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SNAP 10A REFLECTOR ASSEMBLY

DESIGN DESCRIPTION

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AEC Research and Development Report

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SNAP 10A REFLECTOR ASSEMBLY
DESIGN DESCRIPTION

(Title Unclassified)

By

R.I. JETTER

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ABSTRACT

This report summarizes the configuration and performance of the SNAP 10A reflector assembly. The performance requirements and design criteria are presented for the various phases of operation included in ground handling and testing, prestartup orbit, and orbital startup and operation. A design description is presented which discusses the function and configuration of the various components which make up the reflector assembly. Stress levels and margins of safety during launch and operation are summarized in the discussion of the structural and mechanical analysis. Reflector and component temperatures during ground testing and orbital operation are discussed in the Thermoanalysis Section of the report.

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I. INTRODUCTION

A. SNAP 10A POWER SYSTEM

The SNAP 10A reactor is intended for use as a primary power source on satellites and other space vehicles. Generation of power in space requires a compact system with remote control capabilities, long life, high reliability, and an ability to operate in a space environment characterized by a high vacuum, meteoroid showers, and other phenomena not common to terrestrial environments.

The SNAP 10A power system (Figure 1) employs thermoelectric elements to convert the heat developed by a compact nuclear reactor into electrical energy. Circulating liquid metal transfers the heat generated by the reactor to the thermoelectric elements. Electrical power is generated as a result of the heat transfer through the elements with heat rejection to space.

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Figure 1. SNAP 10A System

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Figure 2. SNAP 10A Reactor-
Reflector-Shield

B. SNAP 10A REACTOR

The reactor subsystem (Figure 2) includes the reactor structure and core, the reflector assembly, the radiation shield, and reactor control equipment. Although it is mounted on the reactor structure, the thermoelectric pump is not a part of the reactor subsystem. Reactor controlling elements such as timers and the reactor controller are located in the instrument compartment below the radiation shield.

C. REFLECTOR ASSEMBLY

The reflector assembly (Figure 3) is required to control reactivity during system startup and to shut down the reactor at the end of one year of operation. The reflector consists of a beryllium sleeve, approximately 2 in. thick, surrounding the reactor core.

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Figure 3. SNAP 10A Control and Reflector Assembly

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Control of reactivity is obtained by using four control drums which rotate into cavities in the reflector, thus decreasing neutron leakage and increasing reactivity. The reflector assembly can be divided into five subassemblies which overlap in many respects, but are sufficiently distinct to explain the various features of the completed assembly. These subassemblies are the reflector and control assembly, support assembly, ejection assembly, diagnostic assembly, and ground safety assembly. The ground safety assembly is discussed in Reference 1.

The succeeding sections of this report will present the reflector assembly performance requirements and design criteria, the operation and design configuration of the reflector components, and a discussion of the thermal and structural analyses which support the design. Test results will be discussed in the analysis section.

Some parts of the reflector assembly were developed as separate components. These components will be discussed in general; however, a detailed discussion will not be presented herein.

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II. PERFORMANCE REQUIREMENTS AND DESIGN CRITERIA

The reflector assembly is required to control the reactor reactivity level during reactor system startup and operation. It must survive and operate within the environments characteristic of:

- a) Ground handling and testing
- b) Launch
- c) Prestartup orbit
- d) Orbital startup and operation

A. SHOCK, VIBRATION, AND ACCELERATION

The most severe shock, vibration, and acceleration environment for the reflector assembly occurs during launch. Packaging, handling, hoisting, etc., are accomplished in such a way that ground handling loads do not govern the design of the reflector assembly. The ground handling limit load is 2 g in all directions.

To simulate launch conditions, the reflector assembly is tested in conjunction with the reactor structure. In addition, reflector assembly components and subassemblies are tested individually. Table 1 summarizes the shock, vibration, and acceleration test criteria for assemblies and components. These test criteria are developed from the acceleration loadings that must be reacted by the SNAP 10A system during launch. These loadings arise from three major sources:

1. The Propulsion and Maneuver Acceleration Loads

The propulsion acceleration load acts in the axial direction with an initial magnitude of 1.1 g. This acceleration force increases with time until burnout when it reaches a maximum of approximately 6.9 g. The guidance acceleration loadings due to maneuvering of the missile are small and result in lateral accelerations of less than 0.1 g.

2. Mechanical Vibrations Transmitted Through the Missile Structure

These vibrations occur due to the response of the missile at one of its natural modes. Since the important natural modes of the complete missile are below 30 cps, no significant mechanical vibrations with frequencies above 30 cps

TABLE 1

SHOCK, VIBRATION, AND ACCELERATION REQUIREMENTS FOR THE SNAP 10A REACTOR

	Shock				Vibration			Acceleration	
	Shape	Axes	Magnitude (g)	Duration (μ sec)	Axes	Magnitude (g)	Frequency (cps)	Axes	Magnitude (g)
Assemblies	Half sine wave	Long.	5.5	8	Long.	0.5 in. DA	5 to 12	Case (1) Long.	+7.5 to -2.5
		Lat. and norm.	1.5			3.5	12 to 400		
						7.5	400 to 3000	Lat. and norm.	± 1.0
					Lat. and norm.	0.5 in. DA	5 to 10	Case (2) Long.	± 2.0
						2.5	10 to 250		
						5	250 to 400	Lat. and norm.	± 5.0
Components	Half sine wave	Long.	20	6	Long.	1/4 in. DA	5 to 20	Long.	9.4
		Lat. and norm.	10			5	20 to 400	Lat. and norm.	6.25
						7.5	400 to 3000		
					Lat. and norm.	1/4 in. DA	5 to 20		
						5	20 to 400		
						7.5	400 to 3000		

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will be transmitted through the missile structure. The magnitude of these low frequency inputs peak at approximately 20 cps and are of the order of 0.15 g laterally and 1.5 g axially.

