SolSTUS Solar Source Thermal Upper Stage Utah State University Logan, Utah

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Introduction:

During the past academic year the members of Utah State University's Space Systems Design class have worked on the design of SoISTUS (Solar Source Thermal Upper Stage), a solar propulsion system that could be carried into low earth orbit by small launch vehicles and still carry useful payloads into higher energy orbits or interplanetary missions. To demonstrate the capabilities of the SoISTUS the class worked to meet the requirements of a specific design reference mission. The reference mission was a lunar mapping and science mission launched from a Taurus launch vehicle.

Several aspects of the solar thermal propulsion concept were quite challenging. The major driving requirement in the design of this system was the volume of available launch vehicle shrouds. Because of the low density of the hydrogen used as propellent, we could not fit within a standard Taurus shroud [1]. Other challenging areas of the design were the storage of propellants at cryogenic temperatures, concentrating the solar radiation to heat the propellent, low values of thrust, long time periods required to complete the orbit transfer, and the deployment of solar collectors.

This design is a system design and did not deal with the detailed development of individual components needed for use on a solar thermal rocket.

Solar Propulsion Concept:

The Solar Thermal Rocket STR concept is really very simple. The STR takes solar energy and concentrates it into one small area. This concentrated energy is used to heat a propellant (usually hydrogen) to very high temperatures. The propellant is expanded through a nozzle to provide thrust as shown in figure_1. The advantage of this system is the high specific impulse (Isp) obtained. Engine designers such as Hercules claim a specific impulse (Isp) as high as 900 to 1000 sec [2] (960 for Hercules). You can compare this to conventional systems with Isp's of 200-400 sec. However, solar rockets have very low thrust, in the range of 1 to 20 Newtons (.25 to 5. Ib). The low thrust of the system limits the STR to space based operations with long periods of operation. The propellant used by the STR is hydrogen. Use of other propellants can cause significant drops in Isp and negate the reason for using a STR. We designed to an lsp of 960, with a thrust of 4.5 N.

Because of the need for long term attitude control, power, and communication, the SoISTUS will be an integrated system. This means that the attitude control, power, and communications systems of the SoISTUS vehicle will remain with the payload and will be designed to meet most foreseeable payloads and missions



Figure 1 STR concept

Design Reference Mission:

There are several types of missions that the SolSTUS would be ideal for. The SolSTUS upper stage has the capability of efficiently raising payloads from a low earth orbit to geoschronous orbits, translunar trajectories, interplanetary orbits, or near earth asteroid rendezvous. Each of these missions trajectories were studied by the design group but will not be discussed in detail.

The design reference mission chosen for the SolSTUS is a lunar science mission to provide a high resolution map of the lunar surface and a study of lunar surface elements. The scientific objective of the mission is based upon two instruments. The first is a stereo imaging camera for mapping the Lunar terrain to a resolution of 12 m. The second is a gamma ray spectrometer for elemental mapping and searching for water on the poles. The stereo imaging camera is based on a design done two years ago by USU's Space Systems Design class, the Copernicus Lunar Surface Mapper [3]. The gamma ray spectrometer is based upon the Mars Observer and the proposed Lunar Observer [4]. We wanted to launch a viable lunar mission from a Taurus class launch vehicle.

The SolSTUS will place the science payload in a Lunar polar orbit at an altitude of about 300 km. This orbit must be maintained for a baseline of one year. The detailed design of the science payload will not be done here. Our design focused upon the upper stage concept needed to get to the moon and put a payload into a lunar orbit.

SolSTUS Structural Layout

SolSTUS had to be designed to fit within a modified Taurus payload shroud and then to be deployed into the flight configuration in space. This imposed some very tight volume considerations upon the design. The science payload, and all SolSTUS systems must fit within the shroud, along with the propulsion system. The attitude control, communications, power, and the payload are placed within the service module, with the solar collection system on both sides in the undeployed configuration as shown in figure_2. The hydrogen storage tank acts as a major structural member between the Taurus mounting plate, and the payload positioned above the tank.

The deployed configuration is also shown in figure 2. When in space the collectors deploy to collect radiation from the sun and focus it into the motor. Phased array antennas are positioned on five sides of the SolSTUS. The science payload is positioned on one side that will face the lunar surface. The attitude control, system consists of three momentum wheels with controllers, six hydrazine thrusters, and two 9.8 cm diameter hydrazine tanks. Power is generated from a bimodal concept using the solar cells occupying 1 petal of each mirror. For payloads needing large amounts of power, thermionic generators can provide more power (not shown). These are positioned around the engine and utilize the full strength of the concentrated solar radiation. The power storage consists of 16 NiH batteries weighing a total of 20 kg. Other electronic and data storage are included in the payload area.

