SATELLITE PROPELLANT GAUGING SYSTEM USING HIGH RESOLUTION QUARTZ PRESSURE TRANSDUCERS

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ABSTRACT

High resolution quartz pressure transducers have been developed for a propellant gauging system used in advanced, body-stabilized, high power communications satellites. The propellant gauging system permits prediction of satellite end-of-life to within a few months at the midpoint of a 15 year mission. The primary benefit is the ability to plan the launch of replacement satellites.

INTRODUCTION

The overall management and performance of space missions are highly dependent upon accurate predictions of spacecraft orbital life. Thus it is increasingly important to accurately determine the remaining amount of propellants used for orbital and stationkeeping maneuvers typically associated with large payload, body-stabilized space platforms in low-gravity, geosynchronous orbits. The Hughes Aircraft Company has incorporated high resolution quartz pressure transducers manufactured by Aeroquartz, Inc., into a propellant gauging system that represents an order-of-magnitude improvement over prior techniques.

As described in Reference 1, general gauging methods include:

(1) Point and line hydrostatic sensor systems
(2) Accounting Systems
(3) Global systems

Hydrostatic sensing techniques are not used in these low gravity environments because the propellant is not confined to a defined shape in the absense of gravitational or centrifugal accelerations. Although these measurements are possible with spin-stabilized spacecraft, high power communications satellites are usually body-stabilized and do not produce rotationally-generated accelerations.

Accounting systems depend on the monitoring of integrated propellant flow rates which are subtracted from the initial propellant mass to determine the amount of remaining propellant. Only 20% of the initial full load may be left on integrated systems that perform both apogee firing for orbit insertion and thruster firing for attitude control. With long duration missions, the flow rate errors integrate with time and can represent a 10% uncertainty in mission life.

Global systems measure propellant quantity with a single sensor that communicates with the entire tank volume. The technique chosen by the Hughes-Aeroquartz team is based on pressure-volume-temperature measurements using high resolution quartz transducers to accurately sense small pressure changes in pressurant and propellant tanks.

BODY-STABILIZED SATELLITE

The high accuracy propellant gauging system was initially developed for and used on the Hughes HS601 communications satellites. (See Figure 1).

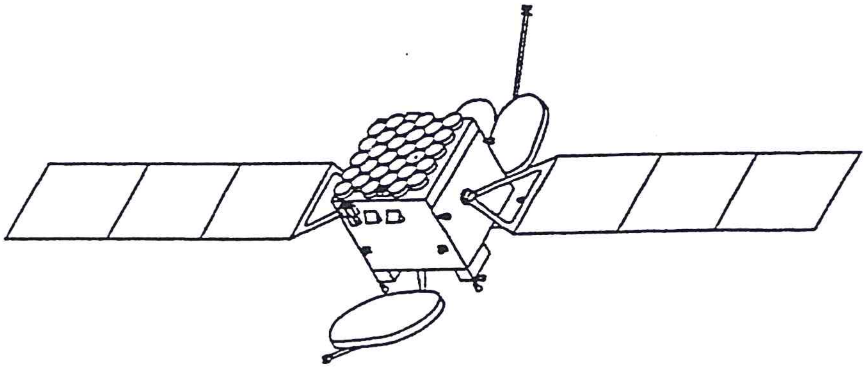


FIGURE 1: HS601 COMMUNICATIONS SATELLITE

This satellite carries up to 1500 pounds of payload, has a 15 year design life in orbit, and can be configured to generate up to 6000 watts of payload power. These satellites employ huge solar cell arrays and a three-axis body-stabilized spacecraft platform. Increasing payload power requirements for applications such as direct broadcasting promote the use of body-stabilized spacecraft platforms. The demands for improved mission performance have increased the use of integrated bipropellant propulsion systems. Orbital attitude control and stationkeeping activities are more critical on geosynchronous communications satellites employing higher gain, more focused antenna patterns. Significant economic and logistic benefits accrue from more accurate propellant gauging capability. This information is particularly useful for end of mission life prediction and spacecraft replacement planning.

PROPELLANT GAUGING SYSTEM (PGS)

A detailed analysis and thermodynamic model of a global pressure-volume-temperature propellant gauging system (PGS) is given in Reference 2. A functional schematic of the PGS is shown in Figure 2.

