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A Superconducting EmDrive Thruster. Design, Performance and Application.

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Abstract

In an IAC-20 paper, the detailed design of a cubesat EmDrive thruster was described. This paper advances that design to a superconducting version. The basic microwave cavity retains the same internal geometry, but is now manufactured from Kovar, a special nickel-cobalt-steel alloy with thermal expansion properties to match the internal Yttrium Barium Copper Oxide (YBCO) superconducting thin film, and substrate. This technology was originally used in a liquid Nitrogen cooled, 3.85 GHz demonstrator thruster, which produced test data verifying cavity performance. The test data was used to predict the performance of this present design. The standard thrust equation, verified over many EmDrive experimental programmes, is used to give a specific thrust of 12.3 N/kW at the operating temperature of 77K. The dynamic operation of the thruster is addressed, with internal Doppler effects described. It is concluded that no compensation technology is required for the predicted acceleration levels. The kinetic energy aspects are analysed and the results of pulse operation are given, and compared to the original cubesat thruster operation. The low operating temperature is reached by a passive cooling system, which extends the concept described for the cubesat. The original 40W microwave input power is retained, but the thermal radiator area is greatly increased, and a liquid Nitrogen cooling loop is incorporated. The thermal radiator fins are maintained in permanent shade by a large sunshield, deployed using folded arms. The radiator fins are deployed using a folded centre tube and end struts. The spacecraft described in this paper, uses two thrusters mounted on single axis gimbals. They are positioned equidistant from the centre of mass of the spacecraft, to enable primary thrust in X, Y and Z planes with the addition of roll from a momentum wheel. Pitch and Yaw are provided by the thrusters, with momentum wheel back up. Power is provided from two rotatable, 95W solar arrays, which allow flights to the inner planets. Use of a 110W NASA Multi Mission Radio Isotope Thermoelectric Generator (MMRTG) would enable fast missions to the outer planets, and interstellar precursor flights. Outline designs of these alternative spacecraft are described, together with initial mass property analyses, to establish the correct positioning of the thrusters relative to the centre of mass. The resulting spacecraft masses are 90kg for the solar powered version and 128kg for the spacecraft powered by the MMRTG.

1.Introduction.

The EmDrive equation for static thrust, which was derived in a 2008 IAC paper [1], can be simplified to:

$$T=\frac{2PQDf}{c} \qquad (1)$$

Where *T*=Thrust

P=Power

Q=unloaded Q

Df = Design Factor

Clearly thrust is directly proportional to unloaded Q.

At room temperature, a typical EmDrive cavity has a Q value of $5x10^4$. However if the cavity inner surfaces are coated with a High Temperature Superconductor (HTS) thin film of Yttrium Barium Copper Oxide (YBCO), then when cooled to a Liquid Nitrogen (LN2) temperature of 77K, the surface resistance is dramatically reduced and the Q value increases to $5x10^{6.}$ If liquid Hydrogen at 20K is used, the Q value can rise to $5x10^8$.The surface resistance (R_S) at a frequency of 3.83GHz is shown in Fig.1.

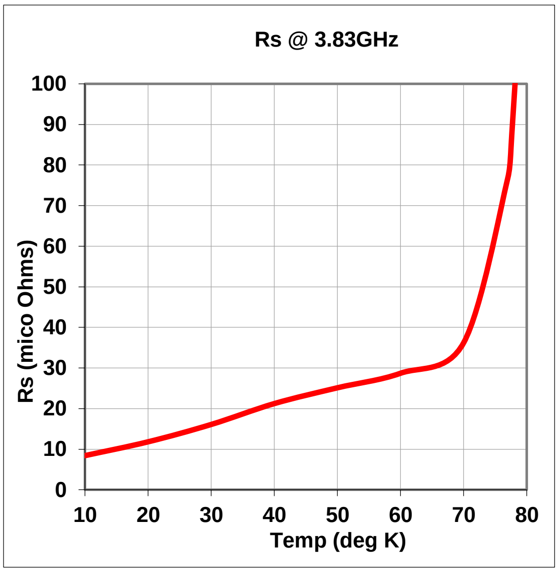

Fig.1.YBCO Surface Resistance

The data is based on HTS manufacturer's data and was verified by measurements made with the experimental thruster, shown in Fig.3.

