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REPORT

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Solar Sail - Solar Electric Technology Readiness and Transfer Assessment

FINAL REPORT

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SOLAR SAIL - SOLAR ELECTRIC TECHNOLOGY READINESS AND TRANSFER ASSESSMENT

FINAL REPORT

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ABSTRACT

General Research Corporation was tasked by NASA Headquarters, Code RX, to conduct a Technology Readiness and Transfer Assessment of Solar Sail and Solar Electric Propulsion Systems for the Headquarters Solar Sail-Solar Electric Propulsion Assessment Committee chaired by Mr. Fred Demeritte, Code RC. The data base for the assessment was obtained by direct contact with the Jet Propulsion Laboratory and contractors. Fourteen contractors were contacted during the study.

A new method of conducting a technology readiness assessment was developed. It uses existing OAST technology readiness and risk criteria to define a Technology Readiness Factor that considers both the required gain in technology readiness level to achieved technology readiness plus the degree of effort associated with achieving the gain.

The results indicated that Solar Electric Propulsion is preferred based on technology readiness criteria. Both Solar Sail and Solar Electric Propulsion have a high level of transfer potential for future NASA missions, and each has considerable technology spillover for non-NASA applications.

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GENERAL RESEARCH CORPORATION SCOPE-OF-EFFECT

The GRC assessment activity for the Solar Sail-Solar Electric Assessment Committee was divided into two tasks. The first task, Technology Readiness, addressed the issue of the current status of technology, technology readiness requirements, and the risk associated with achieving technology readiness for each propulsion system candidate. The assessment of technology readiness was based on direct contact with NASA contractors associated with each propulsion system. In this respect, the assessment was considered to be independent; the Headquarters Assessment Committee dealt with and through JPL, LeRC, LaRC, and MSFC with limited access to direct contractor materials.

The second task, Technology Transfer, considered the application of Solar Sail and Solar Electric Propulsion and associated technologies to future NASA missions as defined by the OAST Space Systems Technology Model. In addition, consideration was given to potential non-NASA applications of the technology associated with both propulsion systems. Both NASA Center and contractor sources were considered in evaluating non-NASA transfer potential.

GRC SCOPE-OF-EFFORT

TECHNOLOGY READINESS TASK

- TECHNOLOGY READINESS ASSESSMENT
- RISK ASSESSMENT

TECHNOLOGY TRANSFER TASK

- FAR TERM NASA MISSION POTENTIAL
- NON-NASA APPLICATIONS POTENTIAL

CONTRACTORS CONTACTED

To provide the data base for the technology readiness and transfer analysis, it was agreed that GRC would deal directly with the contractors that were providing data to the Solar Sail and Solar Electric design teams at JPL. The contractors and names of project leaders were supplied by Dr. L. Friedman and Dr. K. Atkins, at JPL, for Solar Sail and Solar Electric, respectively (see facing table). The technology area follows the name of each contractor. After the decision was made to focus the Sail activity on the Heliogyro, JPL assumed responsibility for this activity in-house. Dr. M. Trubert and Mr. R. Bamford, at JPL, provided the data on the Solar Sail design and structural dynamics. In each case the data required by GRC for the assessment was obtained by direct interview with the people working on the activity located at the contractor facilities.

CONTRACTORS CONTACTED

SOLAR SAIL	DUPONT (Thin Films)	Mr. Don Stephenson
	KENETIC COATING INC. (ION Etching, Metallic Coatings.	Dr. William King
	SCHWEITZER (Metallic Coatings)	Mr. Roy Anderson
	SCHJELDAHL (Manufacturing)	Mr. Jack Daniels
	BOEING (Film Testing)	Mr. Larry Fogdall
	MAYO (Spacecraft Charging)	Mr. R. LaQuey
	JPL (Structures, Structural Dynamics)	Dr. Mark Trubert
SOLAR ELECTRIC	HUGHES RESEARCH (ION Thrusters)	Mr. Jerry Molitor
	BOEING (Concentrator Arrays, Solar Cell Testing)	Mr. Charles Terwilliger
	GENERAL ELECTRIC (Concentrator Arrays)	Mr. George Rayl
	LOCKHEED (Concentrator Arrays)	Mr. Rick Elms
	SPECTRO LABORATORY (Solar Cells)	Mr. John S. Monk
	SOLAREX (Solar Cells)	Dr. Jack Anderson
	SCIENCE, SYSTEMS & SOFTWARE (Spacecraft Charging)	Mr. A. Wilson

GENERAL FINDINGS AND COMMENTS

Some overall general impressions were obtained during contractor interviews; these do not bear directly on technology readiness or transfer but may be of some benefit to the Assessment Committee and are therefore included in this report. In general, there is a strong feeling of enthusiasm for a Comet Halley Rendezvous mission. Quite a few expressed the opinion that this mission was just the challenge NASA needed: a difficult job, very tight schedule with inherent risk, but a job that could be done given the opportunity. Some expressed concern that hardware performance specifications were not more clearly defined at this time. The most asked questions pertained to post-August funding and the NASA position on the mission.

GENERAL FINDINGS AND COMMENTS

- ENTHUSIASM FOR A COMET HALLEY RENDEZVOUS MISSION
- VERY TIGHT SCHEDULE REQUIREMENTS, INHERENT RISK
- CONCERN FOR SPECIFICATIONS
- POST "AUGUST PROJECT" FUNDING
- NASA POSITION ON MISSION
- MISSION APPROVAL PROBABILITY

SOLAR SAIL TECHNOLOGY NEEDS

Initial contact with the JPL design teams focused on the definition of the key technology needs and requirements. From the beginning it was understood that the list of technology areas to be assessed in this effort would be limited to several for each system. It was important that the key technology areas be identified early in the effort such that not only the status could be assessed, but also the rate of progress, which would be reflected in a measure of risk associated with achieving technology readiness.

