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PASADENA, CALIFORNIA

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Jet Propulsion Laboratory
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JULY 1 - DECEMBER 31, 1968

Volume II (OART)

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Supporting Research and Technology
for the Office of Advanced Research and Technology
National Aeronautics and Space Administration

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PREFACE

This document has been prepared under the direction of the Office of Research and Advanced Development of the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

The Semiannual Review of Research and Advanced Development is published in three volumes directed to the appropriate NASA funding offices:

Volume I	Supporting Research and Technology for the Office of Space Sciences and Applications
Volume II	Supporting Research and Technology for the office of Advanced Research and Technology
Volume III	Supporting Research and Technology for the Office of Tracking and Data Acquisition (New Systems and Spacecraft Subsystems)

Previous issues were published as follows:

Fiscal Year	Document No.
1965	TM 33-243
1966	TM 33-272 TM 33-296
1967	TM 33-322 TM 33-353
1968	701-6
1969	701-15 (Vol. II) 701-16 (Vol. I) 701-17 (Vol. III)

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INTRODUCTION

This volume contains a review of all supporting research and technology in progress at the Jet Propulsion Laboratory during the period July 1 to December 31, 1968, under the direction of the JPL Office of Research and Advance Development, for the NASA Office of Space Sciences and Applications.

The work units are arranged in numerical sequence by NASA code in each subject section. To locate a desired unit, refer to the Table of Contents under the appropriate subject heading.

JPL research and advanced development results published during this report period are listed under each work unit

N70-39643

SPACE POWER AND ELECTRIC PROPULSION SYSTEM SRT(120)

ELECTRIC ENGINE SYSTEMS (120-26)

RESEARCH ON MAGNETIC CONTAINMENT ION THRUSTERS

NASA Work Unit 120-26-02-03-55

JPL 320-61701-0-3830

D. J. Kerrisk

OBJECTIVE

The objective of this work unit is to conduct research and advanced development on electron bombardment ion engines of the magnetic containment ion chamber configuration in order to seek higher total efficiencies than are currently available. Further, the objective is to identify problems and characteristics of such engines as might effect their integration into spacecraft systems. It is planned that this work will be conducted under contract rather than at JPL.

STATUS

This contract has not as yet been executed, pending further definition of overall priorities within the solar electric propulsion system technology program.

PUBLICATIONS

None

ELECTRIC PROPULSION POWER CONDITIONING

NASA Work Unit 120-26-04-05-55

JPL 320-60301-2-3420

E. Costogue

OBJECTIVE

The electric propulsion power conditioning activities are directed toward accomplishing two tasks. The first task, SEPST (Solar Electric Propulsion System Technology) II, scheduled to be completed in the early part of 1969, will involve the evaluation testing of a power-conditioning unit for two ion engines. A switching module will be utilized to switch power to the engines by command. The second task, SEPST III, scheduled to be completed in 1970, will involve the design, fabrication, and evaluation testing of the complete power conditioning portion of an electric propulsion system. The power conditioning will consist of (1) three units that will power four ion engines, (2) a switching unit that will be utilized to switch power-conditioning units to available ion engines as required, and (3) a maximum-power-point seeker unit that will examine the solar panel characteristics and verify the available maximum power of the source. The power-conditioning units will be developed under contract. The switching unit and the seeker unit will be designed and fabricated at JPL. Design concepts of a solar array simulator to simulate the solar panel power output of 15 kW and appropriate current-voltage characteristics from 1 AU to 3.5 AU are being considered. The unit will be developed under contract.

PROGRESS

The SEPST II program will utilize a breadboard power conditioner built earlier for the SERT II program. The unit has been modified to supply the power requirements of the present program. Hughes Aircraft Company was awarded the contract to modify the unit (Contract 952229). The modified unit was functionally tested at the contractor's facility and later at JPL. The data obtained verified that the unit met the specified requirements.

The power switching unit has been designed and fabricated. Qualification tests have been completed and the unit delivered. The power switching unit has been integrated with the ion thruster support equipment. Integration testing of the power conditioner with the ion thruster engine has been initiated, and the entire system is expected to be operational in January as scheduled.

The SEPST III program will utilize a breadboard and two experimental power conditioner units. Hughes Aircraft Company was awarded the contract (Contract 952297) to design, develop, fabricate and qualify this unit.

The designing of the power conditioner modules has been initiated. A preliminary circuit design review was conducted in August 1968. A physical layout, mounting configuration, and overall electrical-thermal detail evaluation were conducted in October 1968. A final design review is scheduled in February 1969. All of the units are expected to be delivered by September 1969.

Preliminary design concepts of the maximum-power-point seeker unit and switching unit have been generated. Detail specifications of both units are expected to be formalized early in 1969. Investigations of the capabilities of potential contractors has been initiated, and the preliminary steps for the procurement contract are being formalized.

