Low-Cost Solar Electric Testbed for Ion Thruster Systems

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A novel concept of spacecraft design has been developed to meet the high electric power demand of ion engines and the low payload and small fairing volume constraints of small launchers. It uses a light weight circular solar array. In orbit, the array is deployed by centrifugal force and serves as a gyroscopical stable platform in order to test the axially mounted ion thrusters. The circular array leads to a compact spacecraft: a 1kw testbed satellite can be built less than 200 lb in weight. Two unfolding processes of the array have been tested successfully. A new solar cell connector technique has been initiated which exhibits a high flexibility, a great resistance against thermal gradients and a reduction of fabrication costs of arrays.

Introduction

MORE than ten years ago, scientists and engineers also began to develop ion thruster systems in Europe. In Germany, the development of two ion engines has been completed so far in the laboratories: namely that of the Radio Frequency Ion Thruster RIT 10 of Professor Loeb of University of Giessen and the Electrostatic Kaufman Thruster ESKA 18 of Dr. Au, DFVLR Braunschweig. Now, these engines have to be tested in space.

Problem

From economic considerations, only Scout-class launch vehicles are eligible for the first test mission. This choice seems to be impossible taking the present state-of-the-art into account. Neither a 1 kw rigid panel solar generator nor a roll-up array of that power would fit under the fairing of only 2½ ft useful diameter together with a three axis stabilized satellite. Furthermore, an oversophisticated design tends to increase missions cost and to reduce its reliability. Hence, a novel concept of spacecraft design had to be invented to achieve the primary aim of this mission—continuous operation of at least two ion engines for six months in space.

Configuration of Spacecraft

The basic idea is to use a flexible circular solar array which is stretched out radially from a cylindric satellite by the centrifugal force of spinning (Fig. 1). No rigid structural components are necessary to support the solar cell blankets. Hence, the power-to-weight ratio of this array will be superior to any other solar generator design.

In order to get a maximum of electric power output, the array has to be sun-oriented. This is done by pointing the spin axis at the sun every time. Because of the spin axis' large moment of inertia and the high damping potential of the flexible substrate, there will be only little effects to the spacecraft's attitude from disturbing torques.

To avoid any unwanted changes of orbit parameters, pairs of back-to-back mounted ion motors are installed axially. During normal mode of operation, they eject an equal amount of mercury propellant in opposite directions. Hence, their thrust is fully compensated internally and no effect, neither to the spacecraft's attitude nor its orbit, occurs. To evaluate this configuration further, feasibility studies including several types of ion engines, launchers, etc. have been worked out.[1,2]

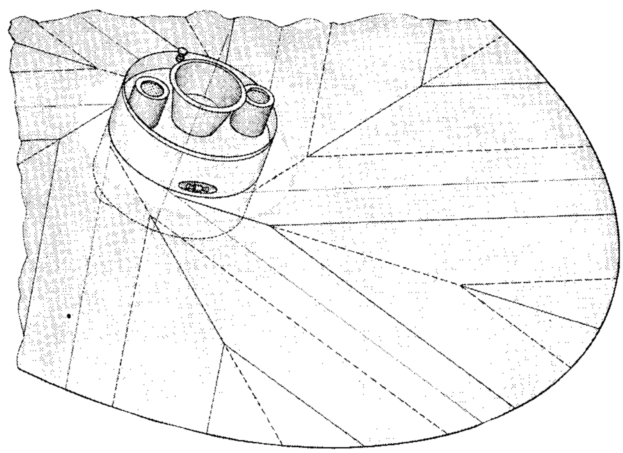

Fig. 1 Spinning testbed satellite.