Accelerators for high energy physics research are typically manufactured from Niobium and are cooled to 4K using liquid Helium. The internal forces generated during pulsed operation of these cavities, cause the axial length to increase and compensation techniques using piezo-electric elements must be applied. A Niobium EmDrive type cavity, manufactured and tested in the US is illustrated in Fig.2. Thrust levels of 1N/kW were reported.

Fig.2. US Experimental Superconducting EmDrive

In the UK, experimental work was carried out with a rectangular cavity, manufactured from Kovar, a special nickel-cobalt-steel alloy, with thermal expansion properties to match the internal YBCO superconducting thin film, and substrate. This technology was originally used in a liquid Nitrogen cooled, 3.85 GHz experimental thruster, which produced a Q of 6.8×10^6. The original SPR Ltd cavity is shown in Fig. 3, and the resonance plot at 77K in Fig.4.

Fig.3. SPR Ltd experimental superconducting thruster.

In the initial experiments, the predicted specific thrust of 36N/kW was unable to be verified, because the internal forces generated, when tested at a power of 20W, caused catastrophic cracking of the 0.5mm sapphire substrates. The high cost of this approach meant that further work was carried out under UK government funding.

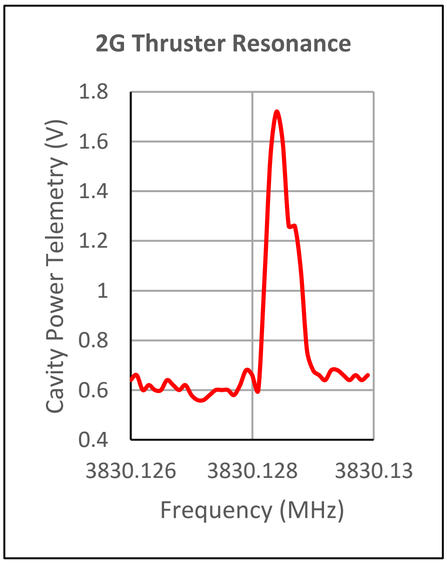

Fig.4 Resonance Plot for SPR Ltd Thruster

2. Superconducting Thruster description

The superconducting thruster described in this paper is based on the cubesat thruster presented in a 2020 IAC paper [2].This thruster was also designed to operate at 3.85GHz with a TE113 mode, and the basic circular cavity geometry is retained. The E and H Field phase plots are shown in Fig.5.

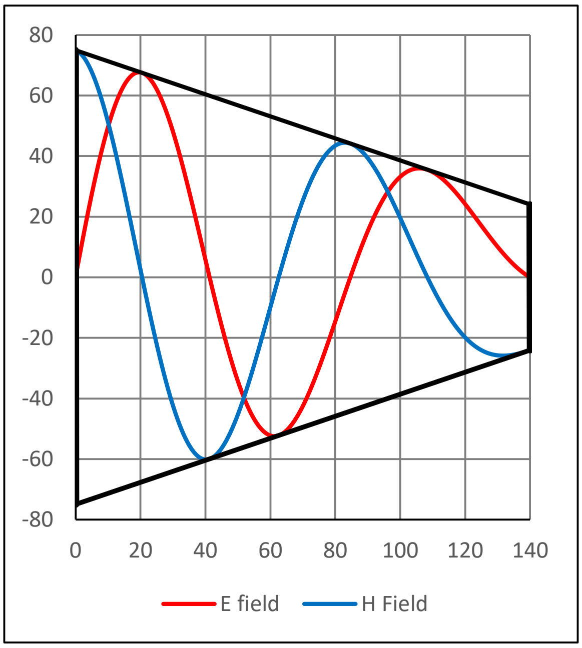

Fig.5. E and H field phase Plots

The cavity geometry comprises a flat small end plate, with the large end plate having a central flat face, and an annular section, with a radius equal to the central axial length, and is illustrated in Fig.6.

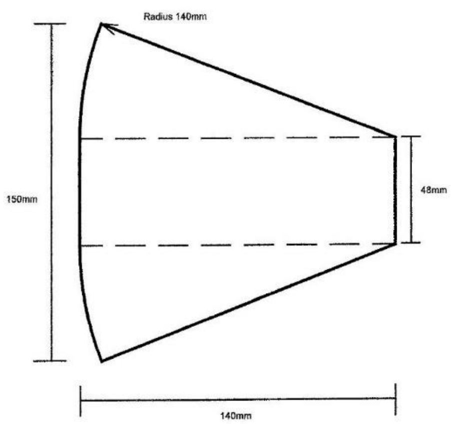

Fig. 6. Cavity Geometry.