3. Acoustic Vibrations Transmitted Through the Atmosphere Around the Missile

The acoustical input to the SNAP 10A system is in a higher frequency range than the mechanical vibrations. Acoustic input is capable of inducing appreciable structural vibration in the frequency range from 30 to 3000 cps. These vibrations are most severe during the period immediately after the Atlas motors are ignited, and a 20-sec interval at the time the missile passes through Mach 1. Since the energy level of acoustic input is limited, it does not have as great an effect on massive items as on smaller components.

The qualification vibration tests specified in Table 1 were designed to provide a test using an electrodynamic shaker which would simulate the damage potential of the flight environment described above.

Two basic acceleration loading conditions were considered. In Case (1), Table 1, the axial static design load of 7.5 g was obtained by taking the maximum combination of acceleration loads due to booster thrust and the acceleration loads due to axial mechanical vibration. This maximum combination of loads occurs just prior to burnout. Immediately after the vehicle is released, and again right after Atlas sustainer or Agena cutoff, the payload could receive a low frequency transient vibration resulting in a 2.5 g negative acceleration.² In Case (2), the lateral static design load of 5 g was obtained by considering the maximum low frequency response of the SNAP 10A system immediately after liftoff. In the frequency range above 30 cps, the test levels were set to cause a response in each component at least as great as it might sustain during a flight.

Experimental evidence shows that acoustic vibrations cause severe accelerations in small components. The relationship between vibration response and weight was found assuming a single fixed amount of energy was available to vibrate each piece in the system. This energy naturally has more effect on the smaller items than on the large items. The design curve shown in Figure 4 based on this assumption shows the design vibration force varying inversely with component weight. The support or mounting brackets for all the components were designed in accordance with this curve.

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Figure 4. Design Load vs Component Weight

B. THERMAL

During ground operations, the reflector assembly is thermal-cycled as part of the reflector acceptance test procedure. Also, there may be as many as five thermal cycles of the reflector during the hot shimming operations in which the reflector thickness is adjusted for operating temperature. In both cases the reflector and component temperatures will be less than during steady-state operation in space. The determination of the operating temperatures in orbit are discussed in the thermal analysis section.

For full power operation in orbit, the reflector assembly must be capable of sustained operation at a reflector block temperature of 700°F. The reflector assembly components will operate close to the reflector block temperature with the exception of the following components which operate either hotter than the reflector block because they are adjacent to the reactor, or colder because they are insulated from the reflector and radiate to space (Table 2).

After the Compact Power Unit is inserted into its orbit, but prior to starting up the reactor, the reflectors will approach their equilibrium temperature in space. As discussed in the thermal analysis section, the maximum and minimum reflector temperatures occur during a full sun-full shade prestartup

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TABLE 2
REFLECTOR COMPONENT TEMPERATURES

Component	Operating Temperature (°F)
Temperature actuated band release device (TABRD)	1000
Electrically actuated band release device (EABRD)	500
Ejection spring	900
Support hinge	800
Reflector retaining band	500
Position indicator	500

orbit in which one reflector half is continuously pointed at the sun. Fifteen to 20 hr after launch, the reflector half pointed towards the sun reaches a maximum temperature of 250°F, the opposite reflector, which radiates to space reaches a minimum temperature of 0°F.

C. VACUUM

During orbital operation, the reflector must operate in a vacuum of 10^{-12} Torr. The reflector is acceptance tested as part of the reactor-reflector assembly at 10^{-5} to 10^{-6} Torr. During the nuclear qualification test (FS-1) and the hot shimming operation, the chamber pressure is in the range of 10^{-2} to 10^{-3} Torr.

D. RADIATION

For 1 yr of orbital operation, the maximum integrated radiation dose levels at the reactor top center are 1.5×10^{10} r gamma and 7×10^{18} nvt fast neutrons. During the nuclear qualification test (FS-1), the reflector assembly will receive a greater amount of neutron radiation than during 1-yr of orbital operation due to back scattering from the test vault walls. At the reactor top center, the radiation doses for 90 days of operation are: 3.8×10^9 r and 1×10^{19} nvt.

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E. CLIMATIC CONDITIONS

Normally, the reflector will be protected against severe conditions of sand, dust, salt spray, fungus, rain, temperature, and humidity. The possibility exists, however, that the reflector assembly might be exposed to uncontrolled environments for short periods of time.

F. RADIO INTERFERENCE

Reflector components must comply with MIL-I-26600, "Interference Control Requirements," Amendment 2, dated May 9, 1960.

G. RELIABILITY OBJECTIVE

The design reliability objective for the assembly for each mission phase is described in Table 3.

TABLE 3
RELIABILITY OBJECTIVES

Mission Phase	Reliability - This Phase Only	Cumulative Reliability Through End of This Phase
Launch and ascent	0.99918	0.99918
Startup	0.99661	0.99580
90-day operation	0.99843	0.99423
275-day operation	0.99575	0.99001

Note: Times specified are sequential

H. OPERATIONAL REQUIREMENTS

The reflector assembly is required to increase the reactivity of the reactor from a subcritical condition prior to startup to full power operation. This is accomplished by inserting the control drums into the reflector block. The reactor startup control period lasts 72 hr. At the end of this time, the reactor should have a stable outlet temperature. The reflector control system is then inactivated. Except for the initial 72-hr startup period, the reactor is passively controlled; that is, control is based on reactor temperature coefficient. At the end of operational life, or if there is a system failure (low converter output voltage) the reflectors will be ejected, thus shutting down the reactor.

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III. DESIGN DESCRIPTION

The reflector assembly shown in Figure 3 can be divided into five assemblies including the safety devices. These subassemblies overlap in many respects but are sufficiently distinct to explain the various features of the complete assembly. These assemblies are the reflector and control assembly, support assembly, ejection assembly, diagnostic assembly, and ground safety assembly.

A. REFLECTOR AND CONTROL ASSEMBLY

This consists of a beryllium sleeve approximately 2 in. thick, surrounding the reactor core. The inside of this sleeve is a cylinder while the outside is made up of plane sections approximating a cylinder.