Ion Engines

Herein, a test mission for the RIT 10 thruster is suggested. Its main difference from a Kaufman engine is it has electrodeless self-sustaining rf-discharge to ionize the mercury vapor. Ten years of work on this principle led to a very compact engine, see Fig. 2. It is integrated with its rf-transmitter

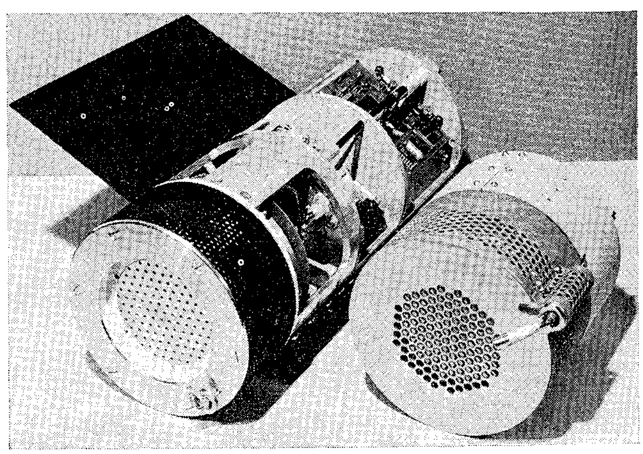

Fig. 2 Radio frequency ion thruster RIT 10. Left: Laboratory prototype with PCU; right: Mechanical prototype.

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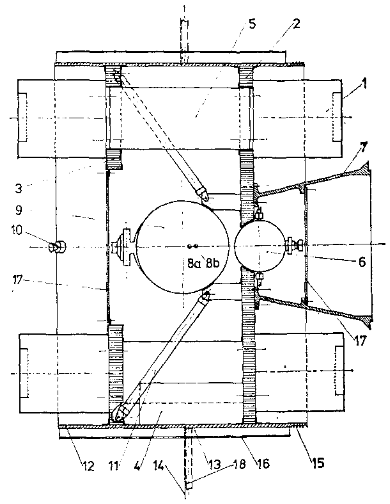


Fig. 3 Cross section of spacecraft.

and the electronic control units to a cylinder 15 cm in diameter. Its weight is only 1.65 kg; the total power consumption including the loss of the power conditioning unit (PCU) at nominal thrust level of 10 mN in about 400 w (Ref. 3). This thruster has been operated for more than 5000 hr is a space chamber and has survived severe environmental tests unaffected.

Spacecraft Design

To accommodate a maximum number of independent thrusters to a very small spacecraft, heat balance will be of primary concern. Figure 3 outlines how four RIT 10 motors can be incorporated into a tiny satellite. The ion thrusters are mounted rigidly to the equipment platforms. Two of them are fed by a single PCU. They are interconnected by a thermal conductor plate, which serves to heat a thruster during non active periods. The propellant vessel is located on the spacecraft's spin axis inside the launcher adapter near the center of gravity. As the centrifugal force separates the liquid mercury from vapor, a rather simple pressurization system, if any, might be used.

The cylindric outer shell, 70 cm diam, is made of solid aluminum alloy for better heat conduction. To maintain a temperature of the high-power electronics of less than 60° C, these units have to be mounted to this massive shell to radiate their power loss directly to space. Out of weight saving purposes this shell is milled chemically to proper thickness and shape.

At the outside the shell carries the 1 kw solar generator in stowed position. The thermal control is passive, but might include some electric heating. The spacecraft's total weight at launch is about 75 kg, see Table 1.

Table 1 Mass breakdown

Propulsion system, including:		20.0 kg
4 RIT 10 thrusters[3]	4.44	
4 electronic control units	2.16	
4 external control units	0.60	
2 power conditioning units[3]	4.60	
Mercury propellant	7.40	
Propellant storage, piping	0.80	
1 kw solar array, including:		11.0 kg
22,680 Si-solar cells, 200μ	4.20	
22,680 cover glasses, 100μ	2.00	
22,680 Stripline connectors	0.18	
Cover glass adhesive, 40μ	0.40	
Solder, appr. 5μ thick	0.40	
Ag-clad Kapton film, 13 m^2	1.60	
Flat cable, about 100 m	0.30	
Cushioning pads	0.65	
Packing bandage, Kapton film	0.10	
Pyrotechnique and electronics	1.17	
Structural subsystem, including:		15.8 kg
Cylindric outer shell	7.2	
Equipment platforms	1.6	
Conductor plates	0.7	
Tubular struts	0.4	
Heat shields	0.5	
Spacecraft adapter	3.4	
Bracketry	2.0	
Telemetry, telecommand, housekeeping		10.0 kg
Attitude measurement and control incl. YoYo, nutation damper		4.8 kg
Battery incl. charger		4.3 kg
Cables and wiring		5.2 kg
Thermal control		1.6 kg
Balance weights		1.0 kg
Contingency		1.3 kg
Total weight of satellite		75.0 kg

Proposed Mission

The mission calls for at least six months continuous operation of two engines in space. To avoid unnecessary risks from engine shut-down and cooling, the Earth shadow has to be shunned for the first test mission. That requires a sun-synchronous polar orbit at least 500 km in height.