The cavity is machined from Kovar, with internal surfaces coated with YBCO superconducting thin film on sapphire substrate. The flat sections of the end plates, which carry the highest currents and thus power dissipation, enable the substrates to be simply attached by special cryogenic adhesive. This process must include very careful application of uniform pressure. For maximum performance the total internal cavity surface is coated, to minimise surface resistance and thus to obtain maximum Q value. However the annular section of the large end plate and the tapered wall section require specialised coating processes, which involve a significant investment in vapour disposition equipment. The performance calculated for the thruster assumes only the flat end plate sections coated with YBCO.

Two thrusters are mounted in the proposed spacecraft, and each is mounted on single axis gimbals, as shown in Fig.7. The whole thruster is mounted in a sealed enclosure filled with Liquid Nitrogen (LN2).Microwave connections to the input loop and stub detector are made through co-axial rotating connectors, at the gimbal axis. The attitude of the thrust axis, along the centre line of the cavity, is controlled by a stepper motor. The angle is monitored by a digital detector.

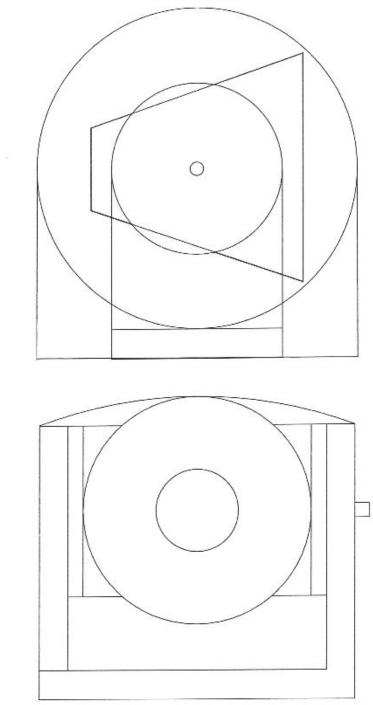

Fig.7. Thruster outline

3. Performance

The unloaded Q of the cavity is critically dependent on the temperature of the YBCO thin film as illustrated by the surface resistance shown in Fig.1. Thus the thrust produced is similarly dependent as shown in Fig.8. The thrust for a silver plated cavity, as described in the IAC-20 paper [2] is also given for comparison. Clearly thrust can be increased by additional cooling, however with the passive cooling techniques proposed this results in a mass penalty at spacecraft level. A static thrust at 77K, with an input power of 40W, is 512mN is assumed. The unloaded Q of the cavity is 2.1×10^6 at this temperature.

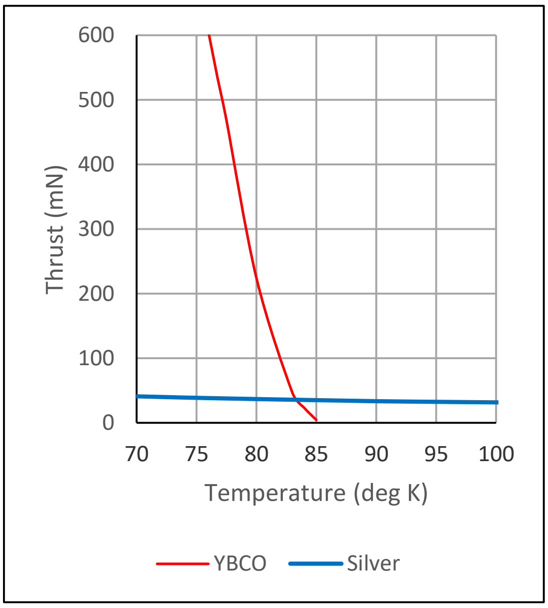

Fig.8. Thrust at 40W

The operation of a High Q EmDrive thruster must take into account the Law of Conservation of Energy.