The positioning of each subsystem can be seen in Figure_3. The componants are positioned on a shelf system within the service payload. There is additional room left to accomodate various payloads. Each of



The mass of each of these systems is:









ft Figure 3 SoISTUS service module interior.

structure tank & fuel	80 646	Communication Attitude Control	65 45
propulsion	60	<u>Science Payload</u>	<u>45</u>
power	50	Total	991

Mission planning:

Because of the low thrust of any STR, longer time periods are needed to accomplish the same job as much larger conventional systems.

Two techniques were studied to place a payload into a lunar trajectory using the SolSTUS: a spiral orbit, and perigee thrust orbits using various angles of thrust as shown in figure 4. The most efficient technique is to use small perigee thrust angles. However, the time needed to do this is quite prohibitive. The quickest is the spiral orbit, but that requires a lot more fuel. We chose a compromise orbit using a 160• thrust angle. The time required for this trajectory is 97 days, using 304 kg of hydrogen to obtain a translunar trajectory. This same technique is used for interplanetary and geosynchronous orbits, the major difference being the completion of the trajectory: entering geosynchronous orbit or leaving the earths sphere of influence.

trajectory	<u>time</u>	<u>fuel</u>
spiral	12 days	325 kg
10• thrust	190 days	275 kg
120• thrust	90 days	290 kg



Figure 4 spiral and perigee thrust orbits (not to scale)

Because of the complexity of the earth- moon system, a simple patched conic analysis was used to determine the SolSTUS trajectory within the moon's sphere of influence. When the SolSTUS is between the earth and moon, a small burst is used to place the vehicle into a trajectory that will take it past the lunar pole. At this point the SolSTUS and payload will be in a hyperbolic orbit with respect to the moon. The SolSTUS must

now thrust continuously for over 32 hours to enter a lunar orbit. Perigee thrusts are then used to change to a 300 km circular orbit. A total of 130 kg of hydrogen is used to complete the orbit insertion. The total fuel used from the earth to the moon is under 440 kg. A convention system would use over 1200 kg of fuel.

Once in a polar orbit, the empty hydrogen tank will be jettisoned to fall to the lunar surface, thus eliminating unneeded mass. For the rest of the orbit the on board hydrazine will provide orbit corrections needed due to perterbations caused by the lunar gravity.

Propulsion System:

There are several different concepts of solar propulsion currently under development. All of these concepts involve some sort of solar concentrator, and a receiver as discussed in the introduction. The SolSTUS receiver is based upon concepts and hardware developed by Hercules Corporation [5]. The motor is an ogive cavity that traps the solar radiation and heats the wall of the chamber. The hydrogen is passed along the wall which is constructed of a porous material. The hydrogen is heated to over 2500 K and expanded out a nozzle (figure_5). To provide 1 lbf thrust with an lsp of 960, hydrogen is passed through the engine at .000545 kg/s with 21600 Watts of heat provided from the mirrors.

Several possibilities of solar concentrators were examined. These include inflatable, foam rigidized, and solid deployable systems. Inflatable systems are subject to microscopic puncture and leaks. The foam rigidized systems, in concept are probably the best because of mass and compactness. They are inflated by a foam that is hardened by LW rave

and stays rigid. However, a



that is hardened by UV rays Figure 5 Hercules receiver/rocket concept [5]

lot of technological development must be done before these become viable systems.

We based our design around a rigid deployable system because of it's more proven technology. This system is also under development by Hercules [2], but because most of their work is proprietary our design is original. The design for the concentrator employs sections of a conic surface cut about a line passing through the focal point of the parabola (figure_6). This allows the section to rotate about its center and still focus light into a stationary receiver, no matter what the direction of the sunlight.

When stored, the mirrors are divided into leaves connected at the center which fan out and snap into place providing an entire dish. The radiation intensity near the earth is 1320 W/m². To provide the required heat input at 80% efficiency 20 m² of effective area must be provided, this equates to 30.6 m² of actual mirror.

This system is similar to several communication and science systems that have been employed in space before. However, the pointing requirements are



Figure 6 mirror shape

greater and more development is needed than this class could provide.

Fuel storage:

One of the major problems with high specific impulse fuels is storage. Hydrogen is the propellant of choice for solar propulsion. However, hydrogen has several problems, (ie. density, storage temperatures, and delivery).

The density of liquid hydrogen is 70 kg/m³. This causes major problems when designing a system to fit within small launch system payload shrouds. To reach and rendezvous with the moon 440 kg of hydrogen is needed, this requires a 6.2 m³ volume. The standard Taurus payload shroud has only 4.9 m³ volume available. To deal with this problem we talked to Orbital Sciences Corporation (OSC), the maker of the Taurus launch system. The people at OSC have done studies on enlarging the Taurus shroud. They said that it would be possible to enlarge the payload shroud to about 18 m³ with about the dimensions shown in figure_7.