After launch the spacecraft will rotate at 160 rpm around its spin axis which lies then in the plane of its orbit approximately normal to sun vector. To lessen gyroscopic stability, the YoYo will be released. That reduces the spin rate to about 50 rpm. Then, the spin axis is pointed to sun by spin-synchronous pulsing of the attitude control jet. After that, the strained bandage of Kapton film that compresses the flexible solar array at the surface of the spacecraft, is cut, and leaves the satellite because of its prestressing. The solar array is stretched out by the centrifugal force radially to a 4.1-m-diam circular plane array, which can provide its full power of 1 kw immediately. While the angular momentum remains constant, the spin decreases to 10 rpm. After a few seconds, any waving and coning will be damped out by the inner friction of the array's flexible substrate material, and the spacecraft represents a stable platfom for test of the ion thruster system.

Test Mode

A typical mode of operation will be to run two ion thrusters on one side of the spacecraft at their nominal thrust level. No change of the testbed's attitude will occur, since no torque is executed with respect to the spacecraft's center of gravity. The effects to the orbit are very small and cancel themselves during a full orbit revolution. The same is true if all four thrusters work at half thrust level or if they are switched on and off randomly. Each engine's operation will be monitored on ground by its telemetered performance data. The spacecraft's attitude will not be influenced if any thruster fails, since there is no balance problem. The center of pressure integrated over one revolution coincides with the spacecraft's center of mass automatically.

To point the solar generator at the sun every time, the spin axis has to be tilted approximately 1° per day. This might be accomplished by the cold gas attitude control system. It can be done also by an automatic control of the ion engine's thrust level. The spin-synchronous output signal of a simple sun sensor acts on the beam voltage of a thruster in a proper phase. Thus, the thrust is varied and the resultant net torque pushes the spin axis back into sun direction.

The installation of an equipment, which measures the produced thrust of an ion motor directly, has been avoided in order to maintain the spacecraft's simplicity. But from the change of orbit parameters, the effective thrust can be calculated on ground, if the motors are operated in a proper manner.

Circular Solar Array

The major new feature of this satellite is its circular solar array. Rigid fold-out and flexible roll-up solar generators include a lot of voluminous sophisticated mechanical gearing to survive launch loads and to provide proper deployment and function in orbit. Therefore they tend to be heavy and expensive.

Because of their great length, they suffer from considerable thermal deflections, they introduce disturbance torques from solar pressure, gravity gradient, etc. to the spacecraft, and their natural bending frequencies are low; thus causing the danger of interference with the spacecraft's attitude control system.

These problems could be avoided by the use of a circular solar array. In stowed position it is folded compactly against the cylindrical outer skin of a spacecraft, see Fig. 3, while in orbit it is stretched out radially to form an annular plane perpendicular to the spacecraft's main axis (Fig. 1). The diameter of that array is minimum, and there is no center-of-area (solar pressure) center-of-mass offset. Nearly all disturbing torques are avoided. This idea was investigated first for spinning systems and then for three axis stabilized ones and led to the following developments.

Stepwise Unfolding Process

First, an evident but knotty manner was used to wrap the circular array and to deploy it, see Fig. 4. The flexible solar array, consisting of many modules 2,3,4,5, is folded in a "meandric" manner to the outer surface of a cylindric satellite 1 and is compressed there by a bandage of Kapton film 6. In orbit, this film is cut and leaves the spinning

