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Fluid Thermal Actuator*

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The purpose of this investigation was to design, develop, and build a thermal actuator for use as the sensor and prime mover of a spacecraft active thermal control system for use on NASA's ITOS (Improved TIROS Operational System) meteorological satellite. Specific thermal requirements of the spacecraft imposed certain design constraints on the actuator, among which were: a predictable operating temperature range, flexibility of range adjustment, over-temperature relief, and a comparatively large force output. Additional requirements were minimum weight and high reliability. Investigation indicated that a design based on the thermal expansion characteristics of a confined fluid was the best means of meeting the requirements. Design philosophy and the implementation are reviewed, and a series of design equations from which predicted performance curves can be derived is given. A comprehensive test program, developed and performed on a breadboard model and on flight-configured units of this actuator, is described, and the results are presented in relation to the specified design goals and the predicted characteristics of the device. The operating parameters of the actuator, as designed for the ITOS satellite, are summarized, and the degree of flexibility of the basic design concept and its adaptation to other systems of spacecraft active thermal control is discussed.

I. Introduction

In the design of any space vehicle, thermal control of the environment is of prime importance in maintaining the operational reliability of the onboard equipment. There are reliable passive techniques of control, such as control of surfaces, location of equipment, and orbit configurations; however, in many cases, they become burdensome and unpredictable, and an active thermal control system is required.

Typically, active thermal control systems vary the effective area of a radiative surface with a louver, or series of louvers, opening and closing in response to temperature. The thermal actuator described in this report (Fig. 1) provides the sensing and prime motion in such a system. The actuator operates on the principle of controlled thermal expansion of a confined fluid; its

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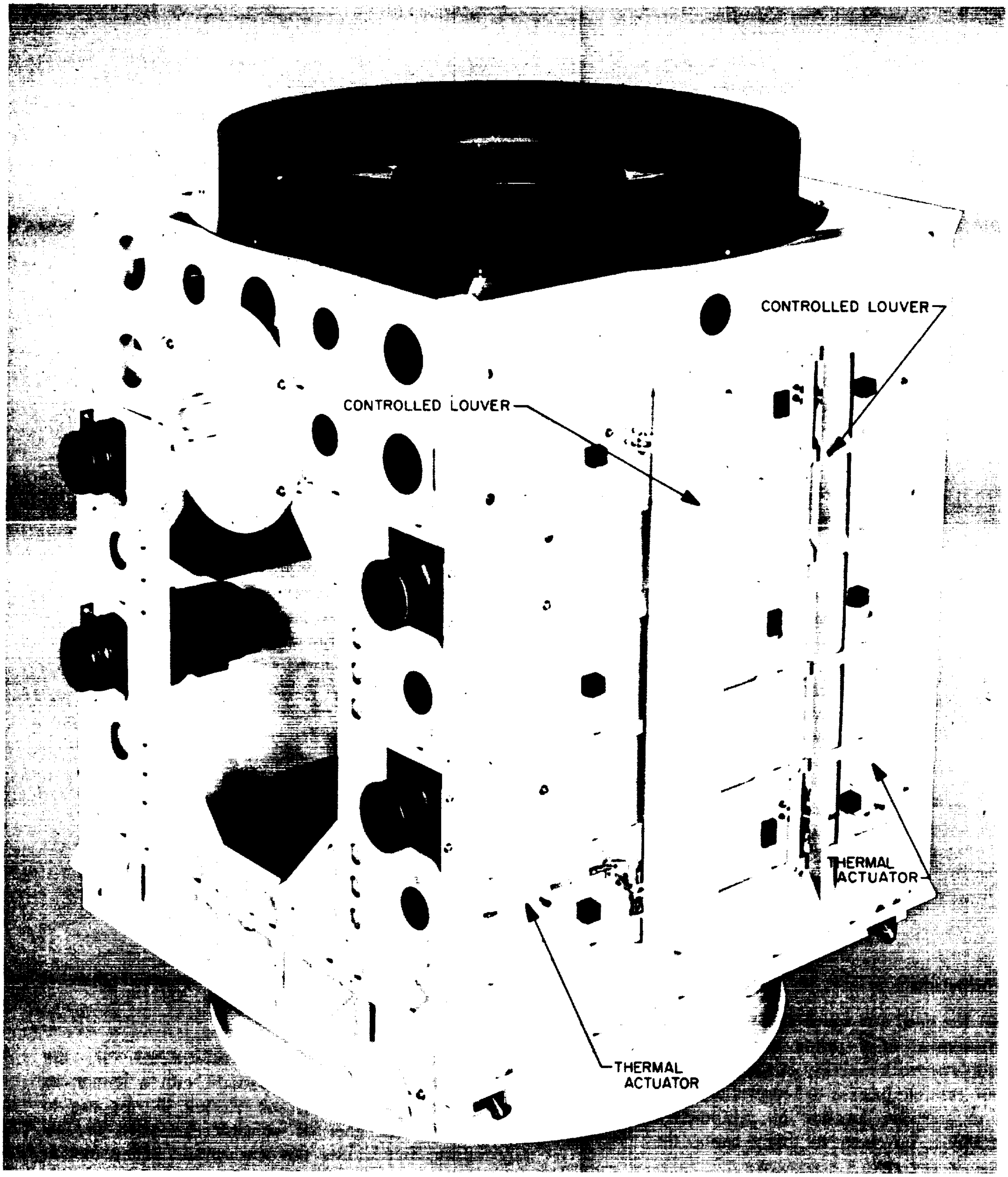