A list of potential technology areas for each system was prepared by GRC and reviewed with the respective JPL design team leaders. In the case of Solar Sail, three technology areas were agreed upon: (1) deployment and control of lightweight structures; (2) thin films; and (3) environmental control. Specific desciplinary issues in each area were identified and are shown on the facing page.

JPL selected the Heliogyro as the Solar Sail candidate for the Comet Halley Rendezvous Mission. The Heliogyro is comprised of a center body to which 12 blades are attached. Each blade is approximately 8 meters wide by 7500 meters long. A separable spacecraft containing the science package and post-encounter propulsion is attached to the center body of the Heliogyro. Once the Heliogyro has delivered the spacecraft to the vicinity of Halley, it is jettisoned and the spacecraft continues the mission by itself.

TECHNOLOGY NEEDS

SOLAR SAIL
HELIOGYRO

- DEPLOYMENT AND CONTROL OF LARGE LIGHTWEIGHT SPACE STRUCTURES
  - —STRUCTURAL DYNAMICS (FLUTTER)
  - —ACTIVE CONTROL SYSTEMS (STABILITY)
  - —FIGURE CONTROL (WRINKLES)
- THIN FILMS
  - —MANUFACTURING PROCESSES (ROLLING, JOINTING & PACKAGING)
  - —COATINGS (REFLECTIVITY, EMISSIVITY)
  - —LIFE TIME (RADIATION RESISTANCE, MICROMETORITES)
- ENVIRONMENTAL CONTROL
  - —PASSIVE THERMAL CONTROL (FILM TEMPERATURE)
  - —SPACECRAFT CHARGING (STATIC, MAGNETIC FIELD INDUCTION)

SOLAR SAIL TECHNOLOGY REQUIREMENTS

A quantitative enabling requirement was defined for each technology area based on analysis performed by the respective design teams at JPL. These requirements served as the evaluation criteria in determining the current state of the art in each technology area, and were also used to assess the risk associated in achieving technology readiness. The enabling requirements are summarized on the facing table for each technology area considered.

In order to rendezvous with Halley inside IAU post-perihelion, it is necessary that the Solar Sail Propulsion System impart an initial acceleration of 1.0 mm/sec^2 to the spacecraft The sail loading factor corresponding to this acceleration level is approximately 9.0 g/m^2. It would appear that approximately 8.1 g/m^2 could be achieved if Kapton can be produced at a thickness of 0.08 mil rather than 0.1 mil which was the initial goal. To maintain a film temperature less than 310° at 0.25 AU (to prevent a phase change in the Kapton film) the sail reflectivity and emissivity requirements are 0.85 and 0.40 respectively. It is proposed that the Kapton film be coated with 1000 to 1200 Å of aluminum on the sun side of the sail and approximately 125 Å of chromium on the dark side of the sail. A flight time of approximately 1600 days is required of which approximately 515 days is spent in a cranking orbit about the sun at 0.25 AU. Maneuvering requirements are shown for both the cranking orbit and terminal maneuvers.

TECHNOLOGY REQUIREMENTS

TECHNOLOGY NEED	ENABLING REQUIREMENT
• LARGE DEPLOYABLE LIGHTWEIGHT SPACE STRUCTURES	ENABLING ~9.0 g/m^2 GOAL ~6.1 g/m^2
• CONTROL OF LARGE SPACE STRUCTURES (Heliogyro Blade – 8 m x 7400 m)	CRANKING ORBIT MANEUVERS – 70° PITCH CHANGE IN 6 – 24 HRS TERMINAL MANEUVERS 40° IN 4 HRS (THRUST MODULATION) 20° IN 4 – 6 HRS (STEERING CHANGES)
• THIN FILMS (KAPTON)	ENABLING 3.6 g/m^2 (0.1 MIL) GOAL 3.0 g/m^2 (0.08 MIL) >0.85 REFLECTIVITY >0.40 EMISSIVITY OPERATE 4 YRS IN SPACE UP TO 0.25 AU
• THERMAL CONTROL	MAX 310° C @ 0.25 AU, MIN – 100° C

SOLAR ELECTRIC PROPULSION SYSTEM TECHNOLOGY NEEDS

Three key technology areas were identified for the Solar Electric Propulsion System: (1) ion thrusters, (2) kilowatt (kW) power systems, and (3) environmental control. Several specific issues are identified for each technology area. The ion thruster proposed for the Comet Halley Rendezvous Mission is the current 30-cm thruster under development by Code RP at the Lewis Research Center. The solar array used to supply the power to run the thrusters is a new array concept employing a variable solar concentrator. The power output of the solar array varies by a factor of approximately four during the course of the flight. To convert the power available most efficiently to thrust, the number of thrusters running is varied several times during the flight, requiring thrusters to be switched on and off. The maximum number of thrusters running at the same time is seven. Conventional power processors are used between the array and the thrusters. Thruster module temperature is controlled by heat pipes, and the charge on the spacecraft is actively controlled by neutralizers on the thrusters.

TECHNOLOGY NEEDS

SOLAR ELECTRIC

(ION DRIVE)

- ION THRUSTERS
  - LONG LIFE HIGH PERFORMANCE THRUSTERS
  - MULTIPLE THRUSTERS (MODULE)
  - THRUSTER SWITCHING
- KW POWER SYSTEMS
  - LARGE DEPLOYABLE SOLAR ARRAY
  - SOLAR CONCENTRATOR
  - SOLAR CELLS
  - SOLAR CELL COATINGS
  - POWER PROCESSING
- ENVIRONMENTAL CONTROL
  - THERMAL CONTROL
  - SPACE CRAFT CHARGING

SOLAR ELECTRIC PROPULSION SYSTEM TECHNOLOGY REQUIREMENTS

To accomplish a Comet Halley Rendezvous Mission with Solar Electric Propulsion, it is proposed to initially fly outbound to approximately 4 AU, turn around, and fly inbound and rendezvous inside 1 AU pre-perihelion. The total flight time from launch to rendezvous is approximately 1330 days. The ion propulsion module will consist of 10-30 cm thrusters. Each thruster will deliver an average specific impulse of 4770 sec and operate for 13,600 hr. The solar array to power the thrusters has a beginning of life capability of 60 kW at 1 AU without concentration. Two concentration factors are used, 2:1 (1.8:1 effective) and 4.7:1 (3.8:1 effective). A 2:1 concentration factor is employed between 1 and 1.5 AU, and a concentration factor of 4.7:1 is employed between 1.5 and 4.5 AU. A solar array power-to-mass ratio of 200 W/kg is required, and the goal is 240 W/kg. A conventional power processor is used to process a total of 10^6 kW/hr. Because conventional drive is employed, array voltage is held between 200 and 420 V throughout the mission.