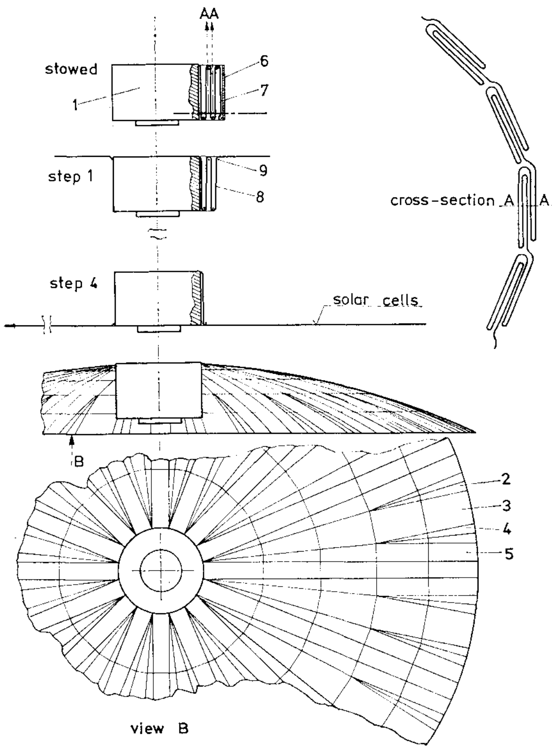
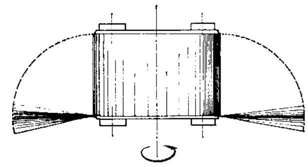


Fig. 4 Stepwise unfolding process.



	before unfolding	after unfolding
moment of inertia	Θ_1	Θ_2
spin rate	ω_1	ω_2
angular momentum	$\Theta_1 \omega_1$ =	$\Theta_2 \omega_2$
energy content of system	$E_1 = \frac{1}{2}\Theta_1 \omega_1^2$	$E_2 = \frac{1}{2}\Theta_2 \omega_2^2$
difference of energy content	$\Delta E = \frac{1}{2}\Theta_1 \omega_1(\omega_1 - \omega_2)$	

Fig. 5 Energies of unfolding.

satellite. Then a string around the outer layer 7 of modules is removed, and this layer swings out in a first unfolding step. When the resultant waving is damped by the friction inside the flexible material, the unfolding of the second layer 8 is initiated by releasing the next string of circumference 9. Finally, a spinning circular array is deployed, which might have a parabolic size to use its backside as a rf-reflector.[1]

Dynamics of Unfolding

It is difficult to calculate the dynamics of this unfolding process exactly, since there are many uncertainties. But the energy content of the system can be examined properly, since no energy transfer to or from the outside takes place, see Fig. 5. A calculation reveals that the rotational energy of the satellite is decreased after one unfolding step by approximately 20%–50%, which has to be dissipated by dilatation and inner friction of the waving array.

A couple of elongation tests on widely used array substrates proved the damping potential of Kapton H film to be high enough to dissipate the released energy through only one cycle of elongation and contraction.

Several mockups of complete arrays, about 2 m in diameter employing up to 2200 dummy cells and also several "Stripline" connected silicon solar cells have been built to investigate the stepwise unfolding process. In spite of the fact that the spinning array showed heavy flutter and waving under atmospheric conditions due to air drag, no silicon solar cell was damaged; in vacuum an extremely stable steady-state rotational moving appeared a few seconds after the start of the stepwise unfolding process.

Wrap-Up Solar Array

Much research work has been spent to gain a less complicated manner to stow the circular solar array. That can be achieved by a novel art of packing circular sheets to the outer surface of a cylindric hub, see Fig. 6. The circular array 1 is folded nearly diametrically in straight main folds 2. They form a certain constant angle α with respect to the radial direction at the cylinder's periphery.

Intermediate folds 3, which split the angle between the main folds, are pleated in the contrary direction. So prefolded, the array can be wrapped around the hub 4 smoothly. If this roll becomes too long, subfolds 5, which are pleated parallel to the main folds at a distance H but in alternate directions, might be used to wrap the overlapping intermediately. Areas of nearly any diameter can be wrapped on a given cylinder. All modules have the same width, which is equal to the height H of the hub. Apart from small strips along the folds, the segments are covered fully with solar cells. Hence, a conventional packing factor might be obtained.

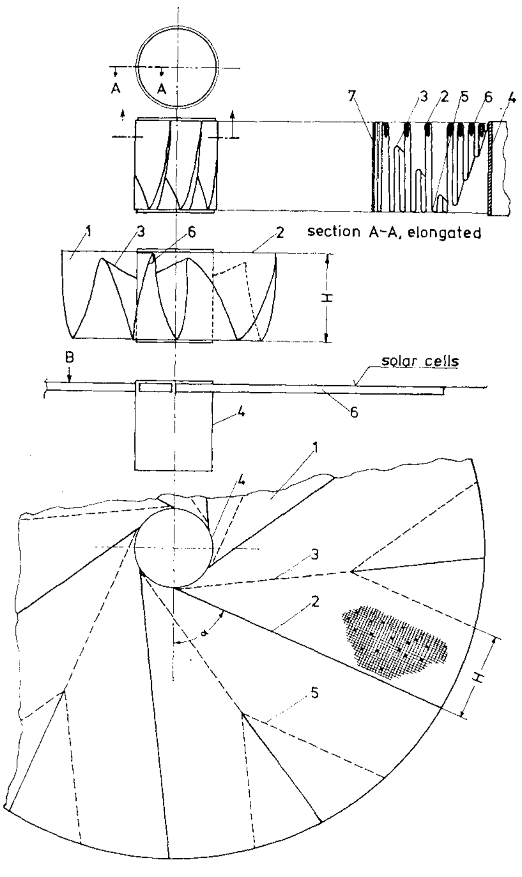


Fig. 6 Wrap-up circular solar array.

The start of this unfolding process is very similar to that described previously. When the strained bandage of Kapton film 7 is removed, the array swings out, but instead of radially in a more tangential smooth motion. As there are no cross-over folds but merely accordion type single folds, no danger exists of tangling.

Central Supported Solar Array

The use of the circular array is by no means restricted to spinning spacecrafts. Spring members, like steel tape or elastic ribs, might be attached to the main folds of the array and wrapped together with the blankets onto the hub. For deployment the springs are released and deploy the array in a smooth motion. That has been proved by means of several models, see Fig. 7.

Compared to rigid panel- or roll-up solar generators, this array offers a lot of advantages: 1) the relative short ribs lead to light structural weight, height bending frequencies, and little thermal deflections; 2) the length of the electric power lines is minimum; 3) a negligible stowage volume is required under the launcher's fairing; 4) the array fits well into given space chambers; 5) a proper designed array can be handled in deployed status under 1 g condition; 6) from the uncomplicated design, development-, fabrication-, and test costs of large arrays will be highly competitive. Of course, the use of the circular array aboard a communication satellite requires an unconventional spacecraft design.[4]

Solar Cell Module Technique

To prevent the prevalent failure mode of solar arrays, the open circuit contact,[5] and to avoid breakage of solar cells during ground handling and deployment, a new interconnector

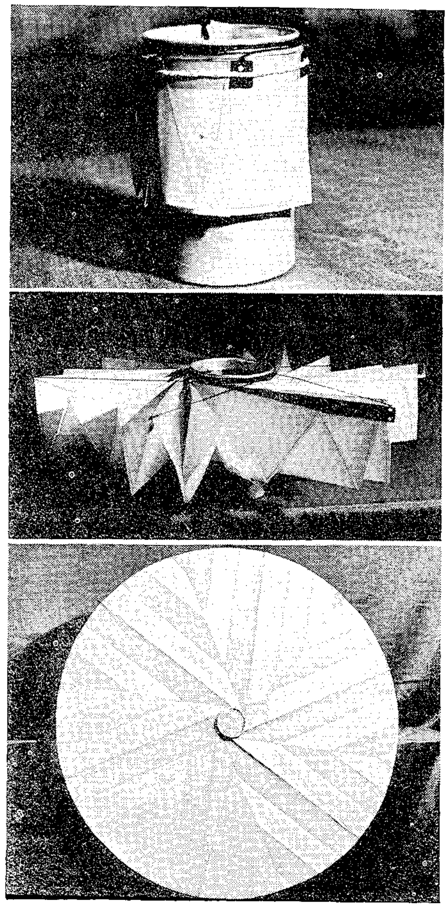


Fig. 7 Unfolding sequence of the central supported solar array. A—Stowed. B—Semideployed; note strings for speed control and automatic redeployment. C—Fully deployed (Model).

has been developed, the "Stripline"-connector. It consists of multiple small parallel metal strips, which are held in place by a little sheet of plastic. Usually it was fabricated by photoexposing and etching copper clad Kapton film into forty to seventy parallel strips (per 20 mm), each about 3 mm long. The tensile strength of a Stripline, soldered to two 2×2 cm silicon solar cells, is about 100 N; the flexibility is far better than that of a conventional, e.g., silver mesh connector.