Control of reflectivity is obtained by using four drums. In their full-in position, these drums complete the reflecting sleeve. However, they may be rotated to a position 135° from the full-in position leaving a cavity in the sleeve. Each drum may be increased in thickness with as many as three 1/8-in.-thick shims. Two of the plane sections of the main sleeve may also be increased in thickness with as many as three 1/8-in.-thick shims. The outer surface of the outer shims on the main beryllium reflector block are coated with high emissivity chrome oxide to enhance heat transfer from the reflector block. With the control drums in their full-out position, the reactor is adjusted to be \$5.90 subcritical at room temperature.

When the startup command has been received, squibs are fired in actuators adjacent to each control drum. This action pulls a pin releasing the drum. The two coarse control drums are spring-loaded and when released are immediately inserted. This adds \$4.60 of reactivity.

Fifty seconds after the startup command is received, the two fine control drums take their first step, and then move a half-degree step each 150 sec thereafter until reactor operating temperature is reached. It is approximately 7 hours after startup before the reactor outlet reaches operating temperature.

A temperature switch, located in the outlet NaK line, is set for $1010 \pm 10^\circ\text{F}$ and will control the reactor during full-power operation. When the outlet temperature drops below the set point, the fine control drums take another step inward. This continues until 72 hours after the startup command at which time the control system is commanded "off".

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Figure 5 is a top view of the reflector assembly showing the reflector block, control drums, actuator motor, snap-in spring, and upper drum support brackets.

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Figure 5. Reflector Assembly (Top View)

1. Coarse Control Drum Package

The unique features of the coarse control drum package include the snap-in spring, coarse control drum stop, bearings, and the drum release system.

The snap-in spring is a flat wire torsion spring made of Rene 41 which exerts a 10-in.-lb moment on the drum shaft in the full-out position and a 5-in.-lb moment on the shaft in the full-in position. The lower torque provides a factor of the safety of approximately 2 over the maximum expected bearing friction and guarantees that the drum will stop in the full-in position. Rene 41 was chosen for the spring material because of its high strength to weight ratio and low relaxation under load at elevated temperatures. When it is initially inserted, the coarse control drum rebounds from the drum stop approximately 90°. After three to five rebounds, this motion is damped out and the drum comes to rest on the drum stop.

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The control drums are supported at either end by self-aligning spherical bearings. These bearings prevent binding due to initial misalignment or thermal distortion, as the control drum is rotated into the main block. The bottom bearing and associated brackets carry all the longitudinal loads, the lateral being shared by both the upper and lower bearings and brackets. The bearing consists of a titanium ball with a cylindrical hole for the control drum shaft. The ball is held in a titanium socket having an aluminum oxide coating with a dry film lubricant to minimize self-welding. The control drum shaft is also coated with aluminum oxide and a dry film lubricant to minimize potential self-welding. The ball and socket assemblies are housed in titanium brackets which are attached to the upper and lower end of the reflector assembly. Titanium brackets connect the control drums and control drum shafts, which turn inside the ball and socket assemblies. Because of its high strength to weight ratio and low scattering cross section, titanium was chosen for the control drum brackets and other structural components which receive their greatest load during launch.

The drum release system includes the drum release actuator and drum lock bracket assembly. Each actuator has two M-130 squibs, though either squib firing alone will cause a successful actuation. The squibs fire into a chamber moving a piston which in turn pulls the pin to release the drum from the full-out position. The lock bracketry on the coarse control drum, which engages the lockout pin, incorporates a safety feature which prevents removal of the ground safety lock if the pin is not engaged with the control drum. The pin must also shear a lockwire to disengage the control drum. After the piston, which pulls the pin, has moved to the end of the chamber, it is held in place by collets which snap into place behind the piston.

2. Fine Control Drum Package

The unique features of the fine control drum package include its drum release system, the control drum actuator, gear linkage, and bearings.

The drum release actuator in the drum release system is identical to the one in the coarse control drum package. Since the brake on the control drum actuator prevents insertion of the drum, even though the lockout pin is removed, the spring-loaded safety feature mentioned above for the coarse control drum is not incorporated in the drum lock bracketry on the fine control drum. The bracketry does include a forked slide which may be disengaged to allow 2° of drum movement with a lockout pin and ground safety lock in place. This permits

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a check of the control system on the launch pad. During the boost phase, this slide will be engaged to hold the drum immobile.

The control drum actuator is a motor that rotates in finite steps. The windings are each connected in series with the brake on the motor shaft. When a signal is received from the controller, the brake is released and the shaft turns a finite distance. Four motor steps complete one duty cycle and rotate the drum $0.5^\circ \pm 0.1^\circ$. Each time the motor is operated, a full duty cycle is completed. The drive motor is mounted on a titanium bracket which is bolted to the main reflector block and also houses the upper control drum bearing.

Two gears link the control drum actuator to the control drum. The pinion gear attached to the motor shaft is made of Haynes Stellite 6B and the gear segment attached to the drum is made of titanium. The gear segment attached to the drum also functions as the upper drum support bracket. The gear materials were chosen to match the thermal expansion of the titanium motor and bearing mounting bracket. These gears are matched sets which limit the backlash with the stepper motor actuator brake on to 0.1° of drum rotation. The gear ratio is 13.65 to 1. A dry film lubricant is used to minimize potential self-welding of the gears.

The fine control drum bearings are similar in all respects to the coarse control drum bearings.

B. SUPPORT SYSTEM

The control and reflector assembly is mounted on the reactor in two halves. Each half is supported on two hinges at the lower end of the assembly. The halves are rotated into position on the hinges until stops located near the top of the reactor are contacted. The complete assembly is then held in position by a band around the upper end of the reflector halves. Both hinges on the side are of similar design, although one is restrained against lateral motion while the other is free to allow thermal expansion. Each hinge sits on a 1/4-in.-diameter pin attached to the reactor structure. The hinge is held down by a 3/8-in.-diameter pin attached to the reactor structure that bears on a cylindrical surface concentric with the 1/4-in.-diameter pin. The 3/8-in.-diameter pin is an eccentric pin and can be adjusted to obtain the proper clearance in the hinge. Ejection springs, described in Paragraph III-C, push upward on the reflector so that the 3/8-in.-diameter pin and cylindrical surface will always be in contact

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except during launch when maximum accelerations are present. Then the hinge will contact the 1/4-in.-diameter pin attached to the reactor structure. Coatings are used on the hinge to minimize potential self-welding. Positioning bolts are used on the upper end of the reflector assembly to adjust the position of the assembly. These bolts bear against the stop brackets attached to the reactor vessel. Again, coatings are used to minimize potential self-welding.