Fig. 1. Thermal actuators and controlled louvers on the ITOS satellite

output is linear motion as a function of the sensed temperature.

The consideration for an active thermal controller on NASA's ITOS meteorological spacecraft stimulated the development of this thermal actuator, which culminated in an actuating device that senses the spacecraft temperature and controls a single 35- × 5-in. louver. Four of these systems in different locations on the spacecraft provide the required thermal environment.

II. Design and Development

A. Constraints for ITOS Actuator

The ITOS active thermal control system had need for a thermal actuator that would meet the following requirements:

(1) Operating temperature range, 20 ±1.5 centigrade degrees.

(2) Range selection from −10 to +10°C and up to +35 to +55°C.

(3) Over-temperature relief, regardless of selected range, of +60 centigrade degrees.

(4) Minimum weight.

(5) Reliable operation in space for 1 year (equivalent to 5000 cycles).

(6) Linearity of the driven louver stroke temperature gain within ±10% of full stroke for any point in the range.

The size of the controlling louver and the resultant bearing design dictated that the actuator have a relatively high force output compared with that of other actuators of a similar function. A further restriction prevented this device from consuming any of the available power from the solar array.

B. Preliminary Study

Actuator selection necessarily had to be fitted to overall system requirements of a particular application. A survey was made of existing actuating devices to determine which was most applicable for the ITOS requirements. The designs investigated included use of the following: (1) bimetallic springs, (2) *on–off* and proportional heater controls, (3) stepper motors and solenoids, and (4) gaseous expansion actuators. None of the schemes reviewed could satisfy the ITOS requirement of high force output without supplementary power drain on the spacecraft power supply. Therefore, it was decided to proceed with a design that had not previously been used for this purpose, one that utilized the controlled thermal expansion of a confined fluid. There were several advantages to this method that was selected for development: (1) such a design would provide local temperature sensing at the actuator, (2) it would not require an external power source, and (3) a large force output could be extracted from the thermal energy imparted to the fluid due to temperature changes.