Stripline connected solar cells survived as many as 1000 thermal shocks from dipping into liquid nitrogen and heating by hot air, while other connectors failed between 10 to 100 cycles. This can be attributed to the small size (0.2×0.4 mm) of a single connecting point. Hence, the severe thermal mismatch between the silicon of the cells and the silver of its contacts can be compensated by tolerable stresses and the silver's ductility. To provide reliability and a sufficient cross-section for low resistance, many connecting strips are needed. To lessen fabrication costs, an integral assembly technique might be used, see Figs. 8 and 9.

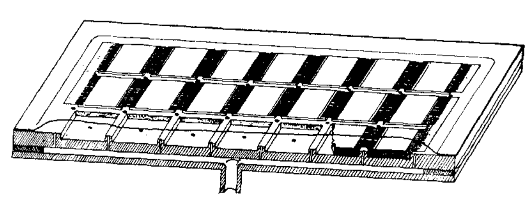


Fig. 8 Soldering device for flexible solar cell modules.

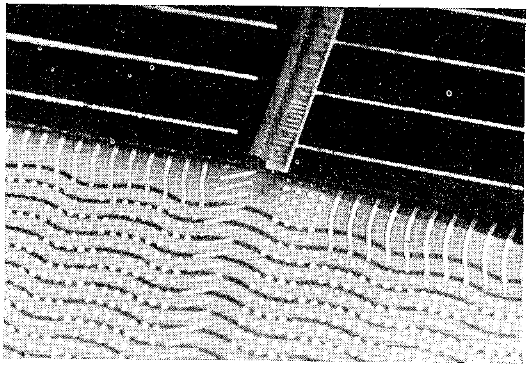


Fig. 9 Cementless assembly technique. Note "Stripline" connector between two solar cells.

The Stripline connected solar cells are positioned upside down into the deepenings of the soldering device. A pre-soldered silver clad Kapton film, all silver except that of the Striplines and the busbar network is removed, is adjusted to the back contacts of the solar cells and covered by a sheet of silicon rubber for sealing. Vacuum is applied, and the device is heated up beyond the melting point of the solder. Hence, millions of connecting points can be fabricated under clean and carefully controlled conditions in one step. To provide a good thermal coupling between the backside of the cells and the substrate, many tiny silver dots can be left beside the Striplines on the substrate film during etching, which are soldered to the backsides of the cells, too, see Fig. 9. This "cementless" assembly technique offers a high potential to survive thermal shocks and cycling. Instead of cover glasses, a single sheet of FEP[6] might be used to protect the solar cells from space hazards. After heat-sealing it to the front side of the proper aligned cells, the same technique might be used to connect the modules electrically. If an electromagnetically "clean" array is required, a double side metal clad Kapton film might be used. The return lines for the module's current are formed by etching its backside into curled parallel strips, see Fig. 9.

Testbeds Solar Array

The actual array embodies 6 intermediate- and 24 subfolds which divide it into 30 modules, see Fig. 1. The main folds are "suppressed." The solar cells are arranged in serial connected strings normal to the subfolds. The submodules contain 540 cells each; 270 cells in series deliver a nominal voltage of 100 v.

At the array's center, a 15-cm-broad strip of the substrate is free of cells to avoid shadowing and heating from the spacecraft's body. To protect the cells from damage, cushioning pads are wrapped between the modules. They might be omitted, if a FEP film is used instead of cover glasses.

To test an ion engine attitude control system, the spacecraft has to be flown in a three axis stabilized mode, and the array has to be stiffened. This might be done by flexible ribs, that are attached to the center lines of the largest modules, see Fig. 1. Such an array can be designed to resist Earth gravity in deployed status. The ribs would add approximately 1.1 kg (10%) to the array's weight. If the blankets are prestretched by proper allocated strings, a natural bending frequency of 1 Hz can be expected.

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