A bottom view of the reflector showing the lower hinge bracket and position sensor support plate is shown in Figure 6.

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Figure 6. Reflector Assembly (Bottom View)

The band to hold the assembly in place incorporates two springs to maintain the band tension within tolerance at all times. The tension of band is set at 165 ± 15 , $- 10$ lb at ambient conditions. During launch, the band will be heated to a maximum of 200°F , which will be hotter than the temperature of the beryllium reflector, but the springs will still maintain sufficient tension to overcome the acceleration forces during launch. During thermal acceptance testing and operation, the band will be cooler than the beryllium reflector, but the springs allow stretching of the band without increasing tension in the band to the yield point. Thus, the band is reusable after the thermal cycles expected prior to launch.

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The band material is 316 stainless steel, chosen because of its ductility and stability at operating temperature. The band springs are 17-7 PH stainless steel which has a very high yield strength when heat treated. A very high strength material was required to fit the spring into the space available on the band.

The retaining band is held out from the reflector block by standoffs. Flexible graphite inserts are used between the band and standoff to minimize self-welding. The band tension is approximately a factor of 15 greater than the total force required to shear all the potential self-welding bonds with the use of the graphite antiseal-welding insert.

The gap between the reflector assembly and reactor vessel is set to prevent contact and possible self-welding or intermetallic diffusion between the reactor and reflector. This gap must be as small as possible to maximize reflector worth. The minimum gap between the reactor and vessel occurs during reactor startup. During startup the beryllium temperature rises much slower than the reactor temperature. Because the fixed hinges are located 3-1/2 in. off the reactor centerline, the reflector centerline moves with respect to the reactor centerline during thermal cycles. To account for this, the reactor-reflector gap at ambient temperature is largest on the side of the reactor vessel opposite the fixed hinges. At the top of the reactor vessel opposite the fixed hinges, the minimum gap is 0.072 in. At the bottom the minimum gap is 0.069 in. On the side of the vessel closest to the fixed hinges, the minimum gap at the top is 0.020 in. and at the bottom 0.012 in. When the reactor first reaches full power, the reflector is approximately concentric with the reactor and the gap at the top of the reactor is reduced to a nominal 0.008 in. The minimum gap, which occurs at the bottom next to the fixed hinges, is 0.005 in. As the reflector temperature increases to operating temperature, the gap between the reactor and reflector increases.

C. EJECTION SYSTEM

Reactor shutdown may be effected by ejection of the control and reflector assembly. Ejection is accomplished by compression springs located at the bottom of the reflector halves. When the retainer band is released, the reflector halves are pivoted outward around their support hinges by the spring force. Prior to ejection of the thermal shield, which maintains the temperature of the converters during launch and insertion into orbit, the reflector halves can be rotated outward at least 7° by releasing the retaining band.

After the thermal shield is ejected, the reflector halves can be ejected completely. However, the two reflector halves will still be connected to the reactor by the electrical wiring. Seven degrees outward rotation of the reflector reduces reactivity by about \$17, and complete reflector ejection reduces reactivity by about \$21.

Two ejection springs are used for each reflector half. These René 41 compression springs are located beneath the reflector adjacent to the reflector half separation. Each spring exerts 100 ± 5 lb on the reflector at room temperature and 85 ± 5 lb at operation temperature. Since the maximum operating temperature of the ejection springs (900°F) is slightly less than $1/2$ the absolute melting temperature of the René 41, the rate of relaxation of these springs is very slow. At operation temperature, the ejection springs initially apply a total moment to each reflector half of approximately 470 in./lb. This is approximately a factor of 2 greater than the torque required to break the maximum anticipated self-welding bonds at the lower support hinge and between the upper positioning bolts. Based on this maximum self-welding bond and a conservatively high estimate of the spring relaxation rate, it will be at least 100 years after startup before the ejection springs have relaxed to the point where they can no longer overcome the self-welding bonds and eject the reflector. The nominal self-welding bonds are approximately an order of magnitude less than the maximum anticipated bonds. For the case of nominal self-welding, the ejection springs will retain enough force to eject the reflectors even after several thousand years in orbit. The ceramic coatings used to minimize potential self-welding between the upper positioning bolts and stop bracket are very stable at operating temperatures and any resulting initial self-welding will not increase as a function of time.

The hinges which support the reflector are described in Section III-B. When the reflector rotates outward about 15° , the $3/8$ -in.-diameter pin disengages from the cylindrical surface allowing the two parts of the hinge to completely disengage. The kinematics of this separation have been verified experimentally. The kinetic energy of the rotating reflector is sufficient to separate the reflector from the ejection springs, as the ejection springs become fully extended. Coatings are used between the ejection springs and the reflector structure to minimize potential self-welding.

Three distinctly different signals are used to initiate reflector ejection. All three signals activate an electrical device, which releases the reflector retaining

band. An electrical signal can be provided by:

- 1) Ground command through the umbilical prior to liftoff
- 2) Telemetry
- 3) A failure sensing device (low converter output voltage).

The failure sensing device starts a 1-min timer, which resets if a malfunction signal is removed. If the signal persists, a 1-hr delay timer is started. This in turn triggers the Electrically Actuated Band Release Device (EABRD).

The EABRD consists of one cylinder inside another brazed together with a low temperature melting alloy. These cylinders house a small electrical heater which receives power when the ejection signal is received. The band release device is built into the retainer band. When the heater raises the temperature of the braze to its melting point, approximately 1250°F, the two cylinders are pulled apart by the springs in the retaining band, thus severing the band. The 1/2-in. overlap of the two cylinders in the EABRD is less than the available stroke of the two springs in the band, thus the springs ensure complete separation of the device.