C. Fundamental Design Equations

The equation describing the volumetric characteristics of a compressible fluid at rest is derived as follows:

$$v = f(T, p, m)$$

$$dv = \frac{\partial v}{\partial T}\,dT + \frac{\partial v}{\partial p}\,dp + \frac{\partial v}{\partial m}\,dm \tag{1}$$

where

v = volume

T = temperature

p = pressure

m = mass

For a closed system, dm is zero. If we define thermal expansion coefficient β_T as

$$\beta_T = \frac{1}{v}\frac{\partial v}{\partial T}$$

and fluid bulk modulus β_p as

$$\beta_p = -v\frac{\partial p}{\partial v}$$

then Eq. (1) becomes

$$dv = \beta_T\, v\, dT - \frac{v\, dp}{\beta_p} \tag{2}$$

Rearrangement and integration of Eq. (2) give

$$\Delta v = v_0\left[\exp\left(\beta_T\,\Delta T - \frac{\Delta p}{\beta_p}\right) - 1\right] \tag{3}$$

Let

$$x = \beta_T \, \Delta T - \frac{\Delta p}{\beta_p}$$

then, from the Fourier expansion of e^x and Eq. (3),

$$v = v_0 \left[\left(1 + \frac{x}{1!} + \frac{x^2}{2!} + \cdots \frac{x^n}{n!} \right) - 1 \right] \qquad (4)$$

By an order-of-magnitude analysis,

$$0(x) = 10^{-2}$$

$$0(x^2) = 10^{-4}$$

Therefore, the terms of $n = 2$ and higher in Eq. (3) can be neglected, and the reduced form of the equation becomes

$$v = v_0 \, \beta_T \, \Delta T - v_0 \, \frac{\Delta p}{\beta_p} \qquad (5)$$

To implement this equation, it is necessary to select a fluid with predictable β_T and β_p, define pressure as a function of temperature, and provide a means of converting Δv into linear motion.

The thermal expansion and bulk modulus coefficients of most fluids are clearly defined and are available as a function of such other parameters as temperature and viscosity. For the actuator of this report, silicone oil is used – primarily for its constancy of expansion coefficient with temperature, its low vapor pressure, and the expansion coefficient selectivity permitted over the range of available viscosities.

Conversion of volumetric expansion into linear stroke is conveniently accomplished with an expandable chamber – namely, a bellows of sufficient stroke and pressure capability. Using a bellows, the relationship between stroke and volumetric change required in Eq. (5) is given by the following:

$$\delta = \frac{\Delta v}{A_M} \qquad (6)$$

where A_M is the mean area of the bellows. This design uses two bellows, one for the driving function and the other to provide adjustment of range and overtemperature relief. The inherent spring rates of these bellows provide the energy necessary for motion as the fluid contracts with decreasing temperature.