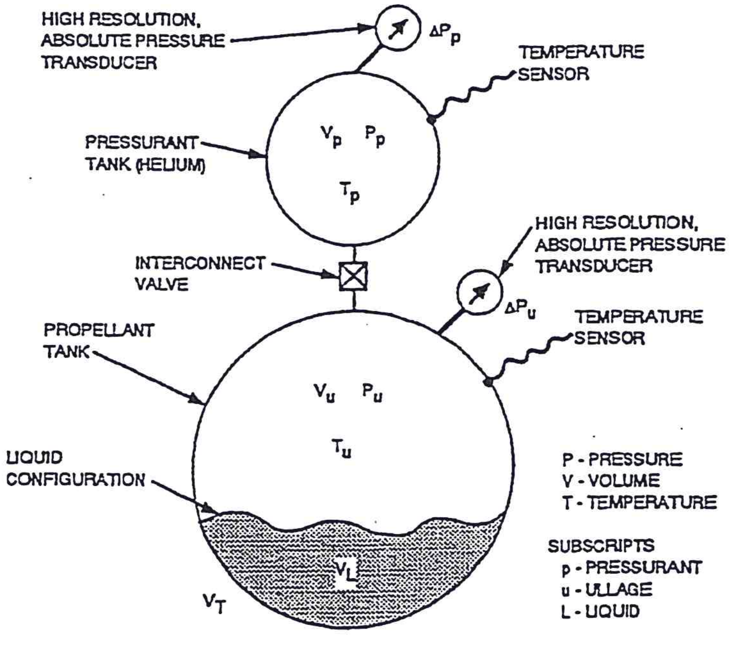


FIGURE 2: FUNCTIONAL SCHEMATIC OF PROPELLANT GAUGING SYSTEM (PGS)

The propellant tank is connected to a helium gas pressurant tank through a latching valve Separate high resolution quartz pressure transducers measure the pressures in each tank. Temperatures of the helium gas and ullage are also measured. The helium pressurant tank volume, V_P, and propellant tank volume, V_T, are known quantities from ground test data. The pressure measurements performed in space determine the ullage volume, V_U, which when subtracted from the propellant tank volume, V_T, yields the desired propellant liquid volume, V_L. In equation form:

$$V_L = V_T - V_U \qquad (1)$$

To determine the ullage volume, V_U, pressure measurements are made before and after the interconnecting latching valve is momentarily opened to allow pressurant gas to transfer from the higher pressure helium tank to the lower pressure propellant tank. Assuming that this process follows the ideal gas law under isothermal conditions, then the helium mass transferred from the pressurant tank equals (the measured pre-transfer pressure of helium minus the measured post-transfer pressure of helium, ΔP_P) times (the known pressurant tank volume, V_P) divided by (the measured pressurant tank temperature, T_P). In equation form:

$$\text{Helium mass transferred from pressurant tank} = (\Delta P_P)(V_P)/(T_P) \qquad (2)$$

Similarly, the ullage pressure rises after the helium transfer and (the pre-transfer ullage pressure minus the the post-transfer ullage pressure, ΔP_U) times the unknown ullage volume, V_U) divided by (the ullage gas temperature, T_U) also equals the helium mass transferred in equation (2).

$$(\Delta P_U V_U)/(T_U) = (\Delta P_P V_P)/(T_P) \qquad (3)$$

Solving for V_U in equation (3) and substituting in equation (1), the propellant liquid volume is:

$$V_L = V_T - V_P \; (T_U/T_P)(\Delta P_P/\Delta P_U) \qquad (4)$$

Therefore the amount of propellant can be calculated from the known pressurant tank volume, V_P, and propellant tank volume, V_T, the measured temperature ratio, (T_U/T_P) and the measured pressure change ratio, $(\Delta P_P/\Delta P_U)$.

