles
- -High force: To 200 N (45 lbs)

During the past year we have met with the Mechanical Devices group at the Jet Propulsion Laboratory and discussed the development of a paraffin powered actuator designed specifically for the aerospace industry. As a result of these discussions the HOP actuator was adapted for aerospace mechanisms to the following requirements:

Table 3: HOP Aerospace Actuator Design Requirements

- -All external components qualifiable to outgassing requirements
- -Qualifiable to vibration and acoustic requirements
- -Internally heated to provide faster response times, efficient heating, and allowing flexibility in case material selection (thermal conductivity) not a requirement
- -Operating range: - 70 °C to 65 °C
- -Redundant, space qualifiable heating element
- -Flexible design allowing custom fabrication for specific requirements :
    - Fabrication from a wide variety of materials including titanium or stainless steel
    - Fabrication from non-gamma emitting or non-magnetic materials
    - Fabricated with a wide range of custom paraffin formulations

The result of the development program is the Internally Heated (IH) HOP actuator. Characteristics of the actuator are listed in Table 4.

Table 4: Characteristics of IH-HOP actuators

-Useful stroke: Maximum nominal stroke is 10 cm .
-Output force: Maximum nominal output force is 4000 N (900 lbs).
-Actuation temperature (temperature at which motion begins): Can be varied from -20 °C to 120 °C by selection of paraffin type.
-Actuation temperature range (temperature rise necessary for full extension after start of motion): Can be varied from 5 °C to 60 °C by selection of paraffin.
-Response time (power on to full stroke): 15 seconds to 20 minutes. Dependent on power input, amount of thermal isolation, and initial actuator temperature.
-Stroke time (extension begins to full stroke): 5 seconds to 4 minutes. Dependent on power input.
-Efficiency (mechanical power out/electrical power in): Approximately 5% once the actuation temperature has been reached.
-Actuator size: Proportional to stroke times force (Figure 3).
-Actuator weight: Proportional to stroke times force (Figure 3).
-Cycle Life: >10,000 cycles at rated stroke distance and force.

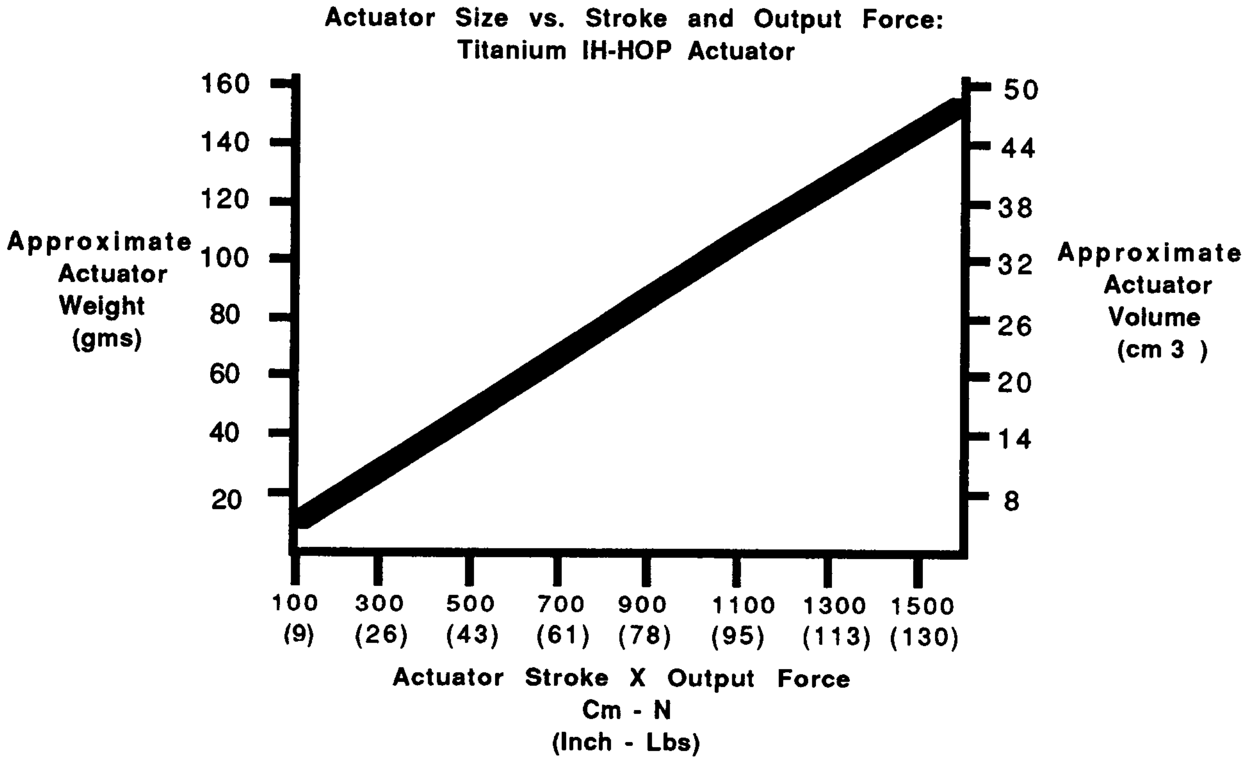

Figure 3: Size and Weight of HOP Actuators

Representative IH-HOP actuators are shown in Figure 4. These specific actuators were designed for mechanisms such as those on the Gamma Ray Spectrometer (GRS) requiring components containing no appreciable nickel, aluminum, chromium or iron. Actuator components are fabricated from commercially pure titanium, resulting in an actuator with total Ni, Al, Cr and Fe at milligram levels. Force-stroke curves, materials of construction, and actuator specifications are listed in Figure 5 and Table 5.

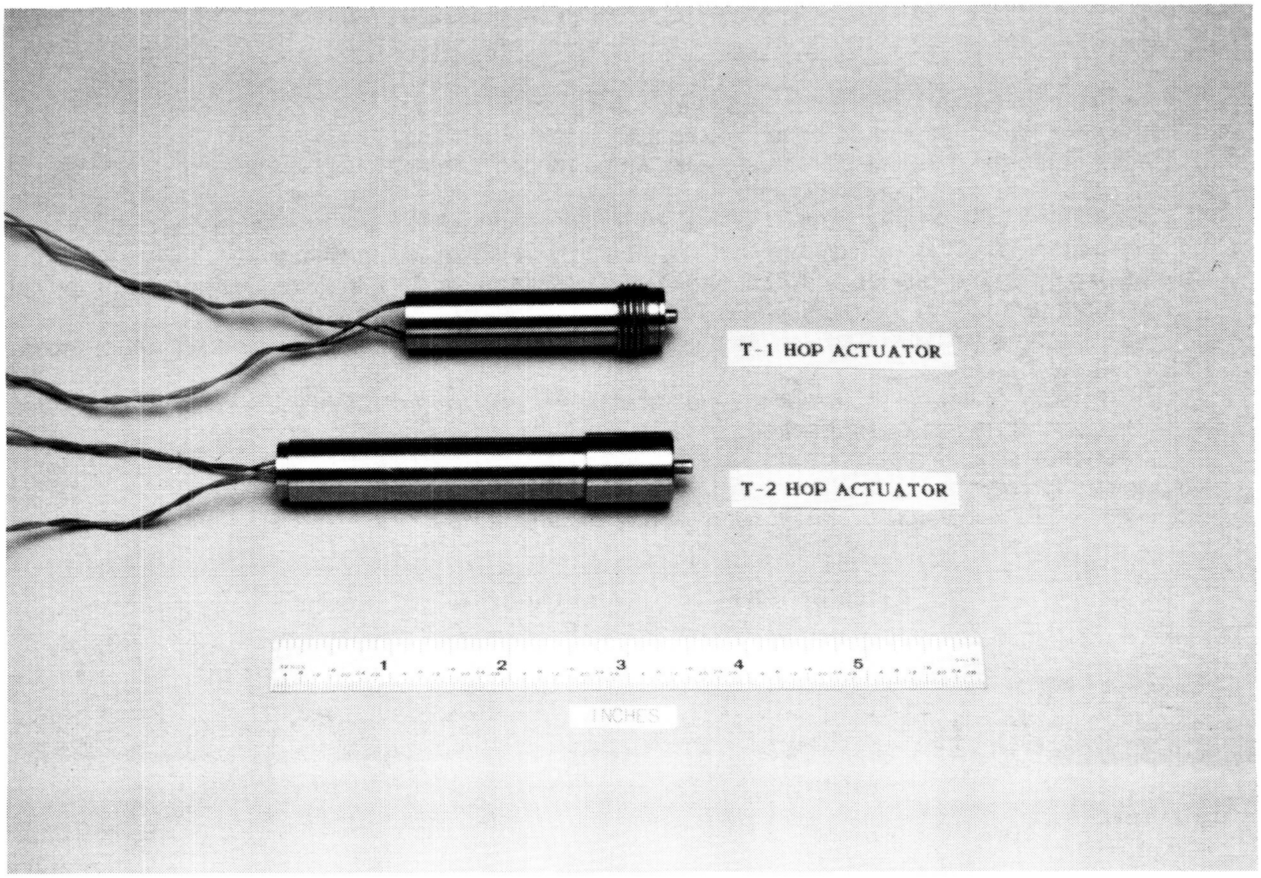

Figure 4: Internally Heated HOP Actuators

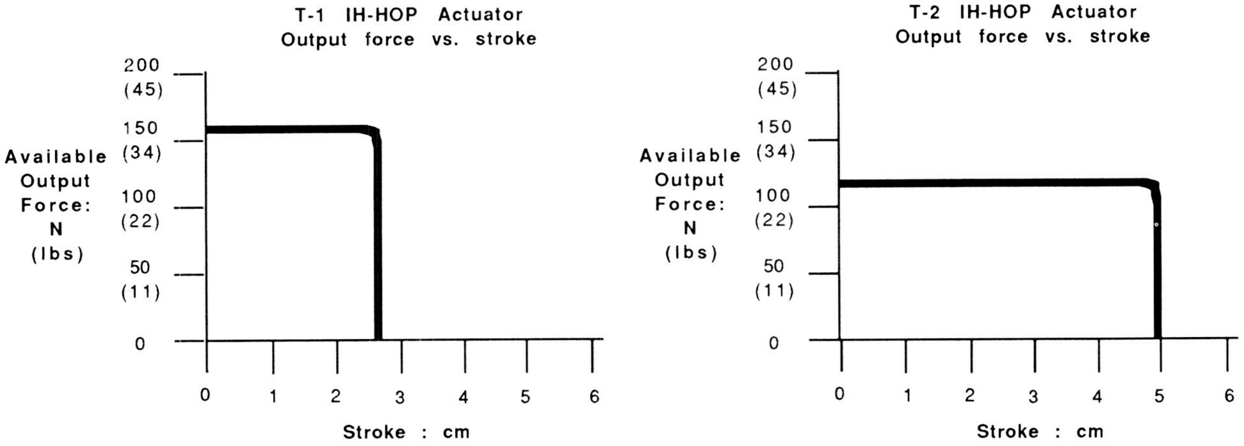

Figure 5: Force-Stroke Curves for IH-HOP Actuators

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Table 5: Specifications for IH-HOP Actuators in Figure 4

	T-1 HOP Actuator	T-2 HOP Actuator
Stroke:	2.5 cm	5 cm
Actuation temperature:	90° C	90° C
Output force	160 N	120 N
Weight	25 gms	42 gms
Unactuated length	5.8 cm	9.0 cm
Power requirement	10 watts @ 28 volts	20 watts @ 28 volts
Response time	2 minutes from 70 F	2 minutes from 70 F

	Materials of construction:
Structural components:	Commercially pure titanium
Heaters:	Fully redundant polyimide film heating elements
Lead wires:	PTFE insulated copper conductor
Lead wire pass-through:	Glass-filled high pressure hermetic seal
O-ring seals:	DuPont Viton B
Squeeze boot:	Castable polyurethane or DuPont Viton B
Paraffin:	Distilled thermally expansive paraffin with suspended copper particles.

Design Detail

A cross-sectional detail of a typical actuator is shown in Figure 6. The design requirements are best discussed by reference to this cross-sectional view:

Operating pressure: The actuator is designed to produce the maximum output force from an internal hydrostatic pressure of 20,700 kPa (3000 psi) generated from the expanding paraffin. The case and seals are designed to withstand a minimum of 48,000 kPa (7000 psi), providing a safety factor of 2.5.

Squeeze boot: The key component in the actuator is the elastomer squeeze boot/seal. Castable two-part polyurethane was chosen as the elastomer for the following reasons:

- Thermoset polyurethanes provide superior outgassing performance (correct stoichiometry produces a "single molecule" component).
- Superior toughness/flexibility.
- Tooling is easily modified for different actuator configurations.

Alternatively, compression molded DuPont Viton B is used for higher service temperature applications.

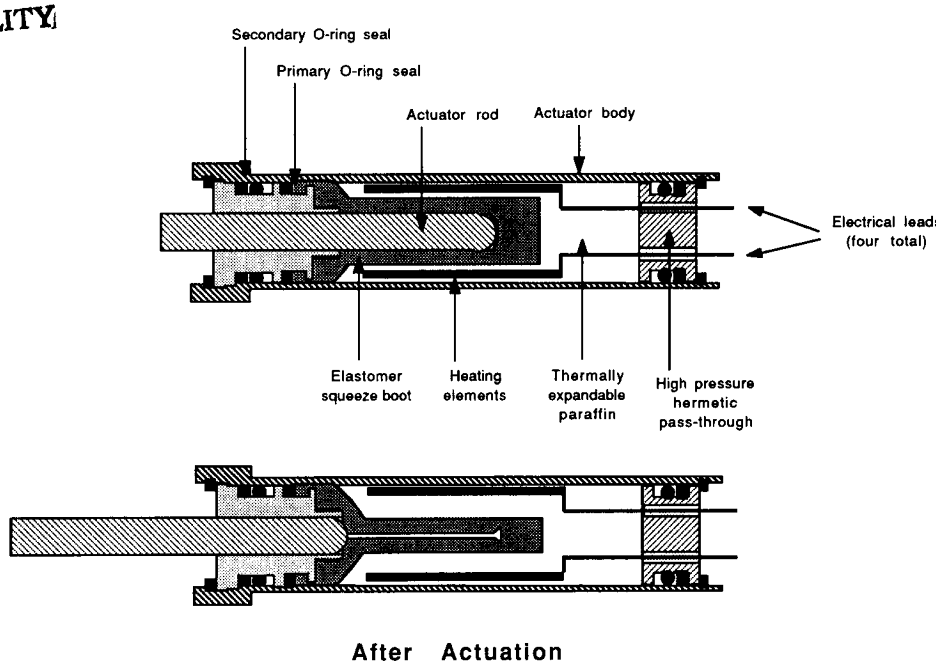

Figure 6: IH-HOP Actuator Cross-Sectional View

<u>Seals:</u> The actuator is sealed by a redundant O-ring type seal: The squeeze boot is fabricated with an integral O-ring which seals between the actuator body and the actuator plug. This is backed up with a standard DuPont Viton O-ring/backup-ring seal. This arrangement provides sealing for internal pressures in excess of 48,000 kPa (7000 psi). Both the O-ring and the urethane boot meet or exceed outgassing requirements according to ASTM E-595-77 (<1 % total weight loss, <.1 % recondensable weight loss at 125 °C, 10^{-6} Torr vacuum).

<u>Actuator body:</u> The actuator body is typically fabricated from either 303 stainless steel or titanium; however, it can be fabricated from any material that will provide the necessary strength to withstand the internal hydrostatic pressure. It is preferable to fabricate the case from relatively low conductivity metals such as stainless steel or titanium to reduce heat loss through the case. These low electrical conductivity materials also minimize Thompson effect currents in the case of material for magnetically sensitive applications.

<u>Expandable paraffin:</u> The actuator is filled with a mixture of copper particles and purified paraffin. The copper is an optional component that increases heat transfer rates in the wax, providing even melting in the actuator. The paraffin is a distilled single or multi component formulation depending on the application. Typical wax expansion curves are shown in Figures 7a and 7b.

Figure 7a is an expansion curve for a paraffin that is used for binary, on-off type actuators that require a quick actuation once the melting temperature is reached. The 15% expansion occurs shortly after the melting temperature is reached. These paraffins are typically a single component formulation.

Figure 7b is an expansion curve for a paraffin that is used for actuators in which actuation over a wide temperature range is desired. In these type of actuators, the temperature of the actuator translates to a specific degree of extension over a wide range of temperatures. These are the types of actuators that can be used for positioning devices or thermal control systems. These paraffins are typically a multi-component formulation.

In both types of actuators the melting temperature of the wax can be varied from -20 °C to 120 °C, depending on the type of paraffin utilized.

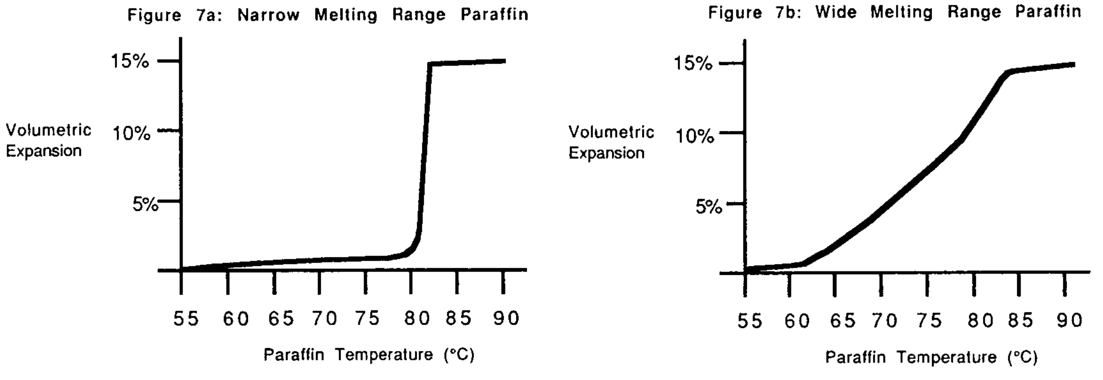

Figure 7: Paraffin Expansion Curves

Heating elements: Two, polyimide film resistance heating elements are used in parallel to provide a redundant heating capability: If one element fails, the actuator will fire with the remaining element. The two elements are mounted midway between the squeeze boot and the actuator case to provide even wax heating. Heating elements are selected on the basis of the application, response time, power requirements, and material requirements. Watt densities in the heaters are currently limited to 12 watts/square cm of element area, which translates to a maximum power input of 30 watts for a 2.5 cm stroke actuator. Satisfactory performance is possible with power inputs as low as 2 watts providing the actuator is thermally isolated.

Pass-through: Power to the internal heating elements is supplied through a four pin high pressure (10,000 psi) glass seal hermetic pass through. The pass-through is sealed to the actuator body with a Dupont Viton O-ring/Backup O-ring seal.

Qualification Issues

Outgassing: All external HOP actuator components are fabricated from materials meeting or exceeding the requirement for 1% total weight loss, 0.1% recondensable weight loss according to ASTM E-595-77. The only actuator component that does not meet that requirement is the paraffin, which is hermetically sealed inside the actuator. For applications that require a higher degree of containment the actuator can be fabricated inside a helium leak tight metal bellows assembly.

Vibration/Acoustic: At the time of paper submittal, vibration and acoustic testing of the actuators is scheduled, but has not been performed.

All internal actuator components are potted in place by the paraffin. Feedback from JPL based on qualification experience with similar devices indicates that the actuators should be qualifiable to extreme vibration requirements.

Vacuum operation: At the time of paper submittal, vacuum testing of HOP actuators is scheduled, but has not been performed.

HOP actuators create work from the pressure differential between the melting wax and the ambient pressure. When operated at atmospheric pressure this differential is approximately 21,000 kPa (3000 psi). Operation in vacuum will have an insignificant effect on this differential, and is expected to have no affect on actuator function.

Thermal cycling: The actuators are internally heated during firing; therefore, the actuator components are warmed prior to actuator function. HOP actuators have been repeatedly operated from -30 °C with no affect on operation. Tests to -70° C are planned.

Actuator Applications

The characteristics of HOP actuators allow the design of more complex, multi-function mechanisms utilizing a single actuator. Specific characteristics that can be utilized in these multi-function mechanism include:

-Repeatability: The mechanism can be designed to repeat a function (such as opening or latching) as many times as necessary. Alternatively, a mechanism can be designed to perform distinct functions on subsequent actuations.

-Positionability: The actuation can be stopped, and the position easily maintained at any point during the stroke, allowing a mechanism to be designed that performs distinct functions depending on length of actuation.

-Long stroke times: A device can be designed that performs a sequence of operations, with distinct delays between operations, as the actuator is fired.

Prototypes of two such mechanisms are discussed below:

Resetable Launch Latch

This mechanism (Figures 8a and 8b) was proposed for the sunshade on the Mars Observer Mission Gamma Ray Spectrometer (GRS), and is operated by the T-1 HOP actuator. The mechanism is designed to allow the sunshade to be unlatched, and then relatched as many as 100 times during the mission. It is a "pin pusher" mechanism, that provides a pin puller type function from HOP actuator extension.

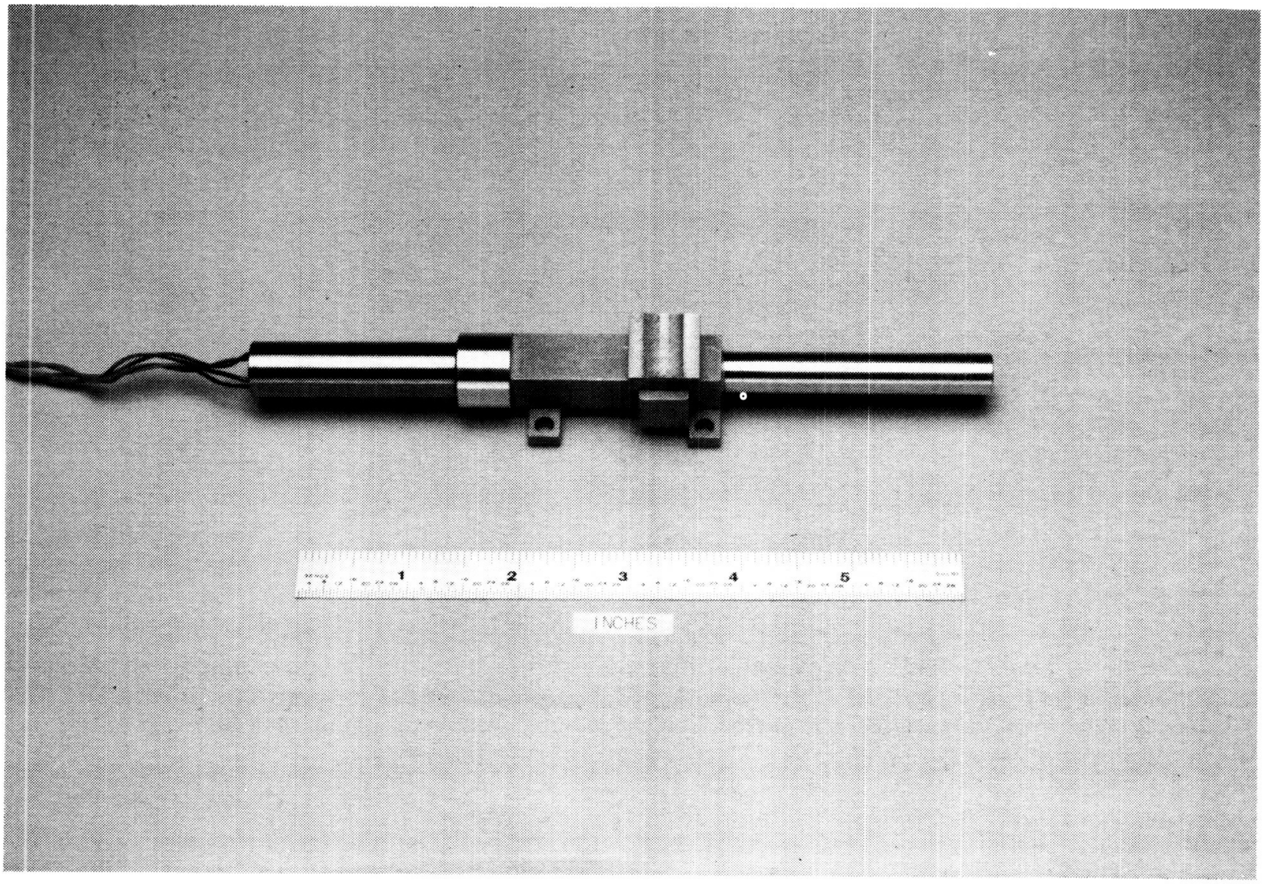

Figure 8a: HOP Actuator Launch Latch

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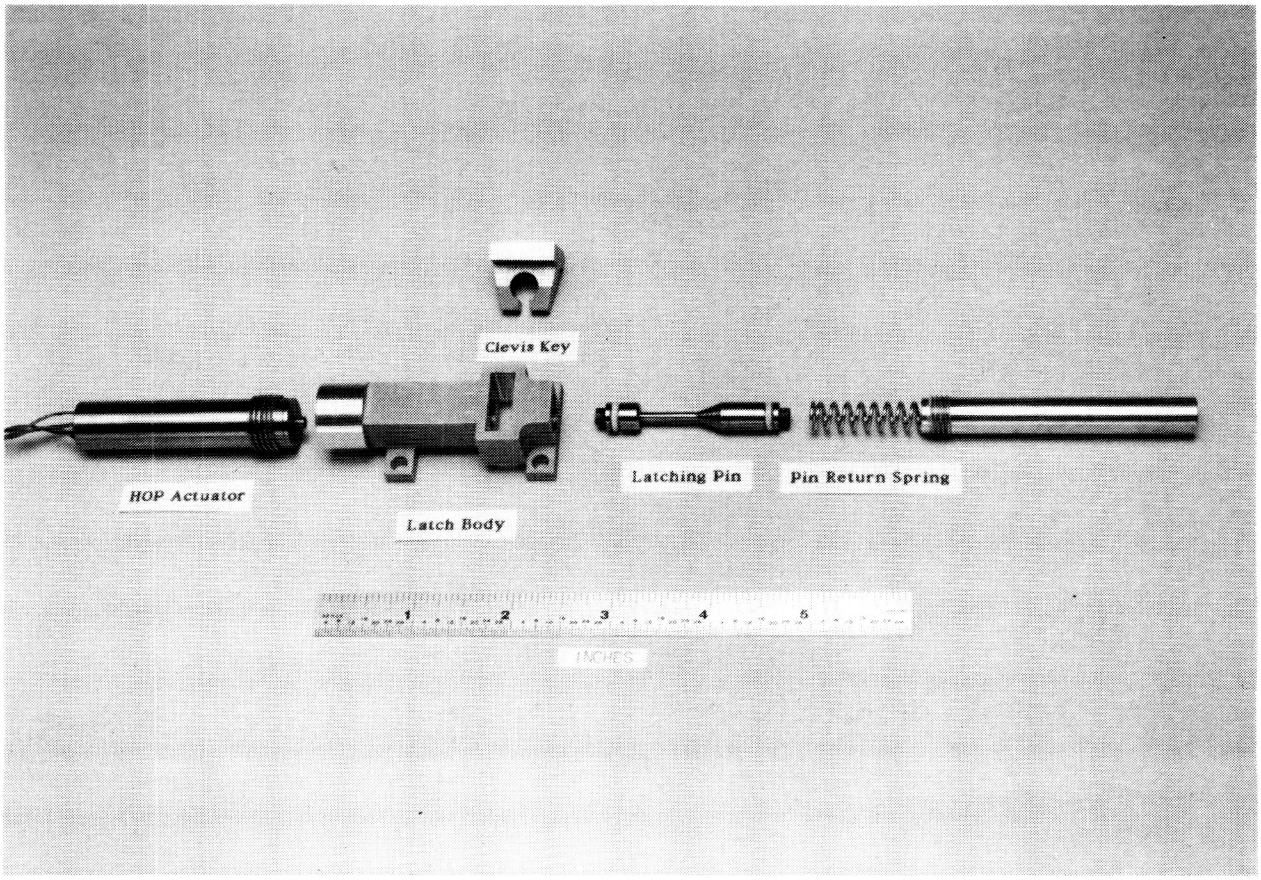

Figure 8b HOP Actuator Launch Latch Components

The sunshade is fabricated with a "clevis key", that mates and latches into an opening on the top of the latch mechanism. The clevis key is a metal tang with a .66 cm ID hole to receive a .64 cm OD pin. , and a .28 cm wide slot below the hole. The latch body contains a latching pin with an OD of .64 cm on one end tapering down to an OD of .25 cm on the opposite end.

In the unactuated position (during launch), the clevis key is held in place by the large diameter portion of the pin, which is in turn held in place by a return spring. The mechanism is unlatched by energizing the actuator, which extends against the latching pin. The pin moves (compressing the return spring) until the small diameter portion of the pin is pushed into the clevis key, releasing the latch (the .28 cm slot allows the clevis key to be pulled from the latch around the .25 cm pin).

The mechanism is relatched by first energizing the actuator, mating the clevis key with the latch body, and then allowing the actuator to cool. As the actuator cools, the return spring pushes the pin back to the original position, locking the clevis key in place.

Sunshade Operator (single actuator/multi-function mechanism)

As an alternative to a discreet latching mechanism and sunshade opening mechanism on the GRS, a single actuator mechanism was proposed to operate both the sunshade and latch. The function of this mechanism illustrates the multi-function capability of HOP actuators. The mechanism will operate the GRS sunshade in the following sequence:

1) Unlatch sunshade.
2) Open sunshade to one of two positions.
3) Latch and hold sunshade in position with no power input.
4) Close door and relatch.
5) Repeat as many as 100 times.

This is accomplished with a single T-2 HOP actuator providing 120 N (27 lbs) of force over a 5 cm stroke . The mechanism is shown in Figures 9 and 10.

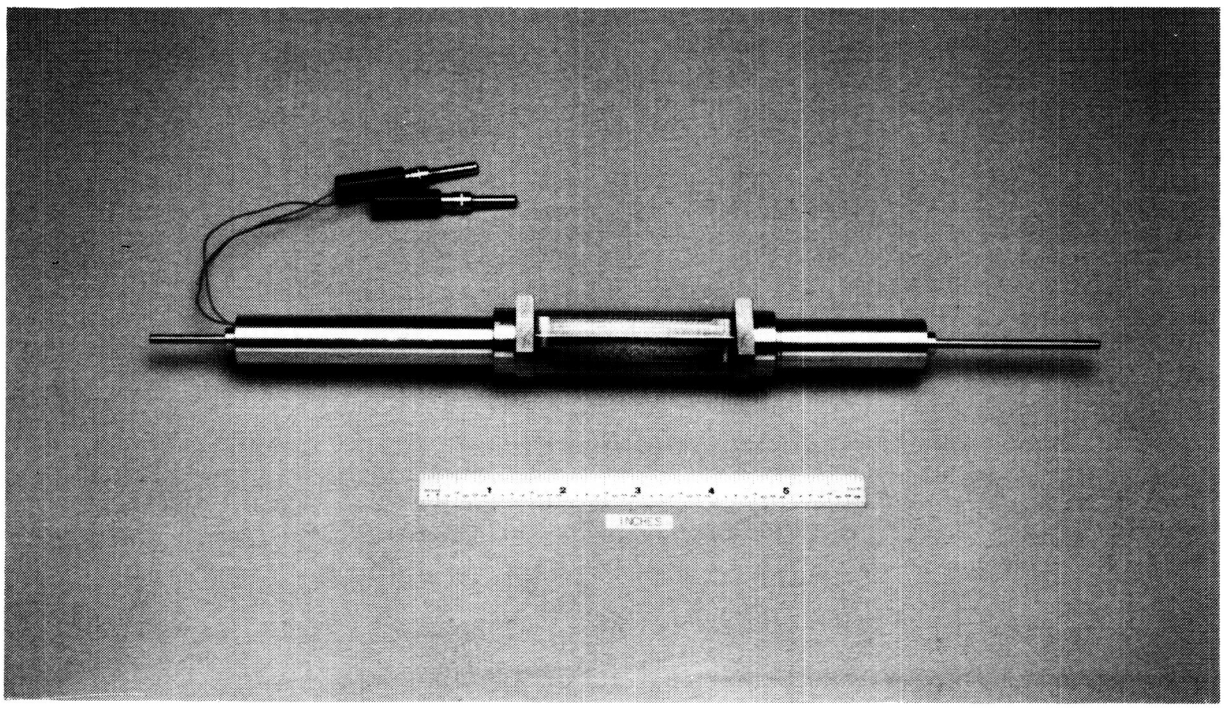

Figure 9: Proposed HOP Actuator GRS Sunshade Actuator

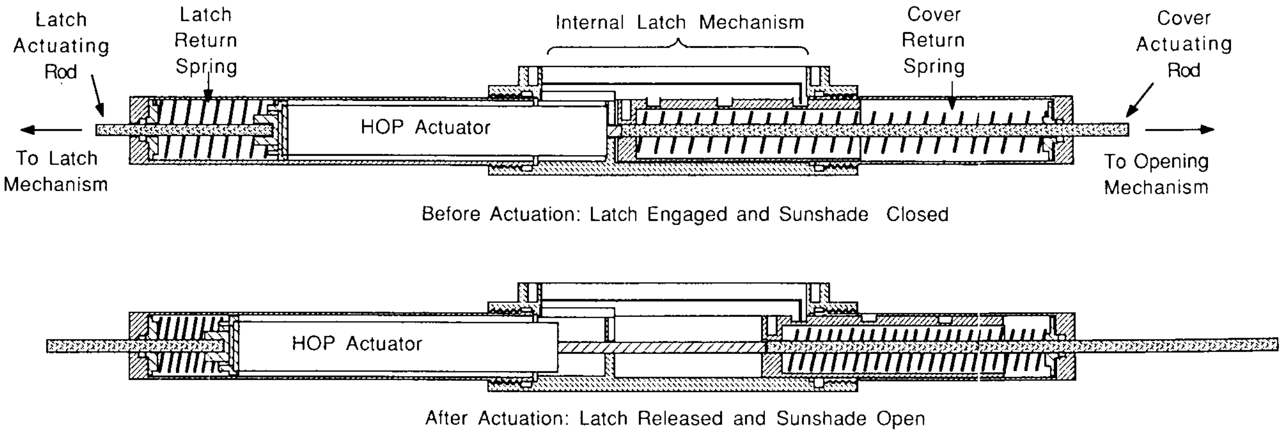

Figure 10: Proposed HOP Actuator GRS Sunshade Operator (cutaway view)

The HOP actuator in the mechanism is located between two bias springs: the latch return spring, and the cover return spring. The springs are balanced so that on actuation, the following sequence occurs:

1) The linear actuator extends, compressing the latch return spring, extending the latch actuating rod 2.5 cm with 45 N (10 lbs) of force, which unlatches the cover (sunshade).

2) The actuator continues to extend against the cover return spring, extending the cover actuating rod as much as 2.5 cm with 45 N (10 lbs) of force, opening the sunshade.

3) When the sunshade is in the proper position, power to the actuator is turned off. The internal latch mechanism is a mechanical binary device that latches the door actuating rod (and thereby the sunshade) in the proper open position as the actuator contracts (in a similar manner to the latching mechanism in a ball point pen).

When the actuator is energized the subsequent time:

4) The latch actuating rod extends, readying the latch.

5) The actuator then continues to extend against the internal latching mechanism, releasing the mechanism.

6)Actuator power is turned off. As the actuator cools it contracts, allowing the cover actuating rod to contract, slowly closing the sunshade.

7) After the sunshade closes, the actuator continues to contract allowing the latch actuating rod to contract, latching the sunshade.

First Scheduled Flight

The first aerospace mechanism to utilize HOP actuators will be a gimble caging device being designed by Aeroflex Labs for a satellite to be launched in the fall of 1988. The mechanism utilizes two IH-HOP actuators providing 220 N (50 lbs) of force over a 1.25 cm stroke to cage and uncage a gimble. The mechanism will be used for both pre-launch testing, and gimble uncaging after launch.

Future Applications for HOP Actuators

Initial interest has focused on applications in which HOP actuators are used as an alternative to pyrotechnic actuators. However, the capabilities of the actuators extend beyond short stroke, single actuation applications. Potential future applications fall into two distinct categories :

- Electrically powered linear motors: The actuator works in conjunction with a resistance heater providing the necessary heat for actuation:

  Some potential applications:

  As an alternative power source (to pyrotechnic actuators, spring/silicone dampers, and small motors) for pin pullers, cable cutters, deployment and latching/unlatching devices, and equipment covers.

  An HOP actuator working in series with a piezoelectric positioning device would provide a "solid state" long stroke positioning platform with micro-positionability.

- Thermal control systems: The actuator provides mechanical work to drive a control system, as a result of temperature changes in the surrounding environment.

  Some potential applications:

  High force (2000-4000 N) actuators have excellent stiffness, and can provide temperature dependent compensating forces for thermally produced strains in large space structures. These compensating strains could be generated by an electrically heated actuator working with a control system, or they could be directly generated by temperature changes in the structure itself.

  High force HOP actuators working in conjunction with a cooling and heating source would provide hydraulic type power that could be utilized for space tools such as riveters, clamps and jacks. The heating source could be solar radiation, and the cooling means could be radiation to space, providing solar powered space tools.

For spacecraft solar collection devices, the actuators provide a method for aiming both flat-plate and concentrating systems. By combining HOP actuators with a shading device that selectively inselates the actuator (depending on collector position), accurate solar tracking can be provided without electronics.

HOP actuators can provide non-electronic proportional temperature control for fluids or radiators: Perturbations in system temperatures are translated to mechanical work that can directly operate control devices such as valves or louvers.

Conclusion

The High Output Paraffin thermal actuator provides an alternative device to the mechanism designer requiring significant mechanical work from a small, compact, reliable component. The work can be generated from heat provided by internal electrical resistance elements, or from environmental temperature changes.

In the internally heated configuration, the advantages over conventional electrically powered actuators can be significant: low weight, resetability, full verification before flight, high force, long stroke, gentle stroke and flexibility in materials of construction. For thermal control applications, the actuators provide a flexibility of design unavailable in alternative thermal actuator technologies.

With the strong industry emphasis on reliability, safety and simplicity, we expect HOP thermal actuators to be developed for a wide variety of future aerospace applications.

Acknowledgement

The author wishes to acknowledge and express his appreciation to Robert int'Hout of the NASA-Jet Propulsion Laboratory Mechanisms Support Group, who provided support and guidance during the development of the HOP aerospace actuator. Adaption of the technology to the requirements of the aerospace industry would have been a much more difficult process without his frequent and invaluable assistance.

References

1. Stange, William C.: The MJS-77 Magnetometer Actuator. 11th Aerospace Mechanisms Symposium NASA-GSFC, April, 1977.