TECHNOLOGY REQUIREMENTS

TECHNOLOGY NEED	ENABLING REQUIREMENT
• LARGE DEPLOYABLE SOLAR CELL ARRAY – POWER LEVEL – POWER TO WEIGHT RATIO	60 KW @ 1 AU, 2:1 CONCENTRATION FACTOR 14 KW @ 4.5 AU, 4.7:1 CONCENTRATION FACTOR ENABLING 200 W/kg, GOAL 240 W/kg
• LONG LIFE ION THRUSTERS – SIZE – LIFETIME – SPECIFIC IMPULSE (Average)	10 – 30 cm THRUSTERS (A MAX OF SEVEN OPERATING SIMULTANEOUSLY), 13,600 HRS ENABLING 15,000 HRS GOAL 4770 SECONDS (AVERAGE)
• POWER PROCESSING	10^6 KW HR 200 – 420 V CONVENTIONAL DRIVE

TECHNOLOGY READINESS EVALUATION CRITERIA

The technology readiness assessment methodology used in the present assessment has been used by OAST before. The basic approach was developed and used by General Dynamics in the 1975 Shuttle Payload Technology Study. This methodology was subsequently used by JPL in the Jupiter Orbiter technology readiness assessment activity of 1976. The methodology utilizes a technology readiness scale from one to seven. The definition of one through seven is shown in the chart on the opposite page. These technology readiness definitions were used to define the current status of technology and the required level for technology readiness.

TECHNOLOGY READINESS EVALUATION CRITERIA

LEVEL 1	BASIC PRINCIPLES OBSERVED AND REPORTED
LEVEL 2	CONCEPTUAL DESIGN FORMULATED
LEVEL 3	CONCEPTUAL DESIGN TESTED ANALYTICALLY OR EXPERIMENTALLY
LEVEL 4	CRITICAL FUNCTION/CHARACTERISTIC DEMONSTRATED
LEVEL 5	COMPONENT/BREADBOARD TESTED IN RELEVANT ENVIRONMENT
LEVEL 6	PROTOTYPE/ENGINEERING MODEL TESTED IN RELEVANT ENVIRONMENT
LEVEL 7	ENGINEERING MODEL TESTED IN SPACE

TECHNOLOGY RISK ASSESSMENT CRITERIA

In addition to technology readiness criteria, risk assessment criteria have been developed and used in previous technology readiness assessment activities. The technology risk criteria developed and used in the JPL Jupiter Orbiter assessment study were selected. It was felt that for the present assessment criteria that had had previous OAST exposure were best. Therefore, neither technology readiness nor risk criteria were created specifically for the Solar Sail-Solar Electric Propulsion technology readiness assessment. The risk assessment in the chart on the opposite page is a simple high-medium-low criterion to which numerical values of 2, 1 1/2, and 1 were assigned, respectively.

TECHNOLOGY RISK ASSESSMENT CRITERIA

LEVEL OF RISK	
LOW (1)	• TECHNOLOGY EXISTS AND HAS BEEN DEMONSTRATED IN OTHER EQUIPMENT • ALTERNATIVES ARE BEING DEVELOPED, ALTHOUGH THEY ARE NOT YET PROVEN • PARALLEL DEVELOPMENTS ARE POSSIBLE
MEDIUM (1 1/2)	• TECHNOLOGY EXISTS BUT HAS NEVER BEEN DEMONSTRATED • ALTERNATIVES ARE POSSIBLE BUT ARE COSTLY IN TERMS OF DOLLARS • RESOURCES AND SCHEDULE ARE MARGINAL FOR PARALLEL DEVELOPMENTS BUT PARALLEL DEVELOPMENTS ARE STILL POSSIBLE
HIGH (2)	• TECHNOLOGY DOES NOT EXIST AND MUST BE DEVELOPED • ALTERNATIVES DO NOT EXIST • PARALLEL DEVELOPMENTS ARE NOT POSSIBLE

TECHNOLOGY READINESS ASSESSMENT METHODOLOGY

Even though technology readiness and risk criteria were not developed for this assessment, a new methodology for quantitatively expressing technology readiness was developed. It was felt that the development of a simple method of quantitatively assessing technology readiness and risk would not only benefit the present assessment, but provide a method whereby the Solar Sail-Solar Electric Propulsion Assessment Committee could express its results.

A "Technology Readiness Factor" was defined that would be nondimensional and encompass both the magnitude of the technology readiness task and the degree of difficulty required to achieve technology readiness. The equation was used to compute a Technology Readiness Factor for each technology issue considered. Risk is not used in the probabilistic sense, but rather as a multiplier greater than one representing the degree of difficulty in achieving a technology readiness goal.

Several alternative methods of computing a Technology Readiness Factor were investigated. Two alternative denominators were, $\sum_i^n TR_{maximum_i} \times Risk_{maximum_i}$ and $\sum_i^n TR_{req'd_i} \times Risk_i$. Technology Readiness factors for each propulsion candidate were computed using each method. No significant differences resulted, and the overall conclusions were unchanged. In reflection, probably a gain × risk definition for technology readiness factor would be sufficient.