Modifications to the foregoing analysis must be made for effects such as pressurant gas compressibility, pressurant gas solubility in propellant, tank elasticity, and heat transfer effects.[2]

The implementation of the PGS on the HS601 satellite is functionally shown in Figure 3. The two helium pressurant tanks, two hydrazine fuel tanks, and two nitrogen tetroxide oxidizer tanks are each instrumented with individual high resolution quartz pressure transducers as well as multiple temperature sensors. Each PGS measurement is performed separately by one helium pressurant tank pressurizing one of the propellant tanks. The three propellant tanks not undergoing the pressurization process can serve as thermal references in order to characterize the measurement thermodynamics more accurately. Even though the pressure transducers have a full scale range of 4,137 kP_a (600 psia) and over-pressure capability beyond 6,205 kP_a (900 psia), during the measurement process, the pressurant tank pressure change, ΔP_P, would typically be about 80 kP_a (11.6 psi) and the propellant tank pressure change, ΔP_U, would typically be about 10 kP_a (1.5 psi). Thus the transducers must measure pressure changes that represent a small fraction of their full scale range.

The excellent performance of the high resolution quartz pressure transducers leaves the dominant errors in the PGS as the inaccuracies in tank thermal characterization and tank volume. Indeed, the errors associated with determining the measured pressure change ratio in Equation (4) correspond to an end-of-life prediction capability of several weeks - not several months.