The conservation of energy in an EmDrive thruster (and compliance with Newtons third law), was demonstrated by measuring the thrust/Load characteristic on a simple beam balance shown in Fig.9. The normalised test data is given in Fig.10. The maximum load test, where Load is greater than thrust, gave a zero balance reading, as thrust and its opposite reaction force summed to zero. The load was then decreased in increments and as the thrust overcame the load, a resultant force was measured on the balance, until the thruster lifted off at maximum balance reading at a Load of one third maximum. Further decrease in Load reduced the balance reading to zero close to zero Load. This zero Load condition demonstrates the need to provide an initial load force in orbit as described in the 2020 IAC paper [2].The tests were further described in a 2019 lecture given at the UK Defence Academy Shrivenham. An edited set of lecture slides can be accessed on the SPR Website [3].

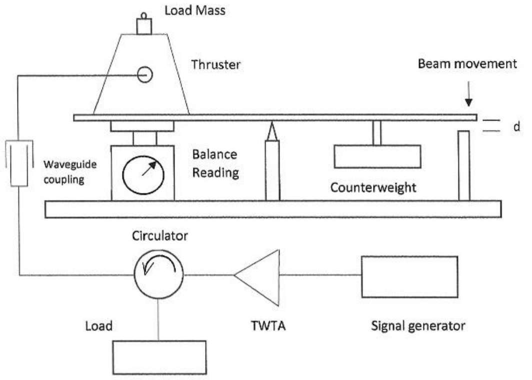

Fig.9. Simple Beam Balance

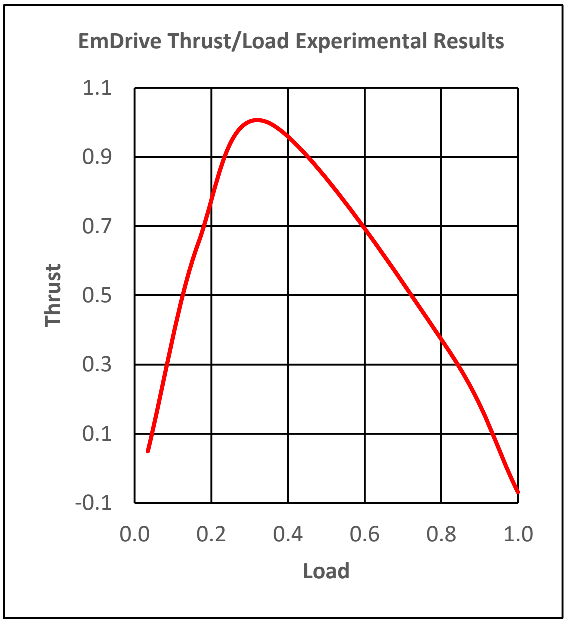

Fig.10. Normalised Test Data

In a paper published in 2015 [4], the total input energy for a mission is given by

$$\mathrm{Ein} = \frac{2PQDfV_{av}t}{c} \qquad (2)$$

Where Vav = average velocity over acceleration period

t = period of acceleration

The energy balance in an EmDrive cavity is shown in Fig.11.

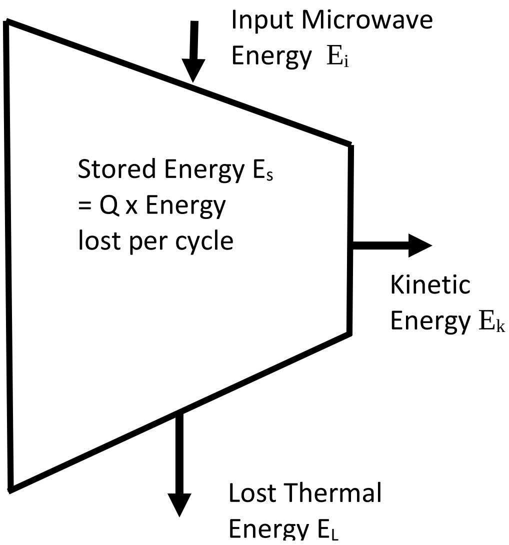

Fig.11. Energy balance in EmDrive cavity

Thus when the thruster is stationary, kinetic energy is zero and $T= T_0$
Where T_0 is the static thrust, which is a maximum value.
In this state both Q and stored energy E_s are maximum values.