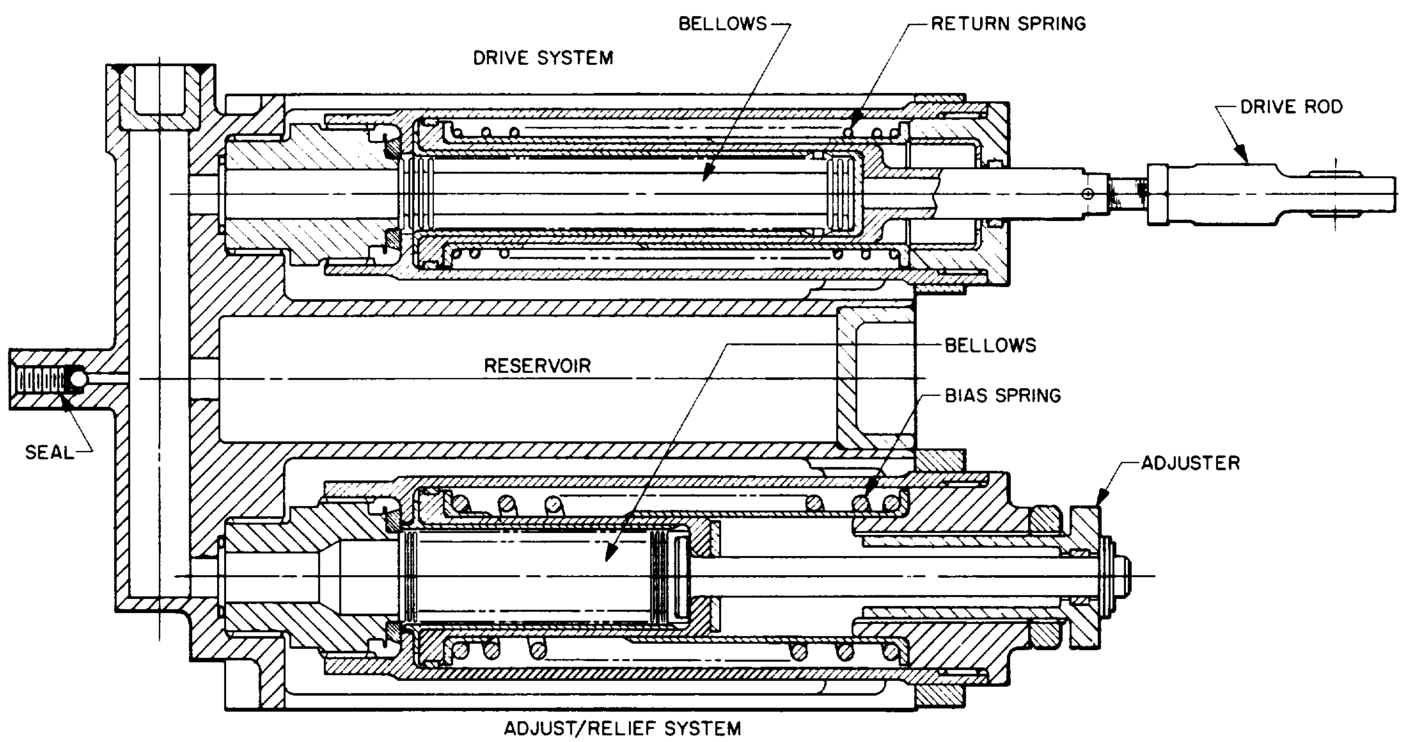

Fig. 2. Cross section of the thermal actuator

Each bellows operates in concert with a drive spring. These springs supplement the bellows spring rate and raise the force level of the system. The bellows/spring combinations are the sole determinants of the pressure buildup in the actuator.

D. Configuration and Operational Description

A cross section of the actuator is shown in Fig. 2. Basically, the actuator can be considered in two parts, referred to as the drive system and adjust/relief system. These two systems are hydraulically coupled to each other and to the reservoir. The fundamental components of the drive system are the drive bellows, drive spring, and drive piston.

The drive piston moves linearly on two piston-ring Teflon bearings. Not being rigidly attached to any fixed part, the piston is free to rotate; this provision allows linear adjustment of the external rod when it is locked on a shaft. The drive bellows is made of nickel and is accurately fabricated by electrodeposition for predictable spring rate, stroke, and pressure capability. To provide a usable stroke in a minimum package, the bellows is used in compression and extension, with the drive spring accomplishing the compression of the bellows.

As the fluid in the actuator expands with temperature, the drive bellows moves linearly to accommodate the expansion, working against the drive spring and moving the drive piston in an outward direction. In a cooling mode, with the fluid contracting, the drive spring provides the necessary force levels.

The drive spring is preloaded so that the minimum force level of the drive spring–drive bellows combination with the drive piston full in ($\delta = 0$) is not less than 4 lb. This available return force increases linearly as the drive spring is compressed with the piston moving out. The calculation of this force reflects the combined spring rates of the spring and bellows. Figure 3 shows the relationship between drive position and available return force.

At first glance, it would seem that the available force in the outward direction during heating would be extremely large and limited only by any compressibility of the fluid. However, the force is limited to the threshold force or internal pressure at which the relief system picks up.