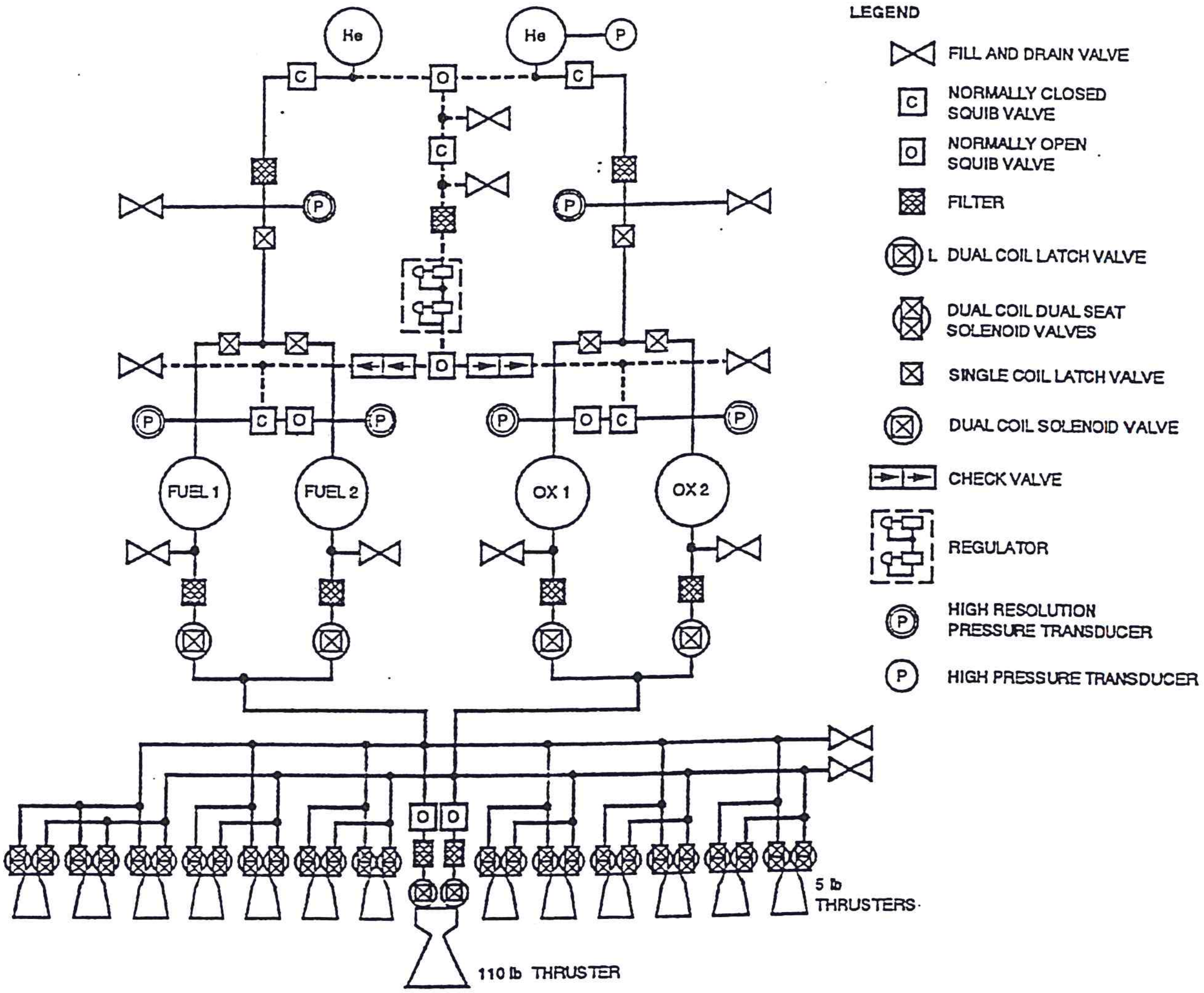


FIGURE 3: HS601 PROPULSION SYSTEM

HIGH RESOLUTION QUARTZ PRESSURE TRANSDUCER DESIGN

Reference 3 describes the construction, operation, and performance of inherently digital pressure transducers with resolution capability better than a few parts per billion of full scale. The basic sensing mechanism is the change in resonant frequency of a force-sensitive vibrating quartz crystal under pressure induced load.

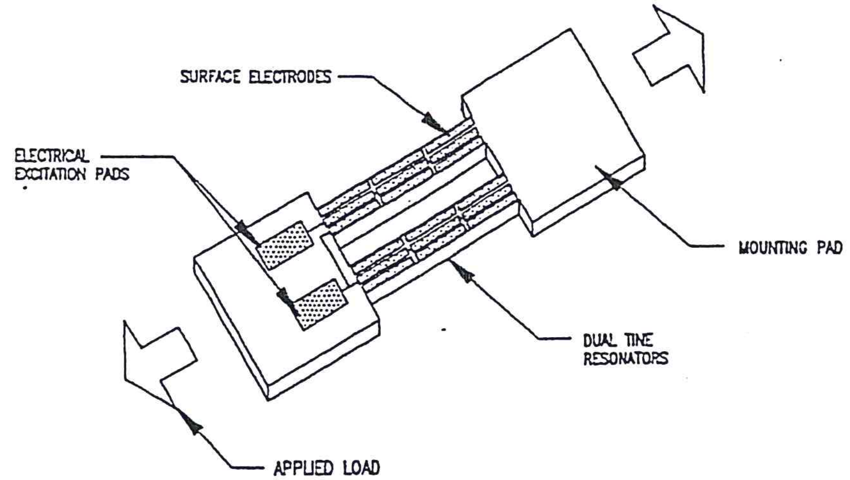


FIGURE 4: DUAL TINE FORCE-SENSITIVE RESONATOR

The load-sensitive quartz crystal resonator is shown in Figure 4. As described in Reference 3, it consists of two beams, or tines, of a double-ended tuning fork, vibrating in 180 degree phase opposition between two mounting pads. Since the two tines are identical, the reactive force and moments cancel resulting in a high Q(low energy loss) resonance. The small amount of energy necessary to maintain resonator vibrations is supplied from an external oscillator circuit that drives the resonator piezoelectrically through surface electrodes. The electrode pattern is produced as part of the photolithographic and chemical milling process used to manufacture the double-ended tuning forks. The resonant frequency of the tines is a function of the dimensions, composition, and applied load between the mounting pads. Similar in concept to the operation of a violin string, the resonator frequency increases with applied tension and decreases with compressional loading.

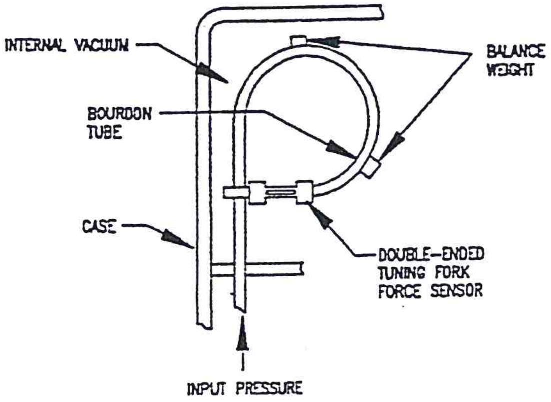


FIGURE 5: PRESSURE TRANSDUCER MECHANISM

The pressure induced loads are generated by a Bourdon tube as shown in Figure 5. Pressure applied to the Bourdon tube generates an uncoiling force which loads the dual-tine resonator. The frequency increases with loading tension and is a measure of the pressure. The transducer is evacuated to eliminate air damping and maximize the Q of the vibrating quartz crystal. The hermetically sealed housing maintains the internal vacuum as an excellent reference for absolute pressure measurements. The Bourdon tube mechanism is acceleration balanced with small weights positioned to make the center of gravity coincide with the effective center of rotation. Thus the transducer has a low sensitivity to shock, vibration, and acceleration.