The second problem is the storage temperatures. To be stored as a liquid, hydrogen must be kept at 20 K and must be isolated from any heat sources. The radiation coming in from the sun which has an intensity of 1350 W/m². For this reason the tank is covered with 4 cm of foam insulation to accomadate ground operations and a 2.5 cm covering of multi layer insulation (MLI) for space operations. This insulation permits almost no heat transfer to the hydrogen tank. The tank must also become a structural member of the system as it is positioned between the payload and base plate and there is no room for structural members around it in the modified Taurus shroud. Because it is a structural member, the connections between the tank and the payload and Taurus must be thermally non conductive. Passive Orbital Disconnect Struts (PODS) are used to connect the tank [7]. Using all of these materials the heat load into the tank is expected to be under 10 W.

The tank was designed to meet a maximum pressure of 100 psi. The tank is a cylindrical tank with oblate spherical ends (D = 1.95m L = 2.3m). It is made of a recently developed alloy of Aluminum and Lithium that has a weld strength of 380 MPa and a density of 2200 kg/m³ which is much better than standard aluminum [8]. Using Aluminum Lithium the tank will have a wall thickness of 2.5 mm and weigh only 60 kg. With the addition of foam insulation, MLI, and miscellaneous plumbing and hardware, the weight of the fuel storage system is 206 kg. As a thin walled pressure vessel this is also strong enough to be the structural member required.





The third problem is hydrogen delivery to the rocket motor. There are no known pumps that can handle hydrogen. Therefore the hydrogen tank itself must be pressurized. The hydrogen will be kept above 50 psi with a maximum pressure of 100 psi. There is also the problem of extracting gaseous hydrogen from a tank in zero gravity with mixed gas and liquid. Extracting only gaseous hydrogen is accomplished with a thermodynamic vent. This vent consists of a Joule-Thompson valve that expands the gaseous hydrogen to a lower pressure. When this happens the temperature of the hydrogen is lowered below the temperature of the hydrogen in the tank. Using a heat exchanger energy is absorbed from the tank such that the final result is extraction of only gaseous hydrogen at about 30 to 35 psi.

Attitude determination and Control

The attitude and position of the SolSTUS must be controlled very precisely. The SolSTUS must thrust tangentially through large sections of successive orbits which requires continual control of the spacecraft and that it be stabilized about all three axes. Because the SolSTUS gets it's propulsive power from the sun, the solar collectors must also be pointed directly at the sun at all times as shown in figure_8.

To determine the position of the SolSTUS with respect to the earth and the sun two main instruments are used, sun sensors, and a scanwheel for horizon sensing. The sun sensors track the position of the sun so that the collectors can be aimed at it. The scanwheel horizon sensors track the SolSTUS's position with respect to the earth or moon. Gyroscopic instruments included with the momentum wheels also help keep track of angular position and rotation.

The main attitude control system of the SolSTUS consists of a combination of momentum wheels and hydrazine propulsion system. The momentum wheels provide the major portion of the control and allow much greater pointing accuracy. Three momentum wheels were used in the design, one Ithaco type B momentum wheel with a scan wheel attachment [9] to handle the in plane rotation keeping the thrust tangential to the orbit, and two smaller type A momentum wheels [9] for any out of plane rotation damping due to rotation of the parabolic mirror collector system. Ithaco type A and type B momentum wheels provide 20 mN-



m, 40 mN-m torque and 4 N-m-s and 19.5 **Figure 8** mirror pointing requirement N-m-s angular momentum capacity respectively for an operating range of 0 to 6000 rpm [9].

The hydrazine system consists of two 9.8 cm radius hydrazine tanks with a total 15 kg of hydrazine, and six .45 N thrusters for additional attitude control and to maintain the lunar orbit [10].

The requirement to collect light from the sun adds another dimension of complexity to the attitude control system. The entire collection system is rotated about the major axis of SolSTUS to be normal to the sun's rays. The mirrors of the collection system are then rotated to point directly at the sun to concentrate the sunlight within a 6 cm diameter receiver. The collector control is done using DC stepper motors for accurate control. Exact positioning must be maintained constantly as the spacecraft goes through it's orbit. The angular momentum of these rotating parts is absorbed by the momentum wheels, keeping the main part of the SolSTUS tangential to the orbit.

Power

Part of the concept of the SolSTUS was to use the solar concentrators for both propulsion and power purposes. When not in use to concentrate solar energy for the propulsion, the solar concentrators have the capability to be used to generate power. There are several ways that the concentrated power can be used to generate electricity, solar cells, thermionics, thermoelectric, or some sort of mechanical generator. The two types of power generation looked into by the class are solar cells and thermionics.