The adjust/relief system consists of a bellows, spring, and piston arrangement similar to the drive system and, also, an adjuster with a locking nut. This combination of components performs the two supplementary functions of the thermal actuator: adjustment of the operating range and over-temperature relief. The spring and bellows spring rates of this system are sized to be compatible with the drive system. That is, the relief system is preloaded such that the minimum pressure required to move it is greater than the maximum pressure developed in the drive side. A typical pressure/temperature plot for the actuator is shown in Fig. 4.

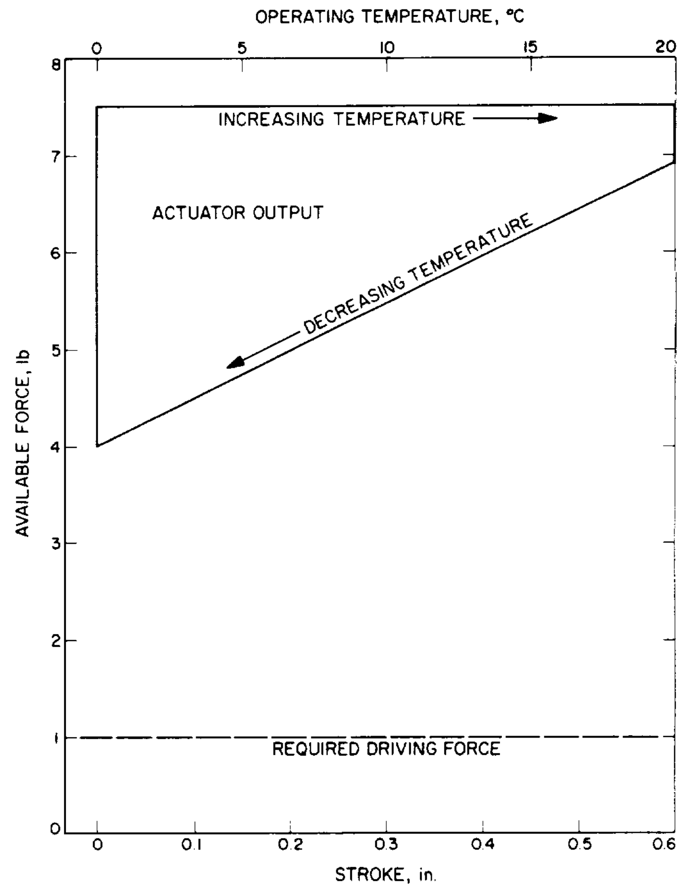

Fig. 3. Available force diagram, thermal actuator

This adjust/relief system also incorporates the adjustment feature that permits the nominal 20 C° temperature range to be selected anywhere between −10°C and +55°C. Adjustment in all cases means adjusting to the temperature at the low end of the 20 C° range. The ability to provide this adjustment can be explained as follows: With the unit filled with a known amount of fluid at a certain temperature, it is true from the thermodynamics of the closed system (Eq. 5) that there is a unique absolute volume of fluid associated with each and every temperature of the bracketed range. Therefore, by