Then $E_i=E_L$ and $E_s=Q_u E_L$

Once the thruster is allowed to accelerate, the thruster gains kinetic energy E_k. In this state
$E_i=E_L+ E_k$

This results in a reduction of E_s and thus a reduction of Q and T_0

The reduction of Q and T_0 continues throughout the period t, as the kinetic energy increases as a function of V^2 where V is the velocity of the spacecraft.
If t is continuous then T will approach zero and acceleration will cease.

Clearly t must be a pulse period, which is determined by the acceleration and therefore by the values of Ta, and m, where Ta is the mean value of thrust over the pulse period, and m is the mass of the spacecraft. The inter-pulse period is determined by the time constant of the cavity.

The effect of conservation of energy at spacecraft level can be seen in Fig.12, which shows the performance of the thruster under CW operation for a spacecraft mass of 90kg.The thrust approaches zero after 7.4 seconds, and acceleration approaches zero.

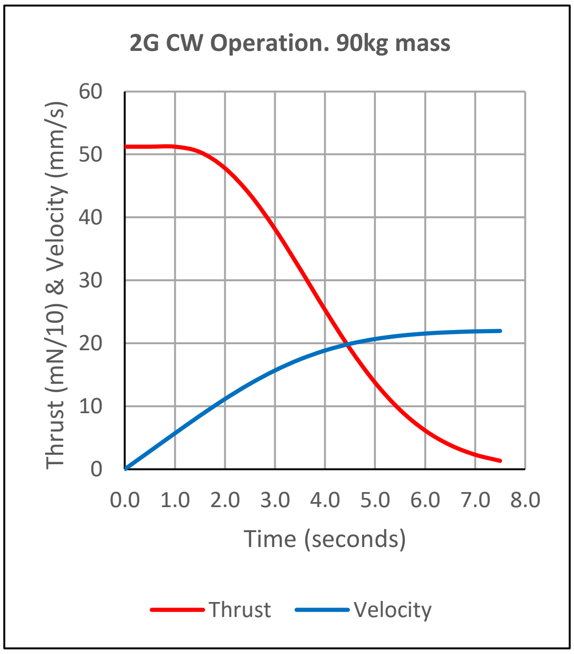

Fig.12. Performance under CW operation.

If the thruster is pulsed with 2 second pulses, the thrust is maintained at a mean value of 503mN, as shown in Fig.13. The inter-pulse period is 0.87 ms. The effect of pulsing the input was also originally shown in the simple beam balance tests, where a flattened Thrust/Load characteristic was obtained.

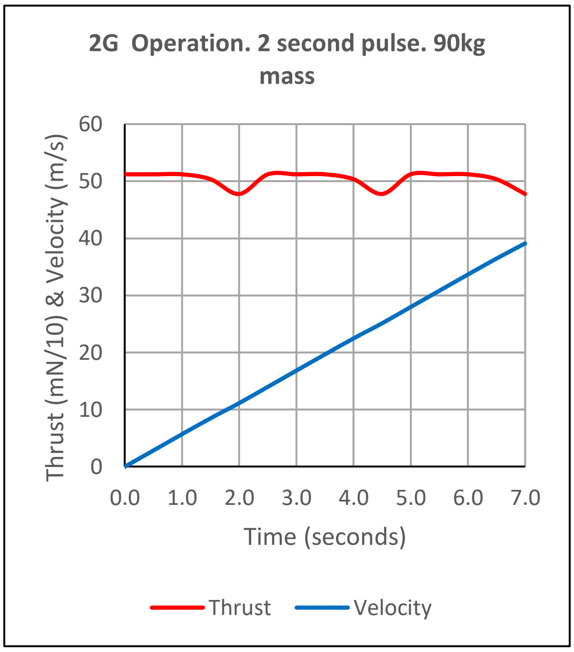

Fig.13. Performance under pulsed operation.

4.Spacecraft Description.

The prime challenge of integrating the 2G thruster into a small satellite is clearly the need to maintain the thruster at 77k whilst dissipating up to 40W of input power. This is achieved by use of a large thermal radiating structure kept in continuous shade using a sunshield and pointed into deep space. For some LEO operations an additional Earth shield would be required. The radiating structure comprises of four fins, fabricated from dual 0.5mm aluminium foil sections. The fins are deployed using a folded centre tube and end struts. The centre tube operates as a liquid Nitrogen heat pipe, where gaseous Nitrogen is fed from the thruster enclosures to an annular tube section, and liquid Nitrogen is pumped back along the central tube, into the spherical tank. The centre of mass of the deployed spacecraft is positioned at the centre point of the fixed central tube, with the two thrusters mounted at equal distance from the centre of mass. The spacecraft is shown in fig.14 in a deployed configuration, with the folded positions of sun-shield, radiator fins and solar arrays indicated.