Solar cells operate at 18% efficiency under normal conditions but when concentrated can get up to 30 to 40% efficient and generate much more power in a very small space. The problem is temperature. Solar cells have a very limited and low

operational temperature range (0 - 60 C). With all of that concentrated light we would need a good radiator system, either a radiator connected directly to the solar cells, or some sort of liquid cooling system to carry the heat to the radiator. Because of the geometry and placement of solar cells, directly connected radiators would be very hard to implement. The system that would need to be used is a liquid cooling system carrying the heat to the back of the mirrors which would act as a radiator. For this reason we placed 4 m² of solar cells directly on the solar collectors to take advantage of already existing solar tracking system and the back of the mirror can act as a radiator. We lose the advantage of concentrated sunlight, but don't have to deal with it's problems

Thermionic power conversion systems are under development by the Idaho Renewable Energy Laboratory (INEL) and their operating principles will not be discussed here [11]. Thermionics seem to have the greatest capability to generate large amounts of power. They operate at high temperatures. This allows for much smaller radiators to shed excess energy. Using the mirrors already employed, the SoISTUS could generate over 2 kW of power. This is much more power than many larger systems are capable of generating. The thermionic generators can be placed all around the rocket motor. While the rocket motor is not thrusting the thermionics can reach temperatures of 2000 to 2500 K. generating electrical power that could be used by systems requireing large amounts of power.

To store the power for times of darkness 16 Nickel Hydrogen electric cells will be used giving a total of 900 Watt hours to 50% discharge when they need to be recharged.

Communications

The communications system on the SolSTUS will consist of five 42 X 42 cm phased array antennas with an omni directional antenna for telemetry and backup. The phased array antennas allow transmission of data at all times during the lunar orbit without having to worry about pointing or reorienting the entire spacecraft as you would with a parabolic dish.

All earth based operations are based upon NASA's 29 meter Deep Space Network. SolSTUS's antennas use the S band used by this system [12]. The phased array antenna will operate at 2 Ghz and a signal to noise ratio of 12.5 and a gain of 16 dB. This allows data to be transmitted at a rate of 1.2 Mbps. The phased array antennas will not be used while orbiting the earth but only after reaching the moon. This will cause interruptions in data collection around the moon, but that can be minimized by transmitting when on the dark side of the moon providing the orbit is in the correct position. One problem is that the Deep Space Network would only be able allocate less than 10 hours per day of communication. This requires the storage of large quantities of data. The second part of the communication group's work was internal communication and data storage. The computer chosen to handle internal communications was the Harris RH 3000. In addition there will be 43 Gigabytes of data storage capacity added to the computer. The rate of scientific data coming in was estimated at 705 Mbps, allowing 13.5 hours of scientific work before the data must be sent to earth.

Because of the sensitivity of scientific instruments and the time of command transmission to the moon, earth-based control of second to second operations is not possible. The control of the system will be mostly autonomous with the computer system controlling the orientation of the SolSTUS from feedback received from the sensors on board. However, all data will be sent to earth and monitored by earth based systems so that any changes can be made when necessary. Any type of orbit corrections, or changes in mission will be sent from earth.

Conclusion

The solar propulsion concept has a lot to offer, it can do more in space with a lot less fuel. However, there is still much development that must be done.

We designed to an enlarged Taurus payload shroud. Even though the enlarged shroud had been studied by Orbital Sciences, one has not actually been designed or built. The envelope characteristics might not be what we hope for.

The deployment mechanism for the mirrors will take substantial development and may prove to be one of the critical design areas. The mirrors must be held rigidly away from the motors, collect large amounts of sunlight, and reflect that sunlight into a very small collection chamber. Doing this with any real accuracy may be hard to do. Deploying and unfurling the mirrors may end up being quite a problem

A much more accurate heat transfer analysis must be done. We have to know better how much heat is being carried away from the motor and how much is being carried into the hydrogen tank. We also would need to study what kinds of structural deformations are caused by temperature gradients in the structure, particularly the mirrors and mirror supports.

Even though cryogenics similar to hydrogen have long been used in space, the design of the hydrogen storage and delivery system would need development. Previous space cryogenics have been smaller systems and this larger system would have additional problems that they did not. In addition, this system must be designed to supply hydrogen at a rate sufficient for motor useage.

Solar propulsion can offer a lot to space utilization and exploration if the obstacles in it's development can be overcome. We will be able to take payloads into high energy and interplanetary orbits at much lower costs than we presently can. It may aid in the exploration of the planets and benefit life here on earth.

Class design groups

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<u>Structure</u> Paul Neilson Brook Ferney

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