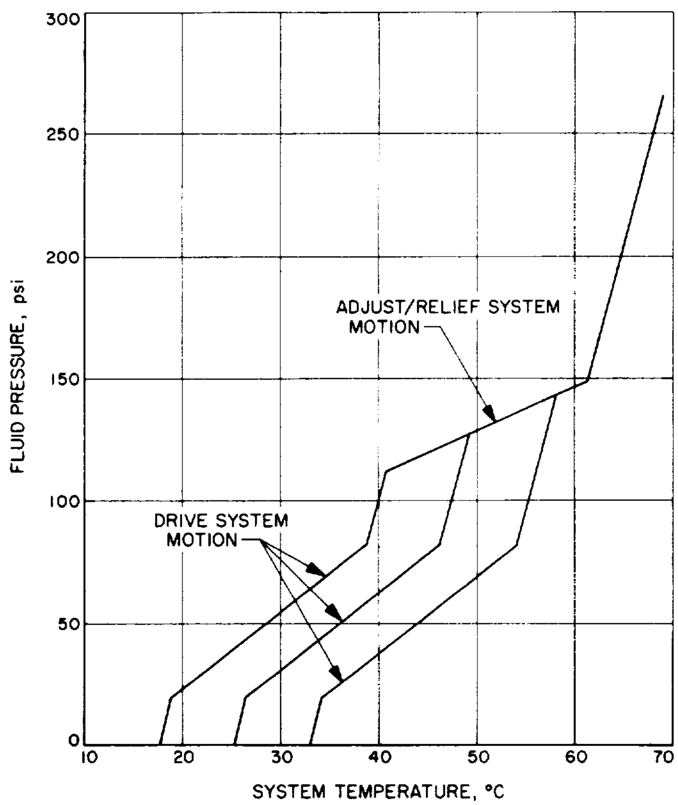

Fig. 4. Thermal actuator fluid pressure as a function of temperature

threading the adjusting nut, which simply expands or contracts the adjust/relief bellows and changes the internal physical dimensions of the actuator, any specific temperature can be selected below which the fluid has not reached a sufficient volume to be effective. This represents the temperature at the low end of the desired 20 C° range.

E. Design Considerations and Materials Selection

1. Prevention of metal-to-metal contact of moving parts. In developing the actuator, there were a number of design considerations, selections, and philosophies that were felt to be pertinent to meeting the outlined goals. Most of these were motivated by the requirement to guarantee operation for 1 year in space. For example, the use of nonlubricated Teflon/steel bearings was dictated to avoid the evaporative and contaminating characteristic of viscous lubricants.

This philosophy was more applicable to the design of the moving louver section of the active thermal controller, but it is reflected in the design of the Teflon rings upon which the drive and adjust/relief pistons move. A related design philosophy is the use of nylon sleeves as guides for the springs and bellows. The design, in total, does not permit metal-to-metal contact of any moving parts.

2. Selection of bellows. The electrodeposited type of bellows was selected because it provided the best combination of available stroke, predictable spring rate, and wall homogeneity. Hydraulically formed bellows are stiffer and do not offer satisfactory available stroke per unit length. Welded bellows have a significant stroke advantage, but their noncontinuous construction does not provide the desired confidence against leakage.

In selecting a particular pair of bellows, the design procedure was iterative within the operating limits of the bellows and the defined parameters for the actuator. With the temperature requirements of range, adjust, and relief, and with a reasonably selected stroke, the design approach was one of selecting the bellows/spring combination to reach a proper balance of the following parameters:

(1) Available force of drive system.

(2) Bias relationship of drive and adjust/relief systems.

(3) Maximum allowable pressure of bellows.

3. Minimizing contaminants. With consideration of a design of this type, it was readily concluded that the ability to predict the operation of the device and, furthermore, to have confidence in the operation was highly dependent on the selection of the fluid, the amount of contaminants introduced, and the sealing quality of the chamber. It was previously mentioned that silicone oil was selected for its low vapor pressure, stability of expansion coefficient β_T, and range of expansion coefficients as a function of viscosity. Other fluids of higher β_T were considered, but they did not offer the flexibility of selecting within their specie a range of expansion coefficients. It is also true that many of these fluids were of magnitudes higher in vapor pressure, which could not be allowed because of the natural compressibility of gaseous vapors.

Because the operation of the device is fundamentally based on the small expansion capability of a confined fluid and because the effect of pressure buildup in the system is to subtract from this effect, it was highly undesirable to introduce compressible contaminants into the device. Of particular concern were traces of volatile components and entrained air in the fluid, air trapped in the bellows during filling, and air introduced during the final sealing procedure. Proper selection of fluid plus a vacuum de-aeration process negated the first concern of volatiles and entrained air.