TECHNOLOGY READINESS ASSESSMENT METHODOLOGY

$$\text{TECHNOLOGY READINESS FACTOR (TRF)} = \frac{\sum_{1}^{n} (\text{gain})_i \times (\text{risk})_i}{\sum_{1}^{n} (\text{Technology Readiness Level Req'd})_i \times (\text{max. risk})_i}$$

where $\text{gain}_i = (\text{Technology Readiness Level Required})_i - (\text{Current Technology Readiness Level})_i$

and $1 \geq \text{gain} \leq 7$

$1 > \text{risk} \leq 2$

LARGE LIGHTWEIGHT SPACE STRUCTURES ASSESSMENT

BLADE DESIGN - Since the selection of the Heliogyro by JPL, further analysis of the blade design has resulted in a completely new design intended to reduce wrinkles. Whether the new design will be adequate will depend on additional analysis.

STABILITY & CONTROL - Several independent groups have looked at the stability and control problem assoicated with the Heliogyro. It is agreed by all concerned that the problems are solvable, but Langley Research Center has taken the position that an in-space test of the Heliogyro is required prior to flight.

FIGURE CONTROL - Centrifugal force is used to deploy and maintain blade stiffness after deployment. Torsional stiffness is also enhanced by carrying tension in multifilar edge members comprised of five cables each. The panel design employing tension springs is intended to reduce wrinkling.

PACKING FRACTION - Detailed analysis, by Langley Research Center, determined that the original blade design produced a package approximately 5 ft in diameter. Design changes have reduced the package to approximately 2 ft; however, there is still some disagreement about the diameter that will actually be achieved.

MANUFACTURING/QUALITY CONTROL - At the time of this assessment, Schjeldahl had not officially received the new blade design. Based on the old design, the manufacturing and quality control programs for the blade had been evaluated and appeared to be with Schjeldahl's capability. Some concern was expressed about the new design, but detailed comment would have to wait until the new blade design had been evaluated.

LARGE LIGHTWEIGHT SPACE STRUCTURES ASSESSMENT

	READINESS		GAIN	RISK
	PRESENT	GOAL		
• NEW BLADE DESIGN, 20 JUNE '77	2	5	3	M
• EXTENSIVE STABILITY AND CONTROL ANALYSIS HAS BEEN COMPLETED BY INDEPENDENT SOURCES	4	7	3	H
• PASSIVE BLADE PANEL FIGURE CONTROL DESIGN ANALYSIS IN PROGRESS	3	5	2	M
• "NEW" BLADE PACKING FRACTION ANALYSIS COMPLETED	3	5	2	L
• "OLD" BLADE MANUFACTURING – QUALITY CONTROL ANALYSIS COMPLETED, NEW DESIGN NOT INITIATED	2	4	2	M

$$TRF = \frac{18.5}{52} = 0.36$$

THIN-FILM ASSESSMENT

PRODUCTION - To date Dupont has demonstrated the direct production of Kapton 0.15-mil thick. It has been projected that a thickness of 0.1 mil can be achieved with modifications to existing equipment, and that it might be possible to produce Kapton with a thickness of 0.08 mil. However, yields of only 10% have been projected. The backup material, Ciba-Geigy, has been manufactured at 0.1 mil in test quantities by Schweitzer.

METALLIZATION - Test specimens of Kapton have been metallized with aluminum and chromium. It may be necessary to increase the thickness of aluminum from 1000 to 1200 Å to meet Heliogyro requirements. Schweitzer is currently installing a metallizer capable of handling material 56-in. wide and 0.5-mil thick. To put on 1000 Å of aluminum will require several passes and is considered to be a very delicate operation with 0.1-mil Kapton.

LIFETIME - Boeing test data has shown that Kapton is susceptible to rapid degradation under ultraviolet radiation. The lifetime of Kapton blades is therefore dependent on maintaining the integrity of the metallic coating.

SHIPPING & HANDLING - After manufacturing Kapton, Dupont will ship it to the metallization facility (Dupont does not metallize Kapton), after which it will be shipped to the blade manufacturer. The Kapton must be handled several times from production until the blades are manufactured. It will not be an easy task and is largely dependent on the "roll formation" quality of 0.1-mil Kapton, which is yet to be determined.

THIN FILMS ASSESSMENT

	READINESS		GAIN	RISK
	PRESENT	GOAL		
• DUPONT HAS DEMONSTRATED 0.15 MIL KAPTON, CIBA-GEIGY HAS BEEN DEOMONSTRATED AT APPROXIMATELY 0.1 MIL	3	5	2	M
• TEST SPECIMENS OF KAPTON HAVE BEEN METALIZED, PRODUCTION EQUIPMENT FOR 56" WIDE MATERIAL IS GOING INTO OPERATION	2	4	2	H
• LIFETIME OF KAPTON AT 0.25 AU IS DEPENDENT ON MAINTAINABILITY OF COATINGS. STATIC LABORATORY TESTS TO DATE	3	5	2	L
• SHIPPING AND HANDLING OF 0.1 MIL KAPTON IS DEPENDENT ON "GOOD ROLL FORMATION"	2	4	2	M

$$TRF = \frac{11}{36} = 0.31$$

ENVIRONMENTAL CONTROL ASSESSMENT

FILM TEMPERATURE - Analysis and test data have indicated that as long as the reflectivity and emissivity coefficient requirements are met, the film temperature will remain below the phase-change point and the strength of the material will be maintained.

CHARGING - Analysis has indicated that placing holes at predetermined locations along the blade prior to metallization will be sufficient to ground the front-to-back side of the blade. It is important that the metallization seal the exposed edge of the material that is a result of the hole cutting. Analysis indicates that a maximum 100 to 500 V charge differential can be expected during the flight.

MICROMETEORITES - The Heliogryo has been designed where possible to avoid single point failures. In the case of the blade, any two of the five cables in the edge members are sufficient to carry the loads and rip stops have been placed at intervals along the blade to prevent rip propagation.