EABRD bodies, which are thin cylinders with band end fittings, are machined from René 41. Each of the tubular sections is approximately 3/16 in. in diameter and has a wall thickness of 0.008 in. The device is designed to operate from a 22- to 28-volt dc power source. At the minimum voltage (22 volts) band separation occurs in 4.5 to 5.0 sec and requires 900 to 1000 watt-sec of total energy. With an initial operating temperature of 500°F, the initial peak current is 20 amps and the average current during the first 5 sec is 8 amps. At the maximum voltage (28 v) heater lifetime is approximately 12 sec. The EABRD will still operate with the source voltage reduced to 10 volts with approximately 15 sec required to effect band separation.

As a backup to the EABRD, a thermal-mechanical device is also used to separate the reflector retaining band. This device, called the Temperature Actuated Band Release Device (TABRD), is actuated by a drop in temperature of the NaK in the outlet line adjacent to the reactor. The TABRD works on the principle of differential thermal expansion of two materials. In this design, a stainless-steel rod is used inside of a molybdenum tube. The two are rigidly fixed together at one end by a notched stud, which also serves as a shear pin

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between two overlapping end fittings of the reflector retaining band, and a bolt. The notch in the stud is in line with the mating surfaces of the band fittings. While the temperature is increasing, the steel rod, which has a much higher coefficient of thermal expansion than the molybdenum, is allowed to grow freely relative to the tube. On rising to a preset temperature ($925 \pm 25^\circ\text{F}$ at the NaK line) established by adjustment of the position of a stepped collar on the free end of the rod, an external type snap ring closes behind the step. Thereafter, when the temperature decreases below the preset temperature, the central rod is forced in tension. When the temperature reaches approximately 500°F , the tension becomes great enough to break the stud at the notched section and release the retainer band. A temperature that will cause the TABRD to release the retainer band can occur in one of two ways:

- 1) NaK flow stoppage
- 2) Loss of NaK.

The outer molybdenum tube of the TABRD is mounted in a beryllium cradle. This cradle is bolted to the NaK outlet line with a compressible graphite strip between the cradle and NaK line to improve heat transfer. To minimize radiation from the TABRD and to ensure that it approximates NaK line temperature, it is covered by a copper sheath and gold-plated radiation foil. The lower extremity is covered with a box-like enclosure of tantulum foil.

To prevent actuation (rupture) of the TABRD during acceptance testing, a spring-loaded nut is used to fasten the stud to the outer tube. When the tension rod shrinks after arming, the spring deflects thereby preventing rupture of the stud.

The retainer band is also designed to release upon reentry heating if reflector ejection has not already occurred. The brazed joint in the electrically actuated band release device will melt at about 300,000 ft by releasing the reflectors. If for some reason this does not occur, the entire band will melt at about 285,000 ft resulting in reflector ejection.³

D. DIAGNOSTIC INSTRUMENTATION

The Diagnostic Instrumentation provides the information required to analyze performance of the control and reflector assembly during operation and will be used in making operational decisions during orbital flight. This system provides

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information only and does not in itself initiate any control sequences. Insofar as the reflector assembly is concerned, its three main diagnostic components are position indicators, limit switches, and thermocouples.

A position indicator consisting of a position sensor and demodulator is provided for each fine control drum. The output voltage of the indicator varies with drum position to give the desired position information. The position sensor itself is mounted on a post opposite each fine control drum. The position sensor is attached to the post through a yoke which prevents any misalignments in the axis of rotation of the position sensor with respect to the control drum from causing excessive drag on the control drum.

Limit switches are installed on the reflector assembly to provide information on the position of both the coarse and fine control drums, the retaining band, and the main reflector block.

Thermocouples are provided on each half of the reflector assembly. These two thermocouples provide a continuous indication of reflector temperature since the reflector block is nearly isothermal.

E. WEIGHT

The weights of the reflector assembly components are listed in Table 4.

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TABLE 4
REFLECTOR ASSEMBLY WEIGHTS

Components	Weights (lb)	
	Individual	Total
A. Reflector and Control Assembly		
1. Beryllium		64.60
a. Blocks (with shims)	38.56	
b. Control drums (with shims)	26.04	
2. Drum Drives		11.71
a. Actuator motors	8.24	
b. Snap-in springs	0.36	
c. Gears	1.07	
d. Bearings	2.04	
3. Squib Actuators		1.18
B. Support Assembly		17.99
(Includes all component support brackets, control drum brackets, hinge brackets, and drum lock brackets)		
C. Ejection Assembly		6.01
a. Ejection springs	2.28	
b. EABRD	0.13	
c. TABRD	2.90	
d. Retaining band	0.70	
D. Diagnostic System and Wiring Harness		8.06
a. Position sensor	2.12	
b. Limit switches	0.24	
c. Wiring harness	5.70	
Total Weight		109.5

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IV. STRUCTURAL AND MECHANICAL ANALYSIS

In this section, the structural and mechanical analysis of the various reflector assembly components are discussed and summarized. For convenience, the reflector is separated into the same subassemblies as discussed in Section III, "Design Description."

The structural analysis is based on the loads and design criteria presented in Section II, "Performance Requirements and Design Criteria." Unless otherwise stated, the margin of safety referred to in the following discussion is based on the yield strength of the structural material. The allowable margin of safety based on the yield strength is zero. Based on the ultimate strength of the material, the minimum margin of safety is 25%.

A. REFLECTOR AND CONTROL ASSEMBLY

1. Bearings

The design of the support bearings for the reflector control drums is such that only the lower bearings react thrust loads. The loads acting on the drum bearings were determined using the design force given in Figure 4, "Design Load vs Component Weight." Each drum was assumed to be in its maximum weight configuration, i.e., including three beryllium shims. The maximum loads have been calculated to be 62.5 lb normal to each bearing centerline, occurring during maximum lateral launch acceleration. The maximum axial load on the lower support bearings is 125 lb, occurring during maximum axial launch acceleration. The lower bearing is retained by a titanium fitting. The critical stress in this fitting occurs due to bending. This has been calculated to be 26,600 psi, which is well below the allowable of 105,000 psi.