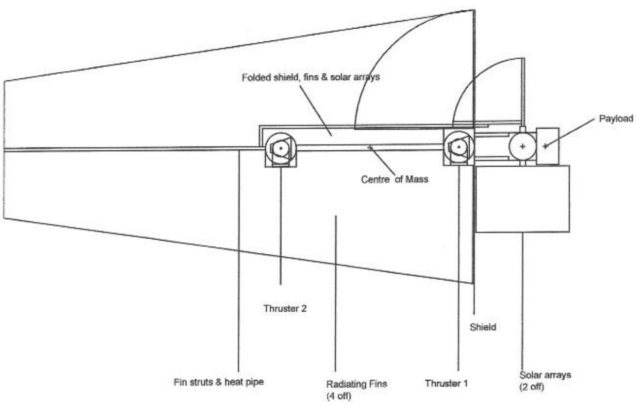

Fig 14. Spacecraft with solar arrays

Fully deployed, the spacecraft overall dimensions are length 415cm and width 200cm.

The gimballed thrusters give X and Z thrust vectors together with pitch attitude. Roll is given by momentum wheels, and together with the thrusters, enabling a Y thrust vector and Yaw attitude control. This degree of attitude and thrust vector control together with rotatable solar arrays enables the thermal radiators to be pointed towards deep space whilst carrying out all mission propulsion requirements. The thrusters are naturally capable of throttling over their full thrust range by simply controlling input power.

An initial mass budget is given in Table 1, where a nominal payload mass of 6kg is assumed and a contingency of 10% is allocated.

The 95W solar arrays allow science missions to the inner planets, and with a continuous thrust of 0.5N for a total mass of 90 kg, short flight times are possible. Alternatively, if the payload comprises of docking attachments or grappling arms, the spacecraft becomes an ideal vehicle for satellite repositioning missions, or for space debris disposal. A typical propulsion system lifetime of 15 years gives a total delta V capability of 1,252km/s, for a client mass of 100kg. This is unmatched by conventional propulsion systems.

Item	Mass (kg)
Thermal radiator panels	39.7
Flexible radiator struts	2.4
Sunshield	10.8
Nitrogen and tank	1.2
Heat pipes	1.5
Thruster assemblies	6
Microwave amplifiers	1.7
AOCS and momentum wheels	0.9
TTC electronics	0.5
Solar arrays	6.9
Batteries and power conditioners	1.6
Spacecraft structure	3
Payload	6
Mass contingency	8.2
Total mass	90.4

Table 1. Initial Mass Budget

If the solar arrays are replaced with an 110W NASA multi Mission Radio Isotope Thermoelectric Generator (RTG) the total mass increases to 128Kg. The additional mass requires a rebalancing of the space craft with the thrusters repositioned to maintain equal distance from the centre of mass. The RTG powered spacecraft, in deployed configuration, is shown in Fig.15.

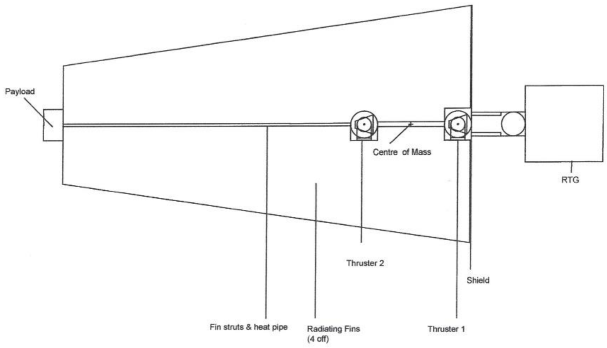

Fig.15. Spacecraft with RTG.

The spacecraft is now able to carry out fast flights to the outer planets or to enable Interstellar precursor missions. The RTG has a nominal life of 17 years [5], allowing extensive science missions to be undertaken.

References

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