The second concern of entrapped air during filling was felt to be minimized by a vacuum backfill technique wherein the fluid is introduced from a filling reservoir into the vacuum of the device. The problem of introducing air during the final seal was solved by use of the sealing mechanics shown in Fig. 2. The device may be sealed completely below the fluid level without the introduction of air.

III. Testing and Results

Testing of the actuator was done on a breadboard model identical to the flight model from the standpoint of operation and performance. Testing was carried out as a development program learning process with two objectives. The primary objective was to show that the actuator performed as designed and that the design goals, stated earlier, had been achieved. The secondary objective was an evaluation of the effect of certain unpredictable variables (mechanical compliance, entrapped air, and a variation in the fluid bulk modulus β_p) on the overall system performance.

All tests were performed in a temperature-controlled chamber. By the use of a potentiometer to monitor displacement and a temperature-compensated strain-type pressure transducer to check fluid pressure, the unit was evaluated over all temperature ranges. Freedom of range selection was demonstrated, as is shown on Fig. 4, which also shows the over-temperature relief capability to be in excess of the desired 60 C°.

Initial tests in the program indicated that the operating range of the actuator was 24 C°, instead of the predicted 20 C°. It was further shown that the operation of the device was identical for any selected range. From consideration of the four parameters (v_0, β_T, Δp, β_p) of Eq. (5) which affect the $\Delta v/\Delta T$ relationship, it became evident that the value of the fluid bulk modulus β_p enjoyed our least confidence. Bulk moduli are typically published for high-pressure ranges, leaving low-pressure values to extrapolation and curve fitting.

Curve fitting from available manufacturer's data, however, resulted in an analytically determined compressibility that was one order of magnitude lower than that originally used. Furthermore, continued testing led to a conclusion that, in fact, we were dealing with other factors that were operating collectively to give us what we now term an equivalent bulk modulus (β_{p_e}). Such factors as entrained volatile fluid components, inherent bellows compliance, and air entrapped during the filling operation could all interact in the equivalent system.

An analytical evaluation of the β_{p_e} reflecting this interaction would at best be difficult because of the interrelated variables listed above. Thus, to substantiate our conclusion and evaluate the equivalent modulus, an empirical approach was undertaken in the form of an over-temperature pressure test. The results of this test are shown on Fig. 4. Above 62°C, a region where $\Delta v \approx 0$, the graph indicates a finite change in pressure as a function of a change in temperature. Analysis of this data by Eq. (5) gives $\beta_{p_e} = 17 \times 10^3$ psi.

To compensate for a decrease in β_{p_e}, which (according to Eq. 5) manifests itself as a reduction in gain, a new fluid with a higher β_T was selected. Subsequent testing showed the operating range to be 20 $\pm$1.5 C° with a linearity of 2% maximum. With the operating range of 20 C°, the over-temperature relief became 60 C°, as predicted.

IV. Conclusion

The tangible result of the developmental effort was the local-sensing thermal actuator with the following characteristics, which met the earlier established design constraints imposed by requirements for ITOS:

(1) Operating range provided was 20 $\pm$1.5 centigrade degrees.

(2) Range selection was from −10 to +10°C up to +35 to +55°C.

(3) Over-temperature relief of 60 centigrade degrees was provided.

(4) Stroke/temperature linearity was within $\pm$2% of the full stroke.

(5) Available force output was 4 to 7 lb.

(6) Weight was 2 lb.

(7) Reliability predicted was 0.995 for 1 year operation in space.

(8) Minimum expected life is 10^7 cycles, based on bellows capability.

(9) Ability to change operating range by changing β_T was provided.

More fundamentally, the effort reduced to hardware and proved through test the reality of a thermally actuated device based on the principle of controlled fluid expansion. Such a device is particularly suited to applications where the consumption of electrical power is not permitted and, at the same time, predictable high force outputs are desirable.

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