2. Gears

The fine control drum drive gears are designed to transmit the torque produced by the stepper motors. The maximum torque output of these motors is 90 in.-lb. In addition, the gear segment serves as a support bracket for the drum.

3. Brackets

The lower bracket is the more highly loaded of the two drum support brackets. This is due to the fact that all axial accelerations of the drum are reacted by the lower bearing only, thereby imposing a high bending load on the

bracket. The resulting bending stress has been calculated to be 63,000 psi. The bracket material is 6AL-4V titanium, and the margin of safety of the design at the noted stress is +91% based on yield strength.

4. Snap-in Spring and Snubber Spring

The coarse drum snap-in spring material is René-41. The material has been solution treated at 1975°F and aged at 1400°F. The spring is loaded in torsion, the maximum torque being 10 in. -lb. The maximum stress in the spring is 98,000 psi, allowing a margin of safety of +73% based on yield strength.

At reactor startup the coarse drum is released and swings to the full-in position as a result of the unbalanced energy of the snap-in spring. The drum is stopped at the full-in position by the snubber spring which is made of René-41 material with an allowable yield stress of 154,000 psi at 70°F. The energy absorbed by the snubber spring at the time of drum impact is 846-in. -lb. The associated stress is 127,000 psi, and the calculated margin of safety is +21% based on yield strength.

B. SUPPORT SYSTEM

1. Hinges

The reflector hinge pin and reflector eccentric pin are loaded in double shear and realize a maximum shear stress less than 2000 psi. Contact stresses, related to the reflector hinge bearing on the eccentric pin have been calculated to be 106,000 psi maximum during launch. The materials in contact are aluminum oxide on aluminum oxide. These materials were coated onto 6AL-4V titanium, the base material of the noted components. The published value of compressive strength of aluminum oxide is 280,000 psi. Vibration tests have been conducted and the coatings were noted to have chipped in localized areas. Interpreting these tests qualitatively, it has been judged that sufficient anti-self-weld material remains to maintain separation between the base materials and thus minimize self-welding in orbit.

Stress levels in the reflector hinge are very low with a maximum bending stress of 1100 psi.

2. Positioning Bolts

Loads in the reflector positioning bolts are derived from a combination of launch loads and reflector band tension. During launch, the maximum load in one of these bolts is 220 lb. During orbit, the maximum load is 150 lb. The positioning bolts are coated with aluminum oxide to minimize self-welding. Test data have been generated which indicate the strength of the self-weld bonds obtained with aluminum oxide bearing on aluminum oxide. The data yield three scattered points which have been incorporated to determine the strength of bond which could be expected to result between the positioning bolts and the drum stops. The maximum data point was 0.9 lb, resulting from a contact force of 16.75 lb. This indicates that a maximum bond strength of approximately 8 lb can be expected. After reflector band release, this bond would be broken by a reflector ejection spring force of 43 lb. The expected bond strength from the test data is a factor of 10 less than the available breaking force. In this case, the bond would be broken by an ejection spring force of less than 5 lb after the retainer band is released.

3. Retainer Band

During launch, the retainer band must hold the reflector halves in position against the upper positioning brackets on the reactor vessel. A moment balance based on a launch load of 320 lb derived from Figure 4, results in a required band tension during launch of 130 lb. During launch the band temperature will increase about 200°F thus lengthening the band. Since the reflector temperature does not change significantly during launch, the band extension will be taken up by the band springs, thus reducing the band tension. A 200°F increase in band temperature will result in a 25-lb decrease in band tension. Adding this to the minimum requirement of 130 lb results in a minimum room temperature band tension of 155 lb. As assembled on the reactor, the band tension is 165^{+15}_{-10} lb.

After steady-state orbital operation is achieved, thermal expansion of the reflector will compensate for the elongation of the retaining band and the resulting band tension will be about 180 lb. At this load, the tensile stress in the 316 stainless steel band is 14,400 psi which results in a margin of safety of 85% on the tensile yield at 500°F. Spot welded doublers are used at the band fittings to keep the stress levels low.

The maximum shear stress in the band spring is 127,000 psi which results in a margin of safety of 25% based on an ultimate shear strength of 17-7 PH in the CH 900 condition of 160,000 psi. At operating temperature, the band spring will relax somewhat. However, the band tension required to hold the reflector in place in orbit is less than 20 lb.

4. Reactor-Reflector Clearance

As discussed in Section III-C, the gap between the reactor and reflector is set to prevent contact during startup. The minimum gap analysis is based on a reflector temperature of 200°F and reactor outlet and inlet temperatures of 990°F and 890°F, respectively. The outlet and inlet temperatures have since been upgraded to 1010 and 900°F respectively. This does not significantly affect the minimum gap analysis. For the 316 stainless steel reactor vessel the thermal expansion coefficient is $= 10.3 \times 10^{-6}$ in./in.-°F; for beryllium, $= 8.2 \times 10^{-6}$ in./in.-°F. The resulting relative radial expansion is 0.036 in. at the top of the vessel and 0.033 in. at the bottom. The centerline shift is 0.026 in. At room temperature, on the side opposite the fixed hinges, the minimum reactor-reflector gap is held to 0.072 and 0.069 in. at the top and bottom, respectively. On the side next to the fixed hinges, the gaps top and bottom are 0.020 and 0.012 in. The resulting minimum gaps during startup are 0.008 and 0.010 in. at the top and bottom of the side opposite the fixed hinges and 0.008 and 0.005 in. at the top and bottom of the side next to the fixed hinges.