ENVIRONMENTAL CONTROL ASSESSMENT

	READINESS		GAIN	RISK
	PRESENT	GOAL		
• FILM TEMPERATURE ANALYSIS COMPLETED, INDICATES THAT TEMPERATURE REQUIREMENTS CAN BE MET	4	5	1	L
• ANALYSIS INDICATED THAT PLACING HOLES AT PREDETERMINED INTERVALS TO GROUND FRONT-TO-BACK IS SUFFICIENT FOR A 100 – 500 V CHARGE DIFFERENTIAL	3	4	1	L
• ANALYSIS INDICATED THAT MICROMETEORITES WILL NOT CAUSE FAILURE OF DESIGN	3	1	1	M

$$TRF = \frac{3.5}{26} = 0.13$$

ION THRUSTER ASSESSMENT

SPECIFIC IMPULSE - The 30-cm thruster has been demonstrated by Hughes over the complete range of mission parameters.

LIFETIME - The present 30-cm thruster design has demonstrated a lifetime of 10,000 hr. It is estimated that the present design could achieve 11,000 hr. By changing the optics design and modifying the beam, it is estimated that the lifetime would increase to 23,000 hr. The changes required to the 30-cm thruster to achieve this lifetime have been demonstrated on the 8-cm thruster.

MULTIPLE THRUSTERS - A cluster of two thrusters has been demonstrated in the current research program.

THRUSTER SWITCHING - During the 30-cm thruster lifetime tests, the thruster was turned off and on again between 30 and 40 times.

ION THRUSTER ASSESSMENT

	READINESS		GAIN	RISK
	PRESENT	GOAL		
• SPECIFIC IMPULSE REQUIREMENTS HAS BEEN DEMONSTRATED	4	6	2	L
• DESIGN CHANGES TO BEAM AND OPTICS DESIGNS COULD DOUBLE THE DESIGN LIFE, CHANGES DEMONSTRATED ON 8 CM THRUSTERS	4	6	2	L
• MULTIPLE THRUSTER (2) OPERATION HAS BEEN DEMONSTRATED	4	6	2	L
• DURING 10,000 HR. LIFETIME TEST, THE THRUSTER WAS SWITCHED OFF-ON 30 TO 40 TIMES	4	6	2	L

$$TRF = \frac{4}{40} = 0.10$$

KILOWATT POWER SYSTEM ASSESSMENT

SOLAR ARRAY - General Electric has proposed and evaluated a design that would achieve 200 W/kg. Boeing has evaluated the design and agrees. Design options have been proposed that use thick cells as well as the thin cells produced by Solarex.

SOLAR CONCENTRATOR - Several solar concentrator designs have been proposed, and evaluated, and limited test data produced which indicates the feasibility of using solar concentrators with solar arrays. Several design changes have occurred recently to accomplish better packaging. It is felt that the present base line is non-optional with respect to maximizing the power-to-weight ratio and could still undergo significant design changes before the array-solar concentrator design is finally selected.

THIN SOLAR CELLS - Solarex has demonstrated the production of thin (2-mil) solar cells. Test data indicates an average efficiency of about 9% compared to 13% for thick cells. Spectrolab is investigating means of increasing efficiency to 11%. Solarex anticipates no problem in meeting production schedule though Spectrolab is concerned. Multiple production sources will probably be required. A key item appears to be cost, which is related to yield.

SOLAR CELL COATING - General Electric has selected and tested Solar Cell Coating RTV-655 silicone for the solar array. The material meets current specifications. Several alternatives are also being considered.

POWER PROCESSOR - The current TRW power processor was selected by Hughes; repackaging is required for maximum utilization.

KW POWER SYSTEMS ASSESSMENT

	READINESS		GAIN	RISK
	PRESENT	GOAL		
• PRESENT SOLAR ARRAY PROGRAM GOAL IS 66W/Kg; DESIGN CONCEPTS FOR 200W/Kg PROPOSED AND ANALYZED	2	6	3	M
• SEVERAL SOLAR CONCENTRATOR DESIGNS HAVE BEEN FORMULATED AND ANALYZED; LIMITED TESTING	3	6	3	M
• PILOT THIN CELL PRODUCTION HAS BEEN DEMONSTRATED; CELL EFFICIENCY IMPROVEMENTS ARE BEING INVESTIGATED	4	5	1	M
• SEVERAL SOLAR CELL COATING ALTERNATIVES HAVE BEEN PROPOSED AND TESTED	3	5	2	M
• EXISTING TRW POWER PROCESSOR WILL BE USED	5	6	1	L

$$TPF = \frac{15.5}{54} = 0.29$$

ENVIRONMENTAL CONTROL ASSESSMENT

THERMAL CONTROL - The ion propulsion module is actively cooled by using heat pipes. The heat pipes are considered state of the art and have been demonstrated on smaller ion thruster applications. The solar array will operate at a higher solar cell temperature because solar concentrators are used. However, the solar cells have been tested at the higher temperatures. Passive thermal control will be used on the solar arrays.

SPACECRAFT CHARGING - The ion propulsion system utilizes an active ion beam to neutralize the thruster ion beam and control the level of the charge buildup on the spacecraft. Active ion beam neutralizers have been tested in space on spacecraft.

ION BEAM/SOLAR ARRAY INTERACTION - Because JPL selected to go with conventional drive, high-voltage arrays are not used as would be the case in direct drive. It is therefore felt that the ion beam-solar array interaction potential would be minimal. A preliminary assessment of the problems supports this conclusion.