The Bourdon tube and quartz resonator are scaled so that full scale pressure of 4,137 kPa (600 psia) changes the nominal 33 KHz resonant frequency by approximately 10%. The output signal is measured using a period averaging technique whereby the resonator gates a high frequency clock and the clock pulses are counted. With an unsophisticated counter-timer scheme, there is an uncertainty of ± 1 count out of the total number of clock pulses. The total number of clock pulses equals the clock frequency multiplied by the integration time (number of resonator periods averaged multiplied by the resonator period). For example, integrating for one second with a 10 MHz clock yields a <u>frequency</u> resolution of the resonator's output of 0.1 parts per million (ppm). The quartz crystal pressure transducer is designed to produce a 10% change in resonator frequency from zero to full scale applied pressure. Thus only 10% of the counts are related to pressure and the <u>pressure</u> resolution would be 1.0 ppm using a 10 MHz clock and update time of 1 second. Higher resolution, interpolating start-stop counters are available with equivalent clock frequency close to the GHz range. With this improved counting system, the resolution is better than a few parts per billion.[3]

The period output from the resonator is linearized in an algorithm that describes the change in frequency of a fixed-fixed beam under load. Thus the linearized pressure, P, is solved for in the equation:

$$P = C\,(1 - T_o^2 / T^2)\,[1 - D\,(1 - T_o^2 / T^2)] \qquad (5)$$

T is the period output at pressure, P, as measured with the gated clock pulses of the counter-timer. C, D, and T_o are coefficients derived though a least-squares fitting routine from calibration data. C is related to the span or sensitivity of the sensor, D is the linearization coefficient, and T_o is the period output at zero applied pressure. Even though quartz crystals and the pressure mechanism design are basically insensitive to temperature, the transducers are calibrated over a broad temperature range and compensated for any residual thermal errors by making C, D, and T_o functions of measured temperature. The quartz pressure transducers not only have high resolution, but they also have excellent repeatability and low hysteresis. Figure 6 shows the total static error band for a 7 MPa (1,000 psi) transducer. The error band is less than 0.002% full scale relative to the primary standard dead weight tester.