C. EJECTION SYSTEM

1. Ejection Springs

The reflector ejection springs are designed to exert a force of approximately 100 lb (maximum fiber stress level, 43,000 psi) at ambient temperatures and during launch. Upon heatup to a maximum temperature of 900°F during reactor operation, the force on the reflectors drops to approximately 90 lb from elastic modulus shift in the springs. Relaxation tests indicate that after approximately 1000 hr at 900°F, the force remaining in the springs is approximately 88 lb. Similar tests conducted at 1100°F indicate that 76 lb of force is still maintained in the springs.

The maximum anticipated self-weld bond between the reflector positioning bolts and the reflector stop is 8 lb. The stress relaxation rates indicate that the springs should still be capable of breaking any self-weld bonds even after 100 yr in orbit. This includes a factor for a possible tenfold increase in spring relaxation rate.

2. Electrically Actuated Band Release Device (EABRD)

The EABRD is fabricated from two concentric tubes with attachment points at each end which attach to the retaining band. For a band tension of 180 lb, the maximum tensile stress is 42,500 psi in the tubular section and 46,000 psi in the clevises. The resulting margins of safety are 260% and 230%, respectively, based on yield strength.

3. Temperature Actuated Band Release Device (TABRD)

The TABRD is designed to separate the retaining band when the NaK line temperature drops to 500°F after having attained operating temperature, and it must hold the band intact during launch and normal operation. The René-41 notched stud in the TABRD holds the band together by a shear load across the notched section. The stud is ruptured during cooldown by a tensile load. The cross-sectional area of the notched section is 0.0058 in.². For a band load of 180 lb, this results in a margin of safety of 216% based on an ultimate shear strength of 100,000 psi. This was verified in a series of shear tests in which the load required to shear the notched stud was 648 ± 38 lb.

For the TABRD notched stud to rupture after a given temperature drop in the TABRD, the difference in thermal contraction between the inner A286 tension rod and the outer molybdenum tube must exceed the sum of the following items:

- a) The elongation of the notched stud at rupture
- b) The extension of the inner rod and compression of the molybdenum tube due to the tensile rupture load in the notched stud
- c) Backlash due to clearances between mechanical interfaces.

A limited number of tensile tests showed that the notched stud would break in the range of 1200 to 1500 lb, with an approximate elongation of 0.005 in. The resulting temperature drop required to rupture the stud was estimated at $225 \pm 50^\circ\text{F}$. This was verified in a series of engineering tests of the TABRD assembly.

As discussed in Section III-E, the TABRD should actuate at a NaK line temperature of 500°F. As initially tested, the inner rod of the TABRD was too cool when the TABRD armed to actuate at this temperature. It was found necessary to add heat shields to reduce radiation losses and to add a compressible

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graphite material between the NaK line and the TABRD. These modifications raised the inner rod temperature at the arming point sufficiently to insure that the notched stud would rupture as intended.

D. DIAGNOSTIC ASSEMBLY

1. Position Sensor

The position sensor is supported opposite its respective fine control drum by a post which is bolted to the lower bearing support bracket. The position sensor is attached to the post by means of a yoke which compensates for misalignments between the position sensor and control drum axis. Based on loads from Figure 4, the stresses in the post and yoke are well below yield. Initially, a thin plate connected the bottom of the position sensor post to the bearing bracket. During low-frequency vibration tests, the position sensor had a large amplitude response, vibrating like a concentrated mass at the end of a cantilevered beam. A stiffening bracket was added, which approximately doubled the natural frequency and attenuated the response.

V. THERMAL ANALYSIS

The thermal performance of the SNAP 10A reflector and components is discussed in the following six sections. Section A presents analytical results for orbital startup and steady-state operation of the reflector and control drums in a space environment (complete vacuum). In the analysis of Section A, the shim interface resistances were considered to be negligible. In Section B, the effects of shim interface resistance on reflector temperature are discussed. The effects of a nonperfect vacuum on reflector temperature during ground testing are discussed in Section C. In Section D the results of ground testing (S10FSM-1) are compared with analytical results for identical test conditions (isothermal NaK temperature of 1000°F and no internal heating in the reflector control drum combination). Minimum and maximum reflector and control drum temperatures prior to orbital startup are discussed in Section E. Component temperatures are discussed in Section F.

A. STARTUP AND STEADY-STATE OPERATION

The reflector temperature startup transient depends on the initial average temperature of the reflector control drum combination, and the reactor startup temperature-power transients. After orbital insertion and prior to startup, the initial temperature of the reflector-control drum combination is determined by the prestartup temperature of the vessel and the space background temperature. The space background temperature is the equilibrium temperature of a body with no internal heating, radiating to a 0°R space and receiving solar radiation. The prestartup temperature of the vessel will range from 75° to 150°F, depending on the orbit of the vehicle. For the analysis, an average vessel temperature of 110°F was assumed. The equivalent space background temperature varies from +240 to -200°F, depending on the position in space and the emissivity of the surface considered. A space background temperature of 130°F compares to a heat flux midway between the two extremes of heat flux, therefore, 130°F was assumed for the analysis. The result of the assumed temperatures is an average prestartup temperature of 120°F for the reflector-control drum combination.

The average vessel NaK temperature and reactor power transients during orbital startup are approximated by a series of linear ramps. Since the response of the reflector-control drum combination to the temperature and power transients

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of the vessel is very slow, the approximation of linear ramps is negligible. If surface contact between reflector and control drum and between reflector and vessel are neglected and a complete vacuum is assumed, the only mode of heat transfer between the various structures is radiation. Shim interface resistance is neglected for this analysis, but is taken into consideration in a later section. The control drums are assumed to be fully inserted during the transient as well as at steady state. This assumption maximizes the calculated temperatures. Since the conductivity of beryllium is high, the axial and radial gradients in beryllium are negligible. Therefore, each continuous structure is characterized by a single temperature. The surface areas and surface emissivities used in the analysis appear in Table 5. The total internal heat generation in the beryllium due to neutron and gamma heating was determined by integrating the average axial heating rate across the thickness of the reflector-control drum combination. The thickness used for the reflector-control drum combination was the

TABLE 5
AREAS AND EMISSIVITIES OF REFLECTOR
AND CONTROL DRUM SURFACES

Surface	Area-ft ²	Emissivity
Exterior surface of vessel	2.40	0.3
Inner surface of reflector	1.99	0.2
Reflector cutouts for control drums	1.99	0.2
Convex surfaces of control drums	2.32	0.2
Flat surfaces of control drums	1.88	0.2
Surfaces of control drums exposed to vessel	0.41	0.2
Top of reflector	0.67	0.2
Flat external surfaces of reflector		
Reflector shims*	0.747	0.85
Unshimmed edges of shimmed faces*	0.254	0.20
Unshimmed faces*	0.807	0.20
	<u>1.808</u>	<u>$\bar{E} = 0.47$</u>

*The reflector shims coated with chrome oxide do not completely cover the face of the reflector.