ENVIRONMENTAL CONTROL ASSESSMENT

	READINESS		GAIN	RISK
	PRESENT	GOAL		
• STATE-OF-THE-ART HEAT PIPES AVAILABLE FOR THRUST MODULE, ANALYSIS AND TESTING HAS BEEN DONE ON SOLAR CELLS AT ELEVATED TEMPERATURES	5	6	1	L
• ION BEAM NEUTRALIZATION HAS BEEN DEMONSTRATED	5	6	1	L
• PRELIMINARY ION BEAM/SOLAR ARRAY ASSESSMENT IS COMPLETE	3	5	2	L

$$TRF = \frac{4}{34} = 0.12$$

TECHNOLOGY READINESS SUMMARY

The results of the technology readiness assessment for Solar Sail and Solar Electric Propulsion candidates are summarized on the accompanying chart. A composite Technology Readiness Factor has been computed for each candidate. Barring unforeseen obstacles, the Solar Sail is approximately 29% away from achieving technology readiness, whereas Solar Electric is approximately 18% away from achieving technology readiness as measured by the Technology Readiness Factor. In the case of the Solar Sail Propulsion System, technology readiness would include a demonstration of the Heliogyro in a space test, whereas the Solar Electric Propulsion System could achieve technology readiness by ground testing only. The results of this assessment indicate a strong preference for the Solar Electric Propulsion System compared to the Solar Sail Propulsion System.

TECHNOLOGY READINESS SUMMARY

SOLAP SAIL	
• LARGE LIGHTWEIGHT SPACE STRUCTURES	$\frac{18.5}{52}$
• THIN FILMS	$\frac{11}{36}$
• ENVIRONMENTAL CONTROL	$\frac{3.5}{26}$
	$TRF = \frac{33}{114} = 0.29$

SOLAR ELECTRIC	
• ION THRUSTERS	$\frac{4}{40}$
• KW POWER SYSTEMS	$\frac{15.5}{54}$
• ENVIRONMENTAL CONTROL	$\frac{4}{34}$
	$TRF = \frac{23.5}{128} = 0.18$

TECHNOLOGY TRANSFER

Task two of the GRC effort, Technology Transfer, is intended to assess the potential utilization of the propulsion candidates and their associated technologies in future NASA and non-NASA programs and activities. In assessing utilization in future NASA programs, the OAST Space Systems Technology Model was used to determine which NASA future program opportunities would be considered. The Technology Model defines 22 mission opportunities in the post-1990's. The technology transfer potential for NASA programs was determined by defining the key technologies for each propulsion system, as well as the propulsion systems themselves, then matching the technology listings and propulsion systems with the technology needs listed for each of the 22 systems in the post-1990's Technology Model. In the case of non-NASA utilization the potential uses of technologies associated with each propulsion candidate by private industry were determined based on currently identified applications by NASA and industrial sources as well as the open literature.

SOLAR SAIL TECHNOLOGY TRANSFER POTENTIAL - NASA

Three key technology areas were identified for the Solar Sail Propulsion System. (1) large lightweight space structures including attitude and figure control; (2) thin films including metal coatings; and (3) passive environmental control, which is primarily concerned with temperature. The potential system applications are listed in the accompanying table. None of the system applications used Solar Sail propulsion because solar propulsion was not considered a viable propulsion system for Earth orbital operation, and planetary mission opportunities were only represented in the technology model by the Automated Planetary Station which was by definition propelled by a nuclear electric propulsion system. However, several attractive mission opportunities have been identified for Solar Sail propulsion during the 1980's, such as comet rendezvous, inbound planetary missions, and a possible terrestrial planetary shuttle.

SOLAR SAIL
TECHNOLOGY TRANSFER POTENTIAL — NASA

TECHNOLOGY AREAS

- LARGE LIGHTWEIGHT SPACE STRUCTURES
- THIN FILMS
- PASSIVE ENVIRONMENTAL CONTROL

FAR TERM MISSION OPPORTUNITIES

- LARGE SCALE MICROWAVE TELESCOPE
- LARGE SCALE ALL WEATHER SURVEY SYSTEM
- HIGH-RESOLUTION SEA SURVEY SYSTEM
- GEOLOGICAL MAPPING SYSTEM
- GLOBAL NAVIGATION SYSTEM
- GLOBAL CROP INVENTORY AND PRODUCTION FORECASTING SYSTEM
- DISASTER WARNING SYSTEM
- SPACE STATION
- SPACE POWER AND RELAY SYSTEMS (SOLAR MIRROR)
- SINGLE STAGE TO ORBIT

SOLAR SAIL TECHNOLOGY TRANSFER POTENTIAL - NON NASA

Non-NASA technology transfer potential has been divided into products, processes, and science. It would appear that the non-NASA technology transfer potential associated with the Solar Sail is centered about thin films, how thin films are produced, the chemistry of thin films, and products that can be derived from thin films. Biomedical applications such as the possible production of synthetic membranes for arteries and veins would have a profound impact in the medical field. High-temperature fire-resistant materials for aircraft and building interiors would also be very important. In fact, there would appear to be so many interesting products and process opportunities that private industry might find it advantageous to invest resources independently of NASA, much as the electronics industry has done in the past. However, in the case of Kapton of 0.1 mil or less, Dupont indicated it would not continue its efforts to produce that thickness unless NASA funded the effort: Dupont is not aware of a significant commercial market for the product.

SOLAR SAIL TECHNOLOGY
TRANSFER POTENTIAL — NON NASA

PRODUCTS

- HIGH TEMPERATURE FIRE RESISTANT MATERIALS
- OPTICAL WAVE GUIDES (LASER FIBER OPTICS)
- SUB-MICRON SIZE PARTICLE FILTERS
- SYNTHETIC MEMBRANES FOR BIOMEDICAL APPLICATIONS
- PRODUCTION OF MATERIALS FOR SEMICONDUCTORS (PHOTOTHERMAL DEGRADATION)
- HIGH PURITY NON-CRYSTALLINE FIBERS
- AIRCRAFT WINDOWS AND CANOPIES

PROCESSES

- THICKNESS MEASUREMENTS
- PHOTOTHERMAL TREATMENT OF FILMS TO PRODUCE UNIQUE ELECTRICAL OR OPTICAL PROPERTIES
- SPINNING TECHNIQUES FOR THE PRODUCTION OF MICRON SIZE FIBERS
- METHODS FOR THE ANALYSIS OF BULK AND SURFACE CHEMISTRY CHANGES IN THIN FILMS

SCIENCE

- UNDERSTANDING THE RELATIONSHIPS BETWEEN BULK AND SURFACE PROPERTIES TO THE CHEMICAL STRUCTURE AND MORPHOLOGY OF THIN FILMS

SOLAR ELECTRIC TECHNOLOGY TRANSFER POTENTIAL - NASA

Significant solar electric propulsion applications exist in the far-term NASA mission opportunities. Especially noticeable are Earth orbital applications. However, it is important in these applications to consider more efficient means of transversing the Earth's radiation belts. Solar concentrated solar array designs less susceptible to radiation effects are needed. The solar concentrated solar array appears to be a major breakthrough in being able to use Solar Electric Propulsion more effectively for missions to the outer planets. In addition, solar arrays which produce power output in kilowatts could have a significant impact on satellite designs and the functions that can be performed in space. Active adaptive spacecraft charging control could also significantly impact satellite capabilites. More efficient, high-capacity heat pipes for spacecraft thermal control is very important in future NASA mission opportunties.

SOLAR ELECTRIC
TECHNOLOGY TRANSFER POTENTIAL — NASA

TECHNOLOGY AREAS →

- ION THRUSTERS
- KW POWER SYSTEMS
- ACTIVE ENVIRONMENTAL CONTROL

FAR TERM MISSION OPPORTUNITIES →

- AUTOMATED PLANETARY STATION
- LARGE EARTH ORBITAL SOLAR OBSERVATORY
- ASTROPHYSICS SPACE LABORATORY
- ATMOSPHERIC PHYSICS LABORATORY
- LARGE-SCALE MICROWAVE TELESCOPE
- LARGE-SCALE ALL WEATHER SURVEY SYSTEM
- HIGH RESOLUTION SEA SURVEY SYSTEM
- GEOLOGICAL MAPPING SYSTEM
- GLOBAL COMMUNICATIONS SYSTEM
- GLOBAL NAVIGATION SYSTEM
- SPACE POWER AND RELAY SYSTEM
- ADVANCED LOW THRUST ESCAPE VEHICLE

SOLAR ELECTRIC TECHNOLOGY TRANSFER POTENTIAL - NON-NASA

The processes derived from the use of ion beams are already finding many non-NASA applications. Surface texturing, for example, has enabled the development of several very important medical products such as those indicated on the facing page. The texturing of the surface by ion beam bombardment has enabled the production of medical products whose surfaces very closely match the texture of natural human parts, thereby increasing compatibility and effectiveness. Ion deposition of metallic films on metallic and nonmetallic materials is becoming a very important industry. Several components developed for electric propulsion such as the liquid metal cathode and the liquid metal plasma valve have many applications in high-voltage electrical applications. As in the case of Solar Sail thin-film technology, it would appear that many products and processes would be funded by private industry based on the present potential commercial demand, independent of NASA funding support for electric propulsion.

SOLAR ELECTRIC TECHNOLOGY
TRANSFER POTENTIAL — NON NASA

PRODUCTS

- LIQUID METAL CATHODE
- LIQUID METAL PLASMA VALVE
- NEUTRAL BEAM INJECTORS
- SELF-ALIGNED GATE FIELD EFFECT TRANSISTOR
- HEART PUMP DIAPHRAMS
- DENTAL IMPLANTS
- PROSTHETIC MATERIALS
- ORTHOPEDIC PROSTHESIS

PROCESSES

- ION BEAM SPUTTERING, SURFACE TEXTURING AND DEPOSITION
- ION BEAM MACHINING, POLISHING DRILLING AND MILLING

SCIENCE

- SECONDARY ION MASS SPECTROMETRY

SUMMARY AND CONCLUSIONS

<u>CENTRAL ISSUES</u> - In the case of Solar Sail, it is not clear whether the Heliogyro should or should not be tested in space prior to mission usage. As more becomes known about the Heliogyro, the more complex it becomes, and design changes become necessary. Kapton has not been produced at 0.1 mil, and the metallization of the film in the required size still remains to be demonstrated.

The solar array with concentration for Solar Electric does not appear to be finalized. Significant design changes could be expected, as more optimal array-concentrator designs are formulated due to packaging and/or weight considerations. Even though 2-mil solar cells have been produced on a pilot line by one contractor, cost and production capacity remain as concerns.

<u>CONCLUSIONS</u> - The Solar Electric Propulsion System is clearly the preferred choice base on technology readiness. Even though the Solar Sail has made significant progress during the past six months, the years of development and testing provide a foundation for Solar Electric which cannot be overcome by a few months of intensive effort on Solar Sail.

Both systems appear to have significant technology transfer applications in future NASA program opportunities. The utilization of the OAST Technology Model biases the propulsion applications in favor of Solar Electric. However, analysis by other contractors have defined several near-term Solar Sail Propulsion applications, but no unique applications of Solar Sail Propulsion have been identified. Both systems have significant non-NASA technology spillover potential in products, processes, and basic science.

SUMMARY AND CONCLUSIONS

CENTRAL ISSUES

SOLAR SAIL →
- SAIL SPACE TEST PRIOR TO LAUNCH
- THIN FILM PRODUCTION AND METALIZATION

SOLAR ELECTRIC →
- SOLAR ARRAY WITH CONCENTRATOR DESIGN/PACKAGING
- THIN SOLAR CELL PRODUCTION COST

CONCLUSIONS

- SOLAR ELECTRIC PROPULSION IS THE PREFERRED CHOICE FOR THE HALLEY COMET RENDEZVOUS MISSION FROM A TECHNOLOGY READINESS STANDPOINT
- NO CLEAR CHOICE EXISTS BASED ON TECHNOLOGY TRANSFER CRITERIA

APPENDIX A

SELECTED JPL PROGRAM MANAGEMENT ASSESSMENT OF TECHNOLOGY READINESS

SOLAR SAIL
TECHNOLOGY READINESS ASSESSMENT

MADE BY

DR. LOUIS FRIEDMAN
SOLAR SAIL PROJECT, JPL

LARGE LIGHTWEIGHT SPACE STRUCTURES ASSESSMENT

	READINESS		GAIN	RISK
	PRESENT	GOAL		
• NEW BLADE DESIGN, 20 JUNE '77	3	7	4	H
• EXTENSIVE STABILITY AND CONTROL ANALYSIS HAS BEEN COMPLETED BY INDEPENDENT SOURCES	3	5	2	M
• PASSIVE BLADE PANEL FIGURE CONTROL DESIGN ANALYSIS IN PROGRESS	3	5	2	M
• "NEW" BLADE PACKING FRACTION ANALYSIS COMPLETED	3	5	2	L
• "OLD" BLADE MANUFACTURING – QUALITY CONTROL ANALYSIS COMPLETED, NEW DESIGN NOT INITIATED	2	5	3	M

$$TRF = \frac{20.5}{54} = 0.38$$

THIN FILMS ASSESSMENT

	READINESS		GAIN	RISK
	PRESENT	GOAL		
• DUPONT HAS DEMONSTRATED 0.15 MIL KAPTON, CIBA-GEIGY HAS BEEN DEOMONSTRATED AT APPROXIMATELY 0.1 MIL	2	4	2	M
• TEST SPECIMENS OF KAPTON HAVE BEEN METALIZED, PRODUCTION EQUIPMENT FOR 56" WIDE MATERIAL IS GOING INTO OPERATION	2	4	2	H
• LIFETIME OF KAPTON AT 0.25 AU IS DEPENDENT ON MAINTAINABILITY OF COATINGS. STATIC LABORATORY TESTS TO DATE	3	5	2	M
• SHIPPING AND HANDLING OF 0.1 MIL KAPTON IS DEPENDENT ON "GOOD ROLL FORMATION"	2	4	2	M

$$TRF = \frac{13}{34} = 0.38$$

ENVIRONMENTAL CONTROL ASSESSMENT

	READINESS		GAIN	RISK
	PRESENT	GOAL		
• FILM TEMPERATURE ANALYSIS COMPLETED, INDICATES THAT TEMPERATURE REQUIREMENTS CAN BE MET	3	5	2	L
• ANALYSIS INDICATED THAT PLACING HOLES AT PREDETERMINED INTERVALS TO GROUND FRONT-TO-BACK IS SUFFICIENT FOR A 100 – 500 V CHARGE DIFFERENTIAL	3	5	2	L
• ANALYSIS INDICATED THAT MICROMETEORITES WILL NOT CAUSE FAILURE OF DESIGN	3	5	2	M

$$IRF = \frac{7}{30} = 0.23$$

SOLAR ELECTRIC
TECHNOLOGY READINESS ASSESSMENT

MADE BY

DR. KENNETH ATKINS
SOLAR ELECTRIC PROJECT, JPL

ION THRUSTER ASSESSMENT

	READINESS		GAIN	RISK
	PRESENT	GOAL		
• SPECIFIC IMPULSE REQUIREMENTS HAS BEEN DEMONSTRATED	4	6	2	L
• DESIGN CHANGES TO BEAM AND OPTICS DESIGNS COULD DOUBLE THE DESIGN LIFE, CHANGES DEMONSTRATED ON 8 CM THRUSTERS	4	6	2	L
• MULTIPLE THRUSTER (2) OPERATION HAS BEEN DEMONSTRATED	4	6	2	L
• DURING 10,000 HR. LIFETIME TEST, THE THRUSTER WAS SWITCHED OFF-ON 30 TO 40 TIMES	4	6	2	L

$$TRF = \frac{8}{48} = 0.17$$

KW POWER SYSTEMS ASSESSMENT

	READINESS		GAIN	RISK
	PRESENT	GOAL		
• PRESENT SOLAR ARRAY PROGRAM GOAL IS 66W/Kg; DESIGN CONCEPTS FOR 200W/Kg PROPOSED AND ANALYZED	3	6	3	M
• SEVERAL SOLAR CONCENTRATOR DESIGNS HAVE BEEN FORMULATED AND ANALYZED; LIMITED TESTING	3	6	3	M
• PILOT THIN CELL PRODUCTION HAS BEEN DEMONSTRATED; CELL EFFICIENCY IMPROVEMENTS ARE BEING INVESTIGATED	4	5	1	M
• SEVERAL SOLAR CELL COATING ALTERNATIVES HAVE BEEN PROPOSED AND TESTED	3	5	2	M
• EXISTING TRW POWER PROCESSOR WILL BE USED	5	6	1	L

$$TRF = \frac{14.5}{56} = 0.26$$

STATUS — ENVIRONMENTAL CONTROL

	READINESS		GAIN	RISK
	PRESENT	GOAL		
• STATE-OF-THE-ART HEAT PIPES AVAILABLE FOR THRUST MODULE, ANALYSIS AND TESTING HAS BEEN DONE ON SOLAR CELLS AT ELEVATED TEMPERATURES	5	6	1	L
• ION BEAM NEUTRALIZATION HAS BEEN DEMONSTRATED	5	6	1	L
• PRELIMINARY SPACECRAFT CHARGING ANALYSIS COMPLETE	3	6	3	L

$$TRF = \frac{5}{36} = 0.14$$

TECHNOLOGY READINESS SUMMARY

SOLAR SAIL	• LARGE LIGHTWEIGHT SPACE STRUCTURES	$\frac{20}{54}$
	• THIN FILMS	$\frac{13}{34}$
	• ENVIRONMENTAL CONTROL	$\frac{7}{30}$
		$TRF = \frac{40.5}{118} = 0.34$
SOLAR ELECTRIC	• ION THRUSTERS	$\frac{8}{48}$
	• KW POWER SYSTEMS	$\frac{14.5}{26}$
	• ENVIRONMENTAL CONTROL	$\frac{5}{36}$
		$TRF = \frac{27.5}{140} = 0.20$