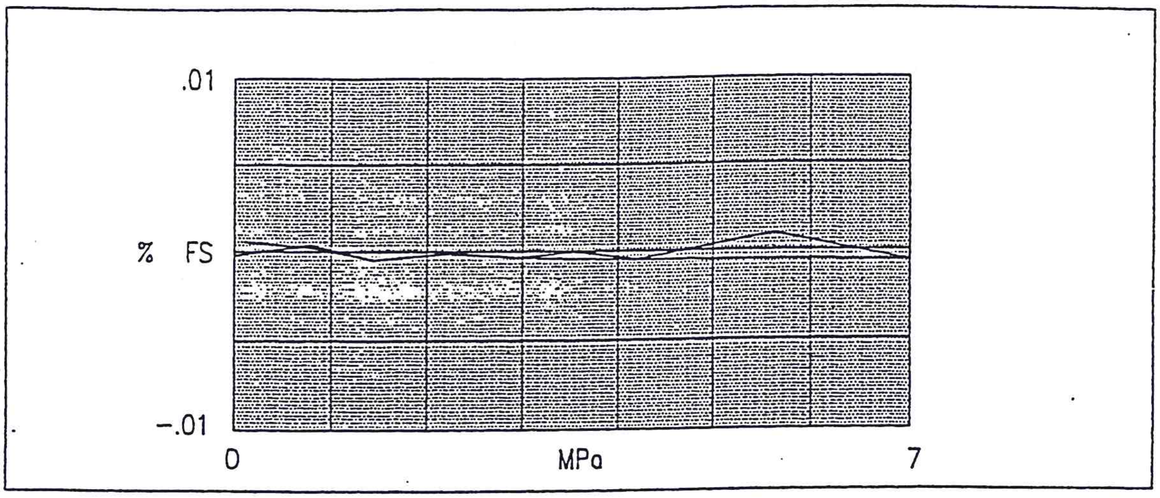
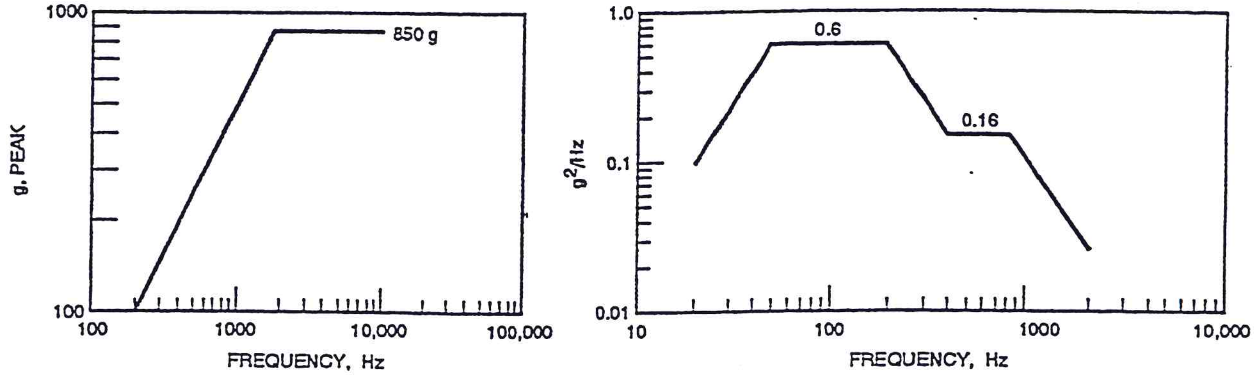


FIGURE 6: STATIC ERROR BAND

The pressure transducer requirements include high resolution and accuracy, digital output, fast response time, low power consumption, and small size and weight. In addition the transducers must maintain a high level of performance after exposure to a variety of environmental factors.

Figure 7 shows the qualification level shock and vibration levels applied to the transducer in its 3.5 cm diameter shock-mounted housing. The transducers survived and met the performance requirements after exposure to both qualification and acceptance levels of shock and vibration.



PYROSHOCK ENVIRONMENT

QUALIFICATION LEVEL RANDOM VIBRATION TEST

FIGURE 7: QUALIFICATION SHOCK AND VIBRATION SPECTRA

Although similar transducers have been used over temperature ranges from -55°C to 180°C, the operational range for these sensors was defined as -34°C to 107°C. Thermal calibration for temperature compensation purposes was focused in the 2°C to 43°C range.

Additional qualification tests involved over-pressure and burst tests. The full scale 4.1 MPa (600 psi) transducer easily met the minimum burst test requirement of 16 MPa (2900 psi) with a sensing mechanism failure at 28 MPa(4000 psi) and no structural deformation up to 60 MPa (8700 psi). The maximum burst pressure was limited by the test equipment capability.

Radiation tests were performed on two transducers to levels beyond the calculated mission dose of 27 K Rads (17 year equivalent commulate dose). The transducers suffered no degradation or output shifts when exposed to 36.5 K Rads (23.0 years) and 31.2K Rads (19.6 years).

Compatibility testing was performed on six samples of Bourdon tube material and two functional transducers. The samples showed no perceptible material loss and the transducers indicated no drift or degradation after liquid nitrogen tetroxide exposure equivalent to 15.9 years.

The extensive development, testing, and qualification of the high resolution quartz pressure transducers resulted in their use in the propellant gauging system (PGS) for the HS601 satellite. The first launch was successfully accomplished on August 14, 1992 with all systems working perfectly.

SUMMARY & CONCLUSIONS

An accurate and reliable propellant gauging system has been developed which uses high resolution quartz crystal pressure transducers. This system can make measurements of propellant tank volumes to within a fraction of one percent. This measurement accuracy offers an order of magnitude improvement over prior methods to predict end-of-life for long duration missions. Benefits include more efficient spacecraft utilization and replacement planning.

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