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thickness of an equivalent volumetric annulus. The average heating rate was also integrated across the control drums, assuming that the control drums were completely inserted. The internal heat generation in the reflector was then obtained by subtracting the internal heat generation in the control drums from the internal heat generation in the reflector-control drum combination.

The steady-state values of reflector and control drum temperatures, neglecting shim resistances, are 615 and 605°F, respectively. Steady-state is reached approximately 14 hr after sensible heat is reached. Due to the high heat capacity of beryllium, the temperature response of the reflector to rapid increases in reactor vessel temperature and power is slow. Therefore, the maximum temperature differential between the vessel and the reflector will occur when the vessel temperature reaches its operating level (1.9 hr after sensible heat). The maximum differential expansion (minimum gap) will occur at the time of maximum temperature differential. Therefore, the problem of critical differential expansion will occur when the vessel reaches its steady-state temperature, rather than when the reflector reaches its steady-state temperature.

B. EFFECTS OF SHIM INTERFACE RESISTANCES

The effect of shim interface resistance to heat flow was not considered in the original analysis above. In order to obtain good heat transfer across the shims, the following are required:

- 1) Good surface finish
- 2) Flat surfaces
- 3) Soft metal or metals
- 4) High pressures forcing the metals together.

It is doubtful if any of these requirements are met with the bolted shim design. Since very little is known about shim interface resistances, the values assumed for contact coefficients can only be considered "best guess" numbers. A steady-state increase of 75°F in reflector temperature (to 690°F) will result from an effective contact coefficient of 25 Btu/hr-ft²-°F. The steady-state control drum temperature increased 60°F (to 665°F) as a result of the same assumption. Figure 7 presents the reflector-control drum temperature response during startup, including the effects of shims.

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Figure 7. Temperature Response of the SNAP 10A Reflector and Control Drums During Startup Including Effect of Shims

C. EFFECTS OF VACUUM LEVEL DURING GROUND TESTING

The presence of gas in the vacuum chamber during ground testing will increase the reflector and control drum temperatures relative to operation in a space environment. The temperature increases are due to conduction across the gap between the vessel and the reflector-control drum combination. The conduction through the atmosphere of the vacuum chamber varies with the composition of the atmosphere. At a pressure of 1μ (10^{-3} Torr), the reflector temperature is 5°F (air) to 10°F (hydrogen) higher than the reflector temperatures in a complete vacuum. At a pressure of 20μ the reflector temperature is increased by 50 to 80°F .

D. SNAP 10A FSM-1 TEST RESULTS

The temperature obtained by the flight thermocouples on the reflector during 90-day operation of S10FSM-1 was 670°F . The vacuum level during FSM-1 testing was approximately 10μ . The previously calculated reflector temperature of 570°F was based on the identical conditions of constant NaK temperature of 1000°F and no internal heating in the reflector, assuming the gas in the vacuum chamber was air. The remaining 100°F of temperature difference was

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due to either the effects of shim resistance or to a combination of shim resistance and effects of the hydrogen content of the atmosphere in the vacuum chamber. If the atmosphere was hydrogen rich, the calculated reflector temperature would be from 0 to 45°F higher than the 570°F quoted above for an atmosphere of pure air. Further verification of the effects of shim resistance will be obtained from FS-1 testing.

E. MAXIMUM AND MINIMUM TEMPERATURES IN ORBIT PRIOR TO STARTUP

The maximum and minimum temperatures of the reflector-control drum combination will occur in a constant sun-constant shade orbit with one reflector half completely in the sun and the other half completely in the shade. The solar heat flux to the reflector-control drum combination was integrated over the orbit. For conductive heat transfer through the brackets and supports between the vessel and the reflector and between the reflector and the control drums, an interface contact coefficient of 200 Btu/hr-ft²°F was used. An isothermal vessel temperature of 40°F was assumed. The minimum allowable temperature to prevent plugging of the NaK is 40°F.

The transient temperature behavior of the reflector-control drum combination was studied for a 20-hr period (Figure 8). The initial temperature of the reflector-control drum combination was assumed to be 40°F. After 20 hr, the reflector half and the control drums in the sun reached 250 and 220°F, respectively. The reflector half and the control drums in the shade reached 1 and -1°F, respectively, in the same time period. Extrapolating from 20 hr, the maximum attainable reflector and control drum temperatures would be approximately 270 and 235°F, respectively. Similarly, the minimum attainable reflector and control drum temperatures would be approximately -35°F.

F. REFLECTOR COMPONENT TEMPERATURES

The temperature of the various reflector components which are directly attached to the reflector are greatly influenced by the temperature of the reflector.

The average temperature of the position sensor, during full-power operation with the control drum covering the window to the reactor vessel, was 510°F. An equivalent space background temperature of 70°F was assumed.

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The average temperature of the stepper motor housing during full-power operation was 600°F. In establishing the performance requirements for the reflector assembly components, the conservative assumption was made that those components which mount directly on the reflector, including the stepper motors, operate at the same temperature as the reflector block.

The maximum ejection spring temperature was assumed equal to the reactor inlet temperature. The retaining band was estimated to operate at a maximum temperature of 500°F.

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Figure 8. Pre Startup Temperature Transients for Selected Nodes in a Constant Sun-Shade Orbit

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