PUBLICATIONS

None

LIQUID MERCURY CATHODE RESEARCH

NASA Work Unit 120-26-04-08-55

JPL 320-61301-0-3830

D. J. Kerrisk
E. V. Pawlik

OBJECTIVE

The objective of this work unit is to provide an analytical and experimental evaluation of mercury-fed cathodes of liquid and vapor types for use as both main-thruster and neutralizer cathodes in ion engines. Steady-state performance of thrusters so equipped will be determined to allow meaningful performance comparison with state-of-the-art devices.

STATUS

A sole-source contract for this study has been initiated with the Hughes Aircraft Company. The effort began February 5, 1968. Accomplishments to date include:

(1) A breadboard flow system is being assembled as a final demonstration of component utility and system compatibility.

(2) A 30-cm thruster design for use with the liquid mercury cathode has been operated over a range of discharge chamber configurations. This testing has resulted in reduction of discharge loss to 300 ev/ion.

(3) A modified 20-cm thruster has been operated over a 2:1 range in output power. Performance mapping of this thruster has been completed.

(4) Thermal properties have been determined to achieve thermal integration of a high-temperature liquid mercury cathode with the 30-cm thruster.

PUBLICATIONS

Contractor Reports, Interim and Final

1. "High-Temperature LM Cathode Ion Thrusters," Quarterly Progress Report No. 1, May 1968, Contract No. JPL 952131.
2. "High-Temperature LM Cathode Ion Thrusters," Quarterly Progress Report No. 2, August 1968, Contract No. JPL 952131.
3. "High-Temperature LM Cathode Ion Thrusters," Quarterly Progress Report No. 3, November 1968, Contract No. JPL 952131.

ACTUATOR DEVELOPMENT FOR A CLUSTERED ION ENGINE ARRAY

NASA Work Unit 120-26-04-10-55

PL 320-60401-2-3440

G. S. Perkins
J. D. Ferrera

OBJECTIVE

There is currently a great deal of interest in solar-powered electric propulsion systems suitable for interplanetary spacecraft application. One such electric propulsion application is a Jupiter flyby mission in 1975 as described in detail in a report entitled, "1975 Jupiter Flyby Mission Using a Solar Electric Spacecraft," T. A. Barber, et al., ASD-760-18, dated March 1, 1968. In support of these advanced development missions an attitude-control actuation system is required. The long-term objective of this work unit is to develop a new multi-engine array with four engines being gimbaled. This assembly will then be translated in the X-Y directions plus and minus 13 inches. The gimbaled engines provide roll control. The translation of the engine cluster assembly is to align the resultant thrust vector through the center of gravity of the spacecraft for pitch and yaw attitude control.

The immediate objective of this task is to design and build a breadboard assembly. The assembly consists of a two-engine array with each engine supported in gimbals and controlled by a gimbal actuator. The two-engine array is translated in one axis and controlled by a translation actuator. Figures 1 and 2 of SPS 37-54, Vol. III, "Actuator Development for a Clustered Ion Engine Array," show this assembly as it is mounted in the test chamber. All major components needed to test a typical solar electric spacecraft attitude-control thruster system are present.

GIMBAL ACTUATOR DESCRIPTION AND PROGRESS

The characteristics of this actuator are listed in Table 1. A unique feature of this actuator is the drive arrangement utilized to minimize backlash in order to obtain 20 arc-seconds per stepper-motor increment of output rotation. The linear motion of the saddle nut is transformed to rotary motion of the sector through two beryllium/copper straps. The saddle nut is also pinched slightly prior to machining of screw threads which, when replaced, are forced into contact with the lead screw's threads. This technique produces zero backlash between the actuator output shaft and the position feedback pickoff. Aluminum is use for the lead screw to maintain similar metals throughout to minimize thermal expansion. A solid rod connects the saddle nut to the pickoff arm. The pickoff for position feedback is a linear, variable differential transformer. The drive motors in both actuators are size 11, 90-deg permanent-magnet stepper motors. The actuator case is painted black and the intermediate shaft connecting the actuator to the ion engine is made of stainless steel to minimize heat transfer into the actuator. The gimbal actuator has been fabricated and tested. Its performance met the requirements stated in Table 1. The actuator is now installed on the two-engine arrays where it will be used to point the engines for roll control.

TRANSLATION ACTUATOR DESCRIPTION AND PROGRESS

The characteristics of this actuator are listed in Table 1. Two features are particularly noteworthy. One is the application of a harmonic-drive gear train to obtain a very low value of backlash, less than 5 arc-seconds, and a high-output torsional stiffness, 20,000 lb/ft per radian. The other is the space compatibility of the flat-strap type of drive. Fatigue cracks which might develop in the strap are self-healing in space vacuum. In this test, the balls used in the roller bearings which support the moving platform on two one-inch-diameter

Table 1. Table of Actuator Characteristics

	Translation Actuator	Gimbal Actuator
Output travel	±3 in.	±10 deg
Nominal stepping rate	100 steps/sec	50 steps/sec
Actuator slewing rate	0.25 in./sec	5 milliradians/sec
Temperature range	-50°F to +275°F	-50°F to 275°F
Test duration	1000 hours	1000 hours
Resolution	0.0025 in./step	20 arc-sec/step
Backlash	5 arc-sec	zero
Gear train ratio	2830:1	15708:1
Power required	7 watts	7 watts
Output torque at nominal rate	50 in.-lb	60 in.-lb
Weight	7.25 lb	4.3 lb
Leak rate (90%-10% HE)	0.005 cc/hr	0.005 cc/hr
Pickoff scale factor	0.14 volts/deg	12.55 volts/in.
Pickoff linearity	0.5%	0.14% fs
Excitation	±24V dc	24V dc

rails are stainless steel. In a space vacuum application these balls will be made of a ceramic material to eliminate the possibility of coldwelding. A rotary infinite-resolution potentiometer is used for position feedback. Where possible, similar metals are used to minimize thermal expansion. Thermistors are mounted inside the actuator to provide temperature information, since the ion engines are expected to reach temperatures as high as 500°F. Individual electric lines are shielded to prevent electrical interference. The translation actuator has been fabricated and tested. Its performance met the requirements stated in Table 1. The actuator is now installed in the two-engine array where its purpose is to provide X-Y control by aligning the resultant thrust vector through the center of gravity of the spacecraft.

PLANNED ACTIVITIES

A 1000-hour system test using the two-engine array in the vacuum chamber is planned to start in February 1969. Design activity in support of the long-term objective will be carried on. Specific attention will be given to the following areas:

(1) Space and flight environmental compatibility will be principal criteria.

(2) Design problems highlighted during the 1000-hour breadboard system test will be corrected.

(3) Flight prototype design procedures will be followed with special attention begin given to weight and environmental requirements.

PUBLICATIONS

SPS Contributions

1. Ferrera, J. D., and Perkins, G. S., "Actuator Development for a Clustered Ion Engine Array," SPS 37-54, Vol. III, December 1968.

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ELECTRIC PROPULSION SYSTEM PERFORMANCE ANALYSIS AND TRAJECTORY PROGRAMMING

NASA Work Unit 120-26-07-01-55

JPL 320-60501-0-3830

J. W. Stearns

OBJECTIVE

The objective of this work unit is to provide mission performance analysis support to electric propulsion research and development. The close inter-relationships between the mission and spacecraft parameters, and the development of components and subsystems require continuous tradeoff study. This includes weight, reliability, cost, flight constraints, power profile, thrust vectoring, and systems integration.

From R&D studies, estimates are made of electric propulsion component and subsystem parameters such as, specific mass, efficiency, reliability, etc. These elements are then evaluated with respect to potential missions of interest to JPL. Particular emphasis is given to tradeoffs of greatest importance for mission performance and system simplicity. Results of such analyses are fed back into R&D tasks to improve the capabilities of electric prouplsion. Iterative mission and spacecraft feasibility studies are conducted to the point where significant mission potential is shown to exist, at which time, the analysis effort is transferred to other cognizance within JPL.

STATUS

Due to priority effort on other solar electric spacecraft studies under OSSA sponsorship, there was no activity under this work unit during the first half of this fiscal year. During the second half of the fiscal year, this work unit will be used to support JPL study of an asteroid-belt mission with solar electric propulsion.

PUBLICATIONS

None.

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LOW THRUST TRAJECTORY ANALYSIS

NASA Work Unit 120-26-07-03-55

JPL 320-60201-1-31X0

C. B. Solloway

OBJECTIVE

The objectives of this task are to provide an efficient and versatile trajectory performance computational capability, and to carry out parametric studies of the trajectory-related properties of specified advanced propulsion missions.

TRAJECTORY ANALYSIS

Work performed under this task includes solar-electric-propulsion (SEP) trajectory analysis in support of the "Grand Tour" study presently being completed. In this trajectory analysis there are a number of spacecraft-launch vehicle combinations which were investigated with the view of assessing the performance capability of the SEP spacecraft as compared with a representative ballistic spacecraft. The results of this analysis will appear as part of a formal document being written.

Also, a trajectory analysis for anSEP spacecraft for an asteroid probe was investigated. The results of this investigation were presented to the JPL senior staff in November and will appear in the SPS series.

A paper on an SEP planetary orbiter was presented at AIAA/AAS Astrodynamics Specialists Conference in September 1968. This paper gave the results of an investigation of a 1971 Mars orbiting spacecraft, and compared its performance with a representative ballistic spacecraft.

Current work involving SEP spacecraft includes the determination of spacecraft payload for outer major planet flyby trajectories.

Trajectory analysis support is also being supplied to NASA for a nuclear-electric-propulsion study to determine the capability of these vehicles for high energy missions such as outer planet rendezvous. The particular mission being investigated by JPL is a Jupiter orbiter using any one of five selected launch vehicles.

In support for these studies the present low-thrust program is being rewritten in a form more compatible with the UNIVAC 1108 which will be operational soon. This upgraded program will feature a number of improvements such as an improved search routine and inclusion of N-body optimization to make it more compatible with today's requirements.

During the next half-year period, the trajectory analysis support will continue at a slightly reduced pace. In addition, an investigation of computing the partial derivatives required for the solution of the boundary value problem will be made by integration of the adjoint equations. Also included will be an investigation of analytic computation of the near-planet part of the mission for N-body optimization problems.

LOW THRUST TRAJECTORY ACCURACY STUDIES

The CEP and other matrix manipulator programs have been applied to the orbit determination problem associated with a continuously thrusting spacecraft. The effort is concerned with a comprehensive study of the accuracy of state estimation techniques of powered space vehicles which utilize counted doppler tracking data from the NASA Deep Space Network (DSN) facilities. The purpose of the study is to establish the inherent accuracy of the DSN for such tasks and determine whether or not the present system is adequate for future space missions which may employ powered flight over a large portion of the flight path.

Application of the low-thrust techniques is being applied to the Grand Tour as a possible solar electric leg (earth-Jupiter) of a 1977 Grand Tour Mission. Results are to appear shortly in Section II of a forthcoming JPL Grand Tour Mission Study Report.

COMPUTER PROGRAM DEVELOPMENT

The ASTRAL program will optimize the payload for solar-electric or nuclear-powered spacecraft on planetary transfer trajectories. The program should be completed early in FY 69 and will be a useful tool for preliminary analysis of low-thrust mission feasibility. It is currently undergoing a check-out comparison against two other programs, NUTRAL and the JPL low thrust trajectory program (Sauer). The results appear favorable and will be documented in an SPS article. A description of ASTRAL itself appears in SPS 37-54, Vol. III, December 1968.

ADVANCED PROPULSION MISSION STUDIES

A paper entitled "Trajectory Analysis of a 1975 Mission to Mercury Via an Impulsive Flyby of Venus," was presented at the AIAA/AAS Astrodynamics Specialists Conference at Jackson, Wyoming, September 3-5, 1968. The paper showed the feasibility of a mission to Mercury previously thought to be unattractive. The launch opportunity investigated would be the last good ($C_3 \leq$ 33 km^2/sec^2) opportunity in the 1970s.

Two SPS articles were completed and have been published. The first is a summary of the paper given under the previous heading. The article follows the conference presentation and gives added material which was found after the paper was completed. The second article presents 11 missions to the outer planets. The importance of this study was the inclusion of launch period into the mission design, a factor not taken into consideration previously in such studies.

Several supportive studies were conducted during the time period. Those published have been listed in the publication section.

ATTENDANCE AT SCIENTIFIC MEETINGS

1. AIAA/AAS Astrodynamics Specialists Conference, Jackson, Wyo., September 3-5, 1968.
2. Seventh National Fall Meeting of the American Geophysical Union, San Francisco, Calif., December 2-3, 1968.

PUBLICATIONS

Meetings and Symposia Papers

1. Jordan, J. F., "Orbit Determination for Powered Flight Space Vehicles on Deep Space Missions," AIAA/AAS Astrodynamics Specialists Conference, Jackson, Wyo., Sept. 3-5, 1968.

2. Sauer, C. G., Jr., "Optimization of a Low-Thrust Solar-Electric Planetary Orbiter Mission," AIAA/AAS Astrodynamics Specialists Conference, Jackson, Wyo., Sept. 3-5, 1968.

3. Wallace, R. A., "Trajectory Analysis of a 1975 Mission to Mercury Via an Impulsive Flyby of Venus," AAS Paper 68-113, AIAA/AAS Astrodynamics Specialists Conference, Jackson, Wyo., Sept. 3-5, 1968.

SPS Contributions

1. Kingsland, L., and Bollman, W. E., "An Approximate Solution to the Estimate of Navigational Accuracy for a Deep Space Probe During the Planetary Encounter Phase," SPS 37-50, Vol. II, pp. 90-93, Mar. 31, 1968.

2. Kingsland, L., and Bollman, W. E., "The Effect of Target Planet Gravity on the Estimate of Navigational Accuracy for a Deep Space Probe During the Planetary Encounter Phase," SPS 37-51, Vol. II, pp. 37-41, May 31, 1968.

3. Bollman, W. E., "An Approximate Solution to the Analytical Partials of the Spacecraft's Geocentric Range Rate During the Pre-encounter Phase of a Planetary Mission," SPS 37-52, Vol. II, pp 34-37, July 31, 1968.

4. Sauer, C. G., "Optimization of a Solar-Electric-Propulsion Planetary Orbiter Spacecraft," SPS 37-53, Vol. III, Oct. 31, 1968.

5. Wallace, R. A., "Trajectory Analysis of a 1975 Mission to Mercury Via an Impulsive Flyby of Venus," SPS 37-53, Vol. II, Oct. 31, 1968.

6. Sauer, C. G., "A Solar-Electric-Propulsion Asteroid Probe," SPS 37-54, Vol. III, Dec. 31, 1968.

7. Stavro, W., and Alderson, D., "ASTRAL: Optimized Low-Thrust Trajectories Using Approximate Closed Form Solutions to the Equations of Motion," SPS 37-54, Vol. III, Dec. 31, 1968.

JPL Technical Report

Bollman, W. E., "An Ambiguity in the Orbit Determination of Planetary Flyby Trajectories," TR 32-1331, Nov. 1, 1968.

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ELECTRIC PROPULSION APPLICATIONS

NASA Work Unit 120-26-08-01-55

JPL 320-60101-0-3830

D. J. Kerrisk

OBJECTIVE

This work unit has as its objective the demonstration of a flight-ready technology for electric propulsion systems. The central elements of this demonstration are an open-loop test of a partial thrust subsystem early in 1969, and a closed-loop test of a complete breadboarded thrust subsystem during 1971.

STATUS

Effort during the past six months has been concentrated on the preparations for the open-loop subsystem test. Also, work continued on the installation of the 7-1/2 ft vacuum chamber, and on preliminary work for the closed-loop test. Each of these will be considered separately.

Open-Loop Test

Thruster checkout with the cesium neutralizers was completed early in the reporting period. Results indicated satisfactory operation, but also indicated 20% to 100% higher impingement currents. These currents could not be eliminated, and it was judged they were still within tolerable levels. Work on the thruster was terminated to convert the test facility to support the open-loop test.

The two thrusters for the open-loop test were mated to the gimbals, and the assembly was mounted to the translator. The translator and gimbals were then checked in the vacuum chamber and found to perform satisfactorily. The gimbals and translator actuators are described in more detail under Work Unit 120-26-04-07-55.

The switching network, described in detail under Work Unit 120-26-04-05-55, was also delivered and checked out with the thrusters. The failure logic system, which for the open-loop test is relatively simple, has also been fabricated and is now in the final checkout process prior to delivery.

The power conditioning unit, which is the modified unit originally developed under JPL Contract 951144, has also been delivered. Checkout with dummy loads has been completed, and preliminary testing of this unit with the thruster is now underway. This represents the last major step prior to inaugurating the open-loop test. If the present preliminary testing goes well, the partial system test should be started early in the next reporting period.

7-1/2 Ft x 15 Ft Vacuum Chamber

Installation of the 7-1/2 ft x 15 ft vacuum system continued throughout the period. Major effort was concentrated on (1) the electrical hook-up of all the system components and fabrication of the final major pieces of equipment, and (2) the power conditioning chamber and the 3 ft gate valve isolating this chamber from the main chamber. These latter two items have been delivered, and the electrical work is progressing. While a target date of mid-January was established for initial tank pump-down, a March date appears more realistic.

Closed-Loop Test

Activity on the closed-loop test was limited during this period by the demands of the open-loop test. Effort was primarily centered in two areas: (1) the development of the light-weight power conditioning units, described in detail under Work Unit 120-26-08-06-55, and (2) the preparation of functional specifications for each subsystem element to assure that all subsystem interfaces are properly defined and agreed upon. These functional specifications will be followed by detail design and fabrication after the definition of the total system is considered adequate. While this will delay much hardware fabrication into FY 70, it should result in considerable time and cost savings during the ensuing integration phase.

PUBLICATIONS

SPS Contributions

1. Masek, T. D., and Pawlik, E. V., "Hollow Cathode Operation in the SE-20C Thruster," SPS 37-53, Vol. III, October 31, 1968.
2. Masek, T. D., "Plasma Investigation in the SE-20C Thruster," SPS 37-53, Vol. III, October 31, 1968.

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EVALUATION OF ELECTRIC PROPULSION BEAM DIVERGENCE AND EFFECTS ON SPACECRAFT

NASA Work Unit 120-26-08-02-55

JPL 320-61501-0-3830

D. J. Kerrisk
J. R. Womack

OBJECTIVE

The objective of this work unit is to evaluate analytically and experimentally the interactions effects of an ion engine exhaust beam on external surfaces of electric propulsion spacecraft to provide design data for advanced propulsion spacecraft development.

STATUS

Phase I was completed August 1968. A review of the work completed was presented orally September 1968. The rough draft of the final report for this phase has been completed and is being revised. Release of the final report is expected in January 1969.

The following accomplishments summarize the results of Phase I:

(1) The critical experiments and measurement techniques to determine the metallurgical effects of neutral propellant atoms with spacecraft materials have been identified.

(2) The initial modeling of chemical reactions of propellant ions and meutral atoms on nonmetallic spacecraft materials has been accomplished, and the experimental methods to be used in Phase II for the analyses of these reactions have been determined. Initial modeling indicated that cesium is expected to be more deleterious than mercury.

(3) The effects of condensed propellant on surface thermal properties has been theoretically determined. Results were curves indicating the neutral arrival rates required for condensation on the solar array as a function of (1) distance from the Sun and (2) whether the

condensation occurs on the Sun side or dark side of the array. The analysis specifically considered the surfaces of the Boeing Large Area Solar Array. Surface thermal properties of bulk mercury and cesium needed for the analysis were derived by using applicable data from the literature supplemented by theoretical analytical methods.

(4) The initial modeling of propellant beam effects on thermal control coatings have been summarized, and the experimental techniques to be used in the experiments to be performed in Phase II have been selected and designed. Results indicate that thermal control points such as zinc oxide-potassium silicate might be quite susceptible to serious damage by mercury ions. For commonly used low-emittance metals such as copper, silver, and gold, roughening of these surfaces by sputtering can cause a significant increase in their emittance.

(5) Initial modeling predicting the erosion rates of samples by propellant beam interaction has been summarized, and the experimental technique to be used in the Phase II effort has been designed. The initial models indicate that erosion rates are higher for non-metallics than for metallics. The densities of non-metallics are likely to be lower and sputtering yields higher. Primary attention in Phase II will be given to determining the erosion rates of non-metallics.

(6) A vacuum environment ot permit extrapolation of the experimental results obtained in the experimental effort to the conditions of deep space has been achieved. In achieving this environment, experimental techniques were developed to measure the effects of the vacuum contaminants on erosion rates.

The Phase II contract of this program is being negotiated and work is expected to be initiated in early January 1969.

PUBLICATIONS

Contractor Reports, Interim and Final

1. Project Work Plan, TRW Document No. 08965-6001-R000, July 28, 1967.

2. Monthly Status Letter No. 1, TRW Document No. 08965-6002-R000, August 15, 1967.

3. Monthly Status Letter No. 2, TRW Document No. 08965-6003-R000, September 15, 1967.

4. First Quarterly Letter, TRW Document No. 08965-6004-R000, October 20, 1967.

5. Monthly Status Letter No. 3, TRW Document No. 08965-6005-R000, November 15, 1967.

6. Monthly Status Letter No. 4, TRW Document No. 08965-6006-R000, December 15, 1967.

7. Second Quarterly Letter, TRW Document No. 08965-6007-R000, January 20, 1968.

8. Monthly Status Letter No. 5, TRW Document No. 08965-6008-R000, February 15, 1968.

9. Monthly Status Letter No. 6, TRW Document No. 08965-6009-R000, March 15, 1968.

10. Third Quarterly Letter, TRW Document No. 68965-6010, April 20, 1968.

11. Monthly Status Letter No. 7, TRW Document No. 08965-6011, May 15, 1968.

12. Monthly Status Letter No. 8, TRW Document No. 08965-5012, June 15, 1968.

13. Final Report Draft, TRW, December 2, 1968.

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ELECTRIC PROPULSION SPACECRAFT PLASMAS AND FIELDS INTERACTIONS

NASA Work Unit 120-26-08-04-55

JPL 320-61001-0-3830

D. J. Kerrisk

OBJECTIVE

The objective of this work unit is to investigate possible interactions between electric propulsion systems and scientific data collection on unmanned interplanetary spacecraft. Such interactions could influence data collection in three ways: (1) the fields associated with electric propulsion systems could influence the science instruments themselves, giving false readings; (2) the fields could influence the space plasma, disturbing it to such an extent that the measurements taken would give little indication of the undisturbed condition; and (3) the particles associated with the electric propulsion system, particularly the electrons and slow ions, could themselves be detected by the particles measuring devices, and thereby give spurious readings. The severity of each type of interaction must be investigated.

STATUS

Under a previous NASA contract (NAS7-564), an analytical study of possible interactions was made. The results of the study, given in Ref. 1, indicated several possible problem areas, some of which were amenable to further experimental evaluation. A second contracted study to pursue this investigation is now being released. The study, to be performed by TRW Systems, will start early in 1969. The contract has been negotiated, and is now in the approval cycle.

REFERENCE

1. Cole, R. K., Ogawa, O. S., and Sellen, J. M., "Study of Electric Spacecraft Plasmas and Field Interactions," TRW Report 07677-6013-R000, May 1, 1968.

PUBLICATIONS

None

ION ENGINE THRUST VECTOR STUDY

NASA Work Unit 120-26-08-05-55

JPL 320-61101-0-3830

D. J. Kerrisk
E. V. Pawlik

OBJECTIVE

The objective of this work unit is to evaluate the probable uncertainty in the magnitude and direction of the thrust vector of an array of ion thrusters to provide information for use in spacecraft systems analysis and in navigation and guidance analysis.

STATUS

Work was started on this contract by the Hughes Aircraft Company during January 1968. The contract was modified during October to include experimental determination of the thrust vector. Progress on this study to-date includes:

(1) Analysis of both the effects on ion optics and the causes of grid misalignments has been completed.

(2) A lightweight 30-cm diameter thruster and a device for measuring thrust misalignment have been analyzed and designed.

(3) Parts are being procured for the thruster, thrust stand, grid displacing devices, and position sensors. Portions of the thruster and thrust stand are being fabricated.

(4) A test fixture to measure the low forces, such as the resistance to flexing of the electrical cables between the fixed and floating portion of the test stand has been completed. The spring constant of the cable has been measured.

PUBLICATIONS

Contractor Reports, Interim and Final

1. Ion Engine Thrust Vector Study, Quarterly Report No. 1, April 1968, JPL Contract No. 952129.
2. Ion Engine Thrust Vector Study, Quarterly Report No. 2, July 1968, JPL Contract No. 952129.

ELECTRIC THRUSTER POWER CONVERSION AND CONTROLS

NASA Work Unit 120-26-08-06-55

JPL 320-61201-0-3830

D. J. Kerrisk
T. W. Macie

OBJECTIVE

This work unit is directed toward the development of lightweight, efficient, and reliable power conditioning units for use in solar-powered electric propulsion systems. Its technical goals are the demonstration of 9 lb/kW, 92% efficient, and 96% reliable (for 10,000 hr), power conditioning units at a nominal power level of 2.5 kW.

STATUS

A contract was released to Hughes Aircraft Company in June 1968 for the development of the power conditioning units. The initial schedule called for delivery of a breadboard unit to JPL by January 1, 1969. This date has been modified to April 1, 1969, to facilitate acceptance testing of the unit. As of the most recent design review, the contract objectives were being met. Initial test results on specific circuits verified predicted performance. The contract is proceeding on the revised schedule, and no major obstacles have been encountered.

PUBLICATIONS

Contractor Reports, Interim and Final

1. Quarterly Technical Report No. 1, July 1, 1968, through September 30, 1968, JPL Contract No. 952297.

ELECTRIC PROPULSION ENGINE AND ATTITUDE CONTROL

NASA Work Unit 120-26-08-07-55

JPL 320-61601-2-3440

P. A. Mueller

OBJECTIVE

The objective of this work unit is to support the solar electric propulsion system technology (SEPST) feasibility demonstration program for electric propulsion. The areas of support are thrust vector (attitude) control and ion thruster control. The goal of the demonstration is to conduct a ground test to prove the feasibility for a flight program.

PROGRESS

During this period, work on SEPST—Phase II has continued and work on SEPST—Phase III has begun. In support of Phase II, open-loop electronics for thrust vector control were delivered. The electronics were integrated with the supporting readout and display equipment and with the thrust vector control translator actuator and two gimbal actuators. Ion thruster heating effects on the actuator position transducers were investigated with operating thrusters. It was determined that the present configuration sufficiently shielded the transducers. Further system testing will continue and culminate in a 1000-hour life test during February and March.

In support of ion thruster control in Phase II, analytical and simulation work continued. A nonlinear digital computer simulation of the control loops had been previously carried out for the oxide-coated cathode thruster. The simulation program was used to analyze the effects of the controllers proposed by a vendor. It was also used to help specify tolerances on regulation of fixed-value power supplies used in the thruster power conditioning. The program has been modified to investigate another control scheme for the thruster. This scheme employs the use of a propellant-mass flowrate metering device. During the next period, the program will be modified or rewritten to support investigation of controls for a hollow-cathode thruster in support of Phase III.

The functional and detail system specifications for Phase III have been generated. Phase III is a 10,000-hour system ground test, and several studies have been performed to obtain the information needed for the specification writing. A study of gimbal-thruster combinations was performed to study reliability and redundancy of the system. Gimbaling of the center thruster was investigated and it has been decided to not gimbal the thruster in Phase III.

The specifications for Phase III require demonstration of closed-loop thrust vector control. Spacecraft dynamics simulation was investigated for use in closing the loop. The simulation would require on-line, real-time simulation; therefore, analog computer simulation was investigated. A tradeoff study was made to determine the most cost-effective means of computer use.

It was determined that it would take a large computer for the simulation since the spacecraft torques had to be determined from the positions, angles, and beam currents of the ion thrusters. Other reasons for need of a large computer were the simulation of the mixing matrices, large solar arrays, optical sensors, and the cold-gas attitude control system. Purchasing and leasing of a computer from a vendor and borrowing or using an on-site computer were investigated. It was decided that signal lines could be run from the Phase III site to the large JPL analog computer facility. This would offer the desired part-time use of the computer at the most reasonable price.

During the last half of FY 69, the cables to the analog computer will be installed and the interface with the thrust vector control will be designed. The thrust vector control electronics and associated ground support equipment will be designed and breadboard fabrication will be initiated.

PUBLICATIONS

None

NUCLEAR ELECTRIC POWER SYSTEMS (120-27)

THERMIONIC REACTOR STUDIES

NASA Work Unit 120-27-05-01-55

JPL 320-71501-0-3830

J. P. Davis
H. G. Gronroos

OBJECTIVE

Thermionic reactors are of major interest as potential space nuclear power plants. Objectives of the thermionic reactor studies are to (1) define and investigate those aspects of thermionic reactor design, control and dynamics required to establish the feasibility of these systems; (2) evaluate proposed design concepts relative to configuration, materials, static and dynamic characteristics; and (3) to aid in selection of the most promising directions for future development.

STATUS

Thermionic Reactor Dynamics and Control

During the first half of FY 69, the analytical studies of thermionic reactor dynamics and control continued in a low key due to intervening work on the thermionic diode kinetics experiment described here. The analytical activities were restricted to general studies of control concepts, and to model building of JPL's externally fueled uninsulated-thermionic diode reactor concept. The objective remains, however, to conduct an investigation, using analog computers, of conjectured unstable operating modes resulting from cesium reservoir temperature perturbations. Also, a complete analytical model of the diode kinetics experiment will be developed and analyzed.

Thermionic Diode Kinetics Experiment

The purpose of the thermionic diode kinetics experiment is to study thermionic reactor dynamics and control by non-nuclear means. The experiments principal subdivisions are:

(1) A test bank capable of holding six converters (four only at initial startup) with heat rejected to NaK coolant and enclosed in a 36-inch diameter vacuum chamber.

(2) An NaK heat rejection loop with N_2/NaK heat exchanger, EM pump, flowmeters, and an electrical resistance coil for preheating.

(3) A coupling unit which permits various patterns of series and parallel connections.

(4) Power supplies, controls, power conditioner, and auxiliary systems to support the test program.

A separate development effort was necessary for the high-current low-voltage drop (600 A., 5 mV) switches in the coupling unit, and for the low-voltage power conditioner.

Fabrication and assembly of all subsystems is essentially completed. Shipment of test bank with converters, vacuum chamber and coupling unit, along with their auxiliary equipment, is expected from Thermo Electron Corp. early in January 1969. Final assembly of the subsystems will follow immediately. Start up and implementation of the experimental program will then begin. The present program is scheduled until the end of FY 70.

Contract Monitoring

JPL personnel assisted in the technical monitoring of AEC contracted studies on thermionic reactor design to General Electric, Gulf General Atomic, and Fairchild-Hiller, Republic Aviation Division. The final briefing was held August 5-7, 1968, at ACE headquarters in Germantown, Md. Classified reports describing the contracted work have been released for distribution to cleared agencies and individuals.

These studies focused on a 300 kWe power-plant design. A limited follow-on study for the 50 kWe power level, and an evaluation of thermionic thermal reactor and driver zone designs was also requested by the AEC. The final briefing on these studies was held December 4-6, 1968. The briefing was attended by JPL personnel.

Uninsulated Thermionic Diode

An externally-fueled core-length thermionic diode module design that eliminates the sheath insulator in the core was evolved. The remaining insulators between electrical buses, and at the ends of the module, are in a region with less radiation damage effects. The basic design has gone through various modifications. The evolved concept consists of seven cylindrical modules bundled together, instead of the hexagonal fuel element with seven coolant channels as originally envisioned.

Static one- and two-dimensional neutron transport calculations were performed for the reactor system. In addition, heat transfer codes were acquired for thermal-hydraulic analyses. Such investigations, together with detailed stress analyses and studies of fabrication procedures, will continue during the remainder of FY 69.

Materials Studies

The rate of redistribution of UO_2 nuclear fuel under thermionic reactor operating conditions has been questioned for a considerable period of time. This redistribution affects fission-product venting. Venting is necessary to prevent fuel swelling, which in turn leads to closure of the interelectrode gap.

A tungsten capsule containing UO_2 has been designed and fabricated. A center line tube contains an electron-beam heating filament. This technique allows an approximation of the thermal gradients produced under nuclear reactor conditions. Radiography is used to measure the rate of UO_2 redistribution. First test results indicate that redistribution of UO_2 is initiated within 24 hours at 1700°C capsule temperature with a centerline temperature of 2000 These tests will continue during the remainder of FY 69.

PUBLICATIONS

Meetings and Symposia Papers

1. Peelgren, M., and Speidel, T., "Large Cylindrical Thermionic Diode with Rhenium Emitter for Diode Kinetics Experiment," Thermionic Conversion Specialist Conference, Mass., October 21-24, 1968.

SPS Contributions

1. Gronroos, H., "Thermionic Reactor System Experiment," SPS 37-54, Vol. III, December 31, 1968.

NUCLEAR POWER SYSTEM DEFINITION STUDIES

NASA Work Unit 120-27-06-01-55

JPL 320-70101-2-3420

R. Campbell
P. Gingo

OBJECTIVE

The major goal of this work unit is the development of technologies in nuclear power subsystems required to support advanced planetary missions. Essentially, these studies should provide a base of radioisotope thermoelectric generator (RTG) design information that can be used to support future JPL flight programs requiring integration of a radioisotope power source on the vehicle. Specifically, these studies are presently concerned with the radiation effects produced by the fueled RTG. The major area of concern is the effect of the RTG-produced radiated field on vehicle scientific instruments relative to their functional performance.

Although the major goal of the program is defining and, in some cases, developing the overall technological requirements for the use of radioisotope power sources, the immediate need is the ability to predict, analyze, and reduce RTG/planetary-vehicle radiation-field interactions. The evaluation of source radiation characteristics, effects of the emitted radiation on spacecraft subsystems, and methods of reducing the sensitivity of instruments to the radiation is required.

PROGRESS

Two specific tasks related to the RTG/science radiation interaction have been initiