ThermOmegaTech®
Aerospace & Defense Division

Thermal Actuators in Aerospace and Defense: Enhancing Efficiency and Reliability in Critical Systems

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November 2024

Executive Summary

This whitepaper aims to educate readers about thermal actuators, how they function, the different types, and how they can be used in the aerospace and defense industries. The paper begins by comparing thermal actuators to other types, such as hydraulic, pneumatic, and electromagnetic actuators, highlighting thermal actuators' unique advantages in weight, simplicity, and energy efficiency.

It explains the operating principles of thermal actuators, which use paraffin wax to deliver controlled, repeatable motion as the temperature fluctuates. Various actuator types are discussed, each with specific benefits for high-cycle, high-force, or precise-stroke applications.

The document outlines vital installation guidelines to ensure optimal actuator performance, covering factors like correct alignment and temperature limitations. The paper concludes by examining thermal actuator applications within aerospace and defense, ranging from freeze and scald protection to liquid cooling and environmental temperature control. It underscores their reliability, compact design, and adaptability across mission-critical operations.

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1.0 OVERVIEW OF THERMAL ACTUATORS

Thermal actuators, also referred to as thermostatic actuators, are devices that use the constrained thermal expansion/contraction of certain materials to exert force on adjacent components. They convert thermal energy into mechanical motion. The action created by the force developed in the thermal actuator may be of the open/close, push/pull, or load-motion type. Such actuators can control the flow of fluids or gases or the motion of mechanical components in response to temperature fluctuations.

Thermal actuators are used in a variety of applications. Examples of some of their uses include mixing and diverting fluids, temperature control, regulating airflow, high-temperature shutoff, freeze protection, and scald protection.

Thermal actuators are commonly used for mixing and diverting fluids, temperature control, regulating airflow, high-temperature shutoff, freeze protection, and scald protection.

One of the first thermal actuators was based on the differential expansion of the two metals in a bonded bimetallic strip. The strip's mechanical response to temperature change could be used to open or close electrical contacts. Today's thermal actuators are more complex. Most include temperature-sensitive material such as wax, bimetallic strips, or shape memory alloys, a housing, and a piston or plunger.

The temperature-sensitive material that provides the actuation force could be any type that changes volume when exposed to temperature changes. It could be a gas, a liquid, or a solid. The most common material used is wax, which undergoes a large volume change when transitioning from solid to liquid. Actuators that use wax as their active material are called "wax motors" or "wax thermostatic elements."

1.1 Thermostatic Actuators vs. Other Actuators

While thermostatic actuator's function is based on the principle of thermal expansion and contraction of a material to generate movement, other actuation technologies function by making use of other mechanisms [1]. Each actuator type operates differently and uses a different power source to create motion, or an action, in the device. The type of actuator used in any given application depends on the application's requirements. These may include the amount of force, the durability requirements, and the response time [2].
Here is an overview of the different actuator types by power source:

1.1.1 Electromagnetic Actuators

These types of actuators make use of electric energy and magnetic fields to actuate a device. They are very common actuation devices.

1.1.1.1 AC and DC Servo Motor Actuators

These devices are powered by electrical energy that is converted into mechanical energy and comprises a feedback unit, motor, control unit, and, in some cases, a gearbox/shaft. The shaft rotates when a voltage is supplied to the servo motor terminals [3]. The shaft position, voltage, and current levels are monitored continuously. The controller is used to track the speed of the motor and compare it to the target speed. Voltage and current levels are then adjusted to match the actual speed with the target speed [4]. Servo motors typically only make 90° turns in either direction with a total movement range of 180° [5]. Servo motor actuators are used in saws, mixers, pumps, fans, and related applications.

1.1.1.2 Solenoid Actuators

These devices make use of electromagnetism to convert electrical energy into mechanical motion. A solenoid is essentially an electromagnet that is made up of a conductor coil wound around a ferromagnetic core and a moveable plunger [4]. The iron core is fixed so that it cannot move. When current flows through the wire, the coil acts as an electromagnet. It attracts the core in one direction, compressing the return spring.

When the solenoid is not energized, meaning the power supply is removed, the spring will push the core back to its original position. The actuator's strength, among other things, will depend on the number of loops in the coil. Solenoid actuators are typically connected to valves.

1.1.2 Fluid-Driven Actuators

Fluid-driven actuators use liquid (hydraulic) or gases (pneumatic) to generate motion for actuation.

1.1.2.1 Hydraulic Actuators

These are the most widely-used linear actuators. However, although not as common, hydraulic actuators can also create rotary motions. They make use of liquids to produce mechanical work. They do this by using fluid compression and then converting that into motion. The fluids used in these actuators are almost always oil due to its incompressible nature. This makes it easy for oil to transfer large amounts of energy by volume [6]. These actuators are typically used in situations that require stable levels of high thrust or high forces in a small area [4]. One of their primary benefits is their speed.

1.1.2.2 Pneumatic Actuators

These devices are similar in construction and design to hydraulic actuators. However, energy from pressurized gas or compressed air is used for actuation instead of using liquid as the driving force to produce mechanical motion [7]. These devices have a compact footprint but offer high force and fast speeds. They are ideal for applications that need precise motion. They can be either linear or rotary [4].

1.1.3 Mechanical Actuators

These actuators are generally used to interconvert linear and rotary motions in machines [4]. Examples are gears, crankshafts, pulleys, and chains [1], [4].

1.1.4 Other Types of Actuators

The actuators mentioned here are not an exhaustive list. Other actuators include stepper motors, piezoelectric, and supercoiled polymer actuators [4]. Though they are less common, each is useful in specialized applications.

1.2 Wax Motor Actuator Operation

At ThermOmegaTech, we manufacture thermal wax actuators. These actuators operate using a sealed capsule filled with a paraffin wax compound that expands when heated and contracts when cooled. When the wax melts and expands, it exerts pressure on a diaphragm or piston to create movement.

During phase transitions between solid and liquid, paraffin wax undergoes a predictable volume change that can be used to drive a piston a precise distance. The relationship between temperature and piston movement in an actuator is captured in a stroke curve. Factors such as actuator design, application load, prior service, and wax selection can influence this behavior. The phase transition is marked by heating and cooling phases, resulting in the piston's extension and retraction.

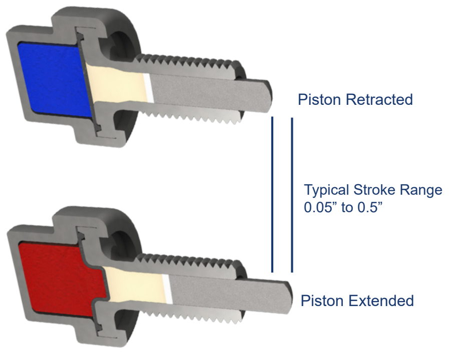

Figure 1: Hot and Cold Positions of a Wax Motor

This thermally induced motion is reliable and repeatable, providing precise mechanical control. The mechanism responds automatically to temperature changes: as temperatures rise, it can close valves or latches; as they fall, it can open them. Wax motors typically have stroke lengths ranging from 0.05 to 0.5 inches and operate effectively within temperature ranges of 15°F to 300°F.

Most wax motors exert extending forces between 5 lbs and 150 lbs, with some specialized actuators capable of delivering over 1000 lbs of force. For situations requiring these higher force outputs or longer stroke lengths, custom actuators may need to be designed to meet those specific needs.

Since wax is essentially incompressible, its expansion can generate significant force. Load changes will have little to no effect on the actuating temperature of wax motors. Actuators are designed to adjust travel distance and manage load, allowing for predictable cycles. They are designed to withstand many high-pressure cycles from wax expansion. Wax selection is used to alter the transition points of the phase change. To some degree, it can also be altered by blending waxes.

1.2.1 Wax Behavior in Thermal Actuators

Figure 2 illustrates a simplified stroke curve to explain the principles of the phase change process. In practice, waxes behave in various ways, and products can be designed to accommodate several types of waxes.

This flexibility allows for temperature modifications in applications such as valve families. Additionally, standalone actuators can be tailored with different waxes, and stroke curves can help customers select the optimal blend for their application.

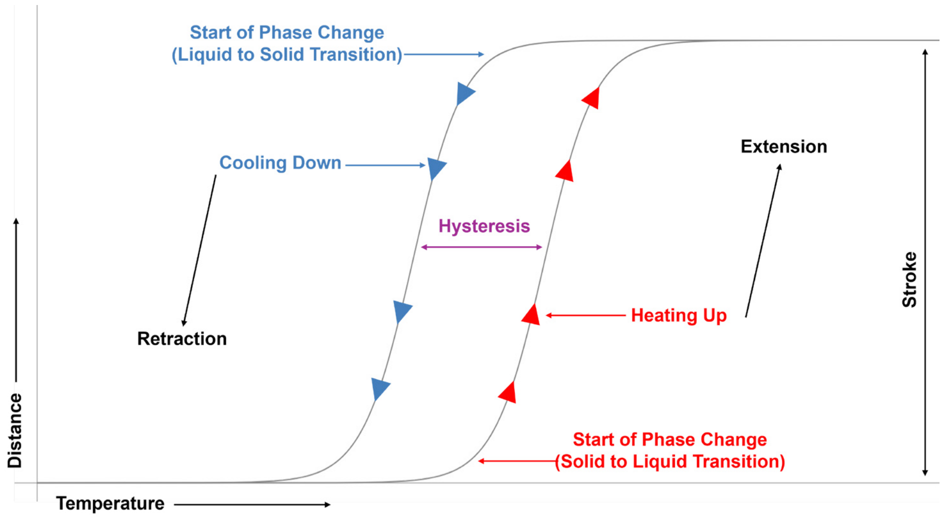

Figure 2: Stroke Curve

1.2.1.1 Key Considerations for Wax Behavior

1. **Hysteresis:** Paraffin waxes naturally exhibit hysteresis, a temperature lag of 5–10°F between phase transitions. Wax blends with a larger hysteresis width react more slowly to cooling temperatures, making the actuator less sensitive to changes. Conversely, a smaller hysteresis width results in a more sensitive actuator that responds more quickly to environmental changes. This behavior is a non-tunable feature of the selected wax, so design considerations need to be made to account for the differences.

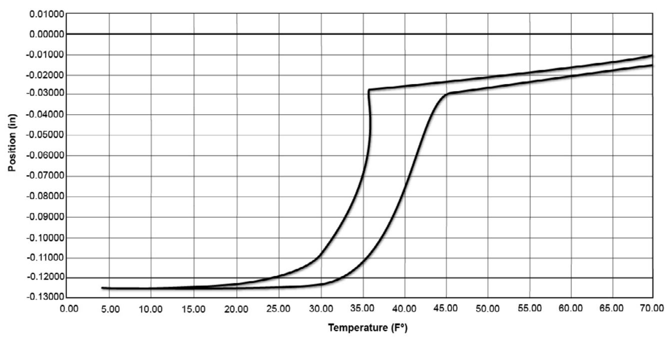

Figure 3: Wax Behavior - Large Hysteresis

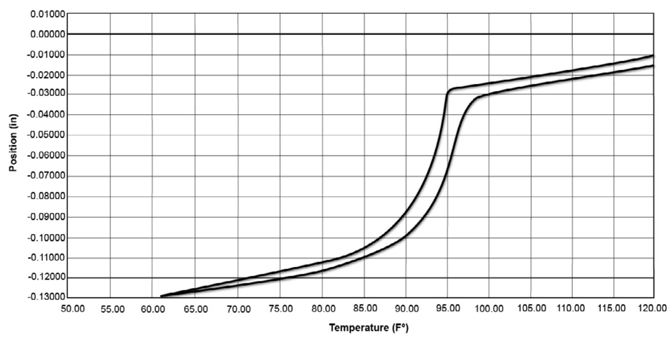

Figure 4: Wax Behavior - Small Hysteresis

2. **Temperature:** Moderate-temperature waxes frequently exhibit a “double knee” phenomenon, which manifests as a multi-stage phase transition that can complicate a design. Similarly, high-temperature waxes (240°F and above) can present design challenges due to their wide hysteresis band of 25°F within the active range. Understanding these behaviors is essential for making the necessary adjustments in product design.

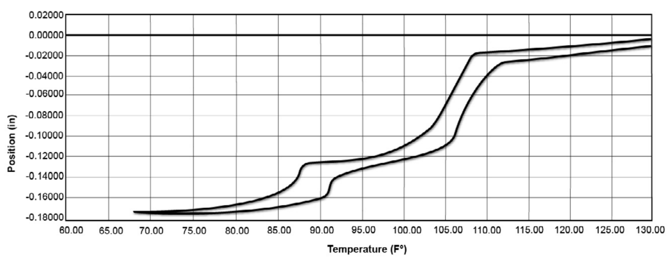

Figure 5: Wax Behavior - Double Knee

3. **Linear Expansion:** After the main expansion phase, wax will continue to expand, affecting over-travel scenarios and maximum temperature evaluations.

1.2.2 Stroke Curve of Thermal Actuators

Stroke is traditionally defined as the total distance an actuator's piston will travel within a 10°F range of the wax's melting temperature. Several factors influence this distance, including wax behavior, production variation, and stroke degradation. When designing a product that incorporates an actuator, it's crucial to consider how the total stroke may change throughout its lifespan.

For example, friction buildup can widen the hysteresis band, reducing the stroke within the original range while maintaining it over a broader temperature span. In the case of the TOT-10 design in Figure 6, stroke loss was approximately 5-10% over the product's lifespan.

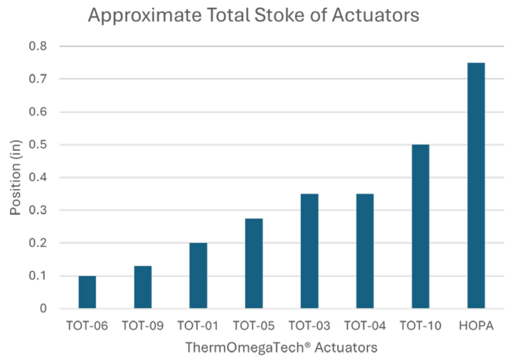

Figure 6: Total Stroke of Actuators

While total stroke provides a quick overview of the approximate travel over a standard temperature range, using a stroke curve and a stroke degradation model is often more effective for describing actuator behavior. This approach is beneficial when designing or selecting a standalone actuator.

Actuators are typically specified by their stroke over a temperature span, but it is also important to account for stroke loss over time. This consideration helps ensure accurate performance predictions. Additionally, application conditions, such as load, can influence outcomes, necessitating thorough cycle testing to gather reliable data. This testing is resource-intensive but essential for understanding actuator performance over time.

1.2.3 Stroke vs. Actuator Response Time

Response time is the duration required for an actuator to achieve a specified stroke target. Several factors, including the temperature gradient, actuator materials, age of the actuator, load conditions, wax selection, and exposure to specific fluids, influence this metric. Due to these variables, response time is often presented as an envelope of possible timeframes, as it can vary significantly.

Design variables offer opportunities to manage response time, allowing for either acceleration or deceleration as needed for different applications. Paraffin wax typically has low thermal conductivity, but incorporating materials like copper into the wax can enhance heat transfer, resulting in a more responsive actuator.

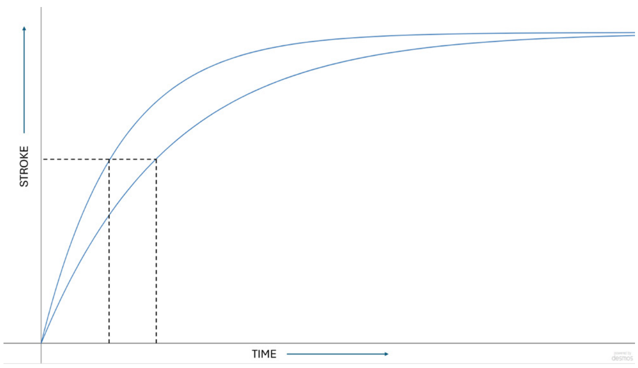

Figure 7: Stroke Vs. Response Time

While stroke curves and response time plots illustrate the behavior of an individual stroke, reliability modes are utilized to predict how many cycles an actuator can endure before failure. ThermOmegaTech® collects reliability data by cycling actuators under application loads until they reach the point of failure. While accelerated testing methods can shorten testing durations, establishing a direct correlation to real-world performance is essential. This connection is a key area of ongoing research for the company.

The number of cycles to failure is recorded and analyzed using standard reliability modeling techniques, such as the three-parameter Weibull distribution with maximum likelihood estimation (MLE) parameter fitting. These models enable the company to assess risk, predict failures, and proactively address product life-cycle issues.

Reliability models are crucial for predicting maintenance cycles and evaluating risks related to mission success. Aerospace customers often require this information in their specifications, and these models are developed as part of the design process when time allows for thorough cycle testing.

1.3 Internal Structure of Different Wax Thermal Actuator Types

Wax thermal actuators have different internal structures based on performance, size, and stroke requirements. The internal structures of these actuators come in three common types:

1.3.1 Squeeze-Push Type Thermal Actuator

The squeeze-push thermal actuator, also sometimes called the rubber-boot thermal actuator, is an actuator in which the piston parts that would otherwise be in direct contact with the wax are enclosed in an elastomeric “bag or boot.” When the wax heats and expands, it exerts pressure on the bag [8],[9]. The bag exerts force both axially (push) and radially (squeeze) on the piston. This means that more actuation force is required, but sealing and piston alignment are improved, increasing actuator durability.

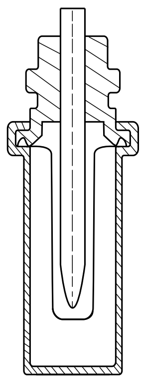
Figure 8: Rubber-boot Actuator

The piston is moved as the wax expands and then ‘squeezes’ or pushes it to displace the piston outward with a temperature rise.
Since there exists a frictional force between the piston and the elastomer bag and some of the force is being bled off in the radial direction instead of all being directed axially, this type of thermal actuator will require a higher external force to return the piston to its original position. A return force, like a spring, returns the piston to its “cold position” when the temperature decreases [9].

These actuators are ideal for requirements where longer strokes are preferred and the open/close temperature is not as critical, such as a car thermostat.

1.3.2 Plunger-Type Thermal Actuator

The plunger-type (or sliding seal-type) thermal actuator typically has a moderate cycle life of around 30,000 cycles in applications that necessitate full-stroke-per-cycle operation (usually ½ inch and longer), such as for diverting fluids. In contrast, this actuator can achieve significantly higher cycle life in applications requiring shorter strokes-per-cycle, such as fluid mixing, where the mixed outlet temperature must be kept at a predetermined setpoint.

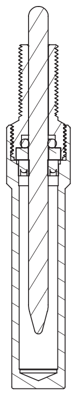
Figure 9: Sliding-seal Actuator

This variation in performance highlights the actuator’s adaptability to different operational requirements. It is also well-suited for high-force applications, such as those involving High Output Paraffin Actuators (HOPAs), which are typically only limited by the available envelope capacity requirement.

This actuator type offers the longest stroke of the three main types. It can deliver the highest actuation force because the plunger mechanism is not limited by an elastomer pocket or diaphragm [8]. Unlike diaphragm-actuated devices that distribute force over a larger area, the force and stroke length depend on the plunger's geometry. This design also occupies less space for a given stroke length.

The piston, or plunger, is positioned directly inside a wax-filled cup in a plunger-type thermal actuator. In terms of operation, the plunger/piston is moved by changes in temperature that cause the wax to expand or contract as it changes phase from solid to liquid and back when heated or cooled [8],[9]. If the temperature of the wax rises, the wax will expand, which will push directly on the piston causing it to move outward.

Similarly, when there is a drop in temperature, this will cause the wax to contract, returning the piston to its original position, often with the help of a return spring [9]. Because the wax is held in place only by the seal between the cup and the plug, sealing can be a challenge [9]. Despite its advantages, this type of actuator faces limitations in terms of size and length constraints and is not ideal for applications requiring high cycle frequencies.

The mechanisms of stroke loss differ between diaphragm and sliding seal designs. Sliding seal actuators are known to leak small amounts of wax with each cycle, which can accumulate over the actuator's lifespan. In contrast, diaphragms retain their wax but often experience a phenomenon known as "settling," which is still not fully understood. We can quantify and account for its effects, but the underlying causes remain to be fully explored.

1.3.3 Flat-Diaphragm Type Thermal Actuator

The flat-diaphragm or molded-diaphragm actuator is the most common type of wax thermostatic actuator. It has a high cycle life of 100,000 cycles or more, depending on the application, and moderate stroke distances of up to approximately ½ inch. This actuator is ideal for applications with relatively lower force requirements (typical range is 10 – 60 lbf) but can also be adapted for high-force applications involving High-Output Paraffin Actuators (HOPAs), but it may require a custom diaphragm and plug to accommodate the increased applied load.

A flat-diaphragm actuator typically consists of a closed cup, diaphragm, wax, and a piston guide. When the temperature increases, the wax will melt, expand, and push against the diaphragm, which pushes against the plug [9]. The movement is transmitted through the plug to the piston. The guide's main function is to ensure the piston travels smoothly in the correct direction. It also concentrates the force of the diaphragm on the piston [9]—the diaphragm experiences elastic (recoverable) deformation.

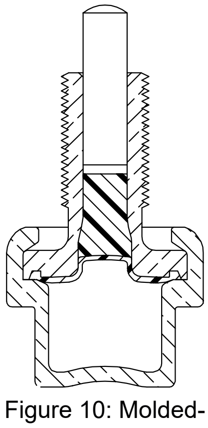

Figure 10: Molded-diaphragm Actuator

When the system cools down, a retraction force, such as a spring, returns the piston to its original position. The best option to maximize reliability is to use a custom-molded diaphragm and plug coupled with conservative stroke expectations. The majority of the thermal actuators ThermOmegaTech® designs are flat-diaphragm types.

2.0 GUIDE FOR THERMAL ACTUATOR INSTALLATION

Thermal actuators must be installed correctly to function properly. It's important to adhere to the manufacturer's instructions that come with your actuator. However, some common mistakes can be avoided. To avoid these common pitfalls, these guidelines should be followed to ensure that your actuator functions as intended:

A. Minimal retraction force: Thermal actuators will extend when heated, but they will not retract when cooled without a restorative force to push against the piston. If the minimal load is applied, it will ensure that the device has smooth extension and retraction during operation.

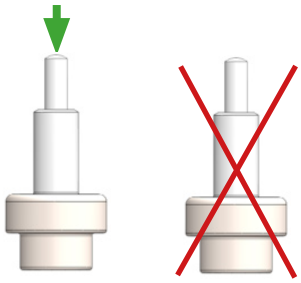

Figure 11: Min. Retraction Force

B. No side loading: Loading must be directed along the axis of the actuator's piston. Loading at an angle could cause the piston to bind and, if severe enough, can cause it to bend the piston and alter its ability to function properly and retract back into the guide.

C. Deadheading: A common oversight when installing thermal actuators is failing to account for the total possible stroke length of the piston. If the stroke range is inhibited, the movement of the piston will be impeded, leading to an increase in the cup pressure. If the piston's extension is restricted enough, it could permanently damage the internal components of the actuator.

To avoid these issues, you can choose one of two options:

a. Give enough clearance for the entire travel of the piston.
b. Install an over-travel spring for actuators that move against dead stops.

D. Exceeding the maximum rated temperature: The actuators at ThermOmegaTech® all have a maximum operating temperature of 150°F (or 65.6°C) over the setpoint or a temperature of 300°F (149°C), depending on which one is lower.

3.0 BENEFITS OF THERMAL ACTUATORS IN AEROSPACE AND DEFENSE APPLICATIONS

Thermal actuators offer multiple benefits in the aerospace and defense industries. Some of the main advantages that are particularly valued in the aerospace and defense sectors are:

A. Self-actuation: Thermal actuators are self-actuating, meaning they do not require an external power source to operate. This reduces overall power requirements, which can be a critical factor in certain applications. It also means they are not susceptible to power failures and other circuit faults, like short circuits.

B. Simplicity: These actuators have a simple design that increases service life and minimizes part failures.

C. Predictable: These devices work on the principle of thermal expansion/contraction in a set temperature range, so they are predictable. The piston moves in relation to temperature.

D. Power and weight: Thermal actuators are typically small and lightweight. They have high power-to-size and power-to-weight ratios.

E. Light on Maintenance: These devices require no periodic servicing or calibration as with other actuator types.

4.0 THERMAL ACTUATOR APPLICATIONS IN AEROSPACE AND DEFENSE

Because of their unique combination of capabilities, there are quite a few applications for thermal actuators in the aerospace and defense industries. These devices are 100% self-powered and are ideal for explosion-proof environments. They can be used in control/activation and heating and cooling applications.

They can be integrated into many diverse types of bodies, systems, and manifolds to generate motion solely with temperature changes. They are used to make it possible to remotely and often automatically drive valves, flaps, or other moving parts.

This technology is very reliable and is frequently used in fail-safe applications to ensure that a particular action can still take place even when the power source of the actual system fails. This technology is so reliable that ASTM utilizes paraffin waxes to calibrate temperature instrumentation.

The applications of thermal actuators fall into three broad categories: actuators installed in an in-line valve housing, actuators installed in mixing/diverting cartridges or valve housings, and actuators used for high-output actuation.

4.0.1 Actuators Installed in In-Line Valve Housings

Actuators installed in in-line valve housings are mainly used for scald and freeze protection in aerospace and defense applications. Examples here are galley scald-protection valves that prevent hot fluids from an aircraft galley's beverage maker from backflowing to the faucet, where the hot fluid could scald a flight attendant, and freeze protection valves used to prevent potable water lines from freezing when naval ships are in port or dry dock.

4.0.2 Actuators Installed in Mixing/Diverting Cartridges or Valve Housings

Some examples of thermal actuators installed in mixing or diverting cartridges or valve housings in the aerospace and defense industry, specifically, include:

- Liquid cooling applications for avionics systems and radar in military aircraft
- Cold-start bypass of hydraulic fluid for faster warm-up for military vehicles
- Coolant temperature control for fuel cell applications in space and underwater vehicles
- Environmental control systems in spacecraft
- Radar cooling in missile systems
- Nitrogen-generating carts for on-ground servicing of military aircraft
- Fuel-oil temperature systems

4.0.3 Actuators Used for High-Output Actuation

High Output Paraffin Actuators (HOPA) are designed to manage higher displacement or forces than regular paraffin wax actuators. HOPAs are used in applications that require relatively high forces over a short distance. They have long, powerful, but gentle strokes. These devices are developed to withstand harsh environments such as space, which include radiation exposure, temperature extremes, and vacuum conditions.

HOPAs can operate under pressure or vacuum conditions and in liquid or gas. They are used on satellites, spacecraft, and deep-sea applications for multiple or one-time release operations.

These actuators can be helpful in applications where the ability to exert higher forces is needed to push, pull, or lift when activated via an external heat source, such as an electric resistor. These devices are an alternative to explosive bolts, which can damage adjacent equipment since they are non-explosive. They also have negligible outgassing.

4.1 Applications Beyond Aerospace and Defense

Beyond the aerospace and defense sectors, thermal actuators are applied to a diverse range of other industries. Some of these applications include pump protection through a thermal discharge valve, mixing or diverting of fluids in industrial systems, hot water recirculation system balancing, scald protection, freeze protection, and thermal control in automotive applications, to name a few.
These devices can be used in almost any situation that requires a temperature-actuated valve, switch, latch, or control.

5.0 THERMOMEGATECH® CAPABILITIES

At ThermOmegaTech®, we design and manufacture flat-diaphragm and sliding seal actuators. Each actuator contains our proprietary Thermoloid® blend, consisting of a precisely mixed paraffin wax and various additives. These actuators are installed into all our thermostatic valves.

Our manufacturing facilities are equipped with state-of-the-art CNC machines. We can provide machined valve parts in aluminum, stainless steel, and exotic metals upon request. We also offer various chemical treatment options for our valves and actuators, including passivation, electropolishing, NACE annealing, Chem Film, and anodizing.

In addition to our comprehensive catalog of standard offerings for electronics cooling, thermal bypass, freeze and scald protection, and airflow control, we offer our clients custom solutions. Our engineers work closely with our customers to find the right thermal control solutions for their unique needs.

We offer many customization options, including the type of metal, configuration, size, elastomer material, stroke length, thread type, and opening and closing temperature. We also offer different control solutions, including stand-alone actuators, valve housing, or cartridge-only options.

6.0 ABOUT THERMOMEGATECH®

ThermOmegaTech® was established in 1983. We specialize in designing and manufacturing thermal actuators, thermostatic valves, and other temperature control solutions. Our products are used in aerospace, defense, railroad, HVAC, plumbing, agriculture, and more to manage and regulate temperature without the use of external power. The key to our success lies in our ability to tailor our product offerings to satisfy our customers' needs through effective collaboration, leveraging our expertise with a strong emphasis on quality.

Our AS9100D certification speaks of our commitment to quality. If our off-the-shelf products do not meet your unique requirements, we will help you find a custom temperature control solution that works for your project.

You can find more information on our paraffin wax thermal actuator technology here.

7.0 REFERENCES

[1] Retrieved October 7, 2024, from: https://www.progressiveautomations.ca/pages/actuators

[2] Retrieved October 7, 2024, from: https://tameson.com/pages/actuator

[3] Retrieved October 7, 2024, from: https://www.kebamerica.com/blog/how-do-servo-actuators-work

[4] Retrieved October 7, 2024, from: https://www.wevolver.com/article/what-is-an-actuator-principles-classification-and-applications

[5] Retrieved October 7, 2024, from: https://www.jameco.com/Jameco/workshop/Howitworks/how-servo-motors-work.html#

[6] Retrieved October 7, 2024, from: https://yorkpmh.com/resources/hydraulic-vs-pneumatic-vs-electric-actuators/#

[7] Retrieved October 7, 2024, from: https://jhfoster.com/automation-blogs/what-are-the-types-of-actuators/

[8] Retrieved October 7, 2024, from: https://waxmotor.com/blogs/the-internal-structure-types-of-wax-motors

[9] Retrieved October 7, 2024, from: https://www.thermal-actuators.com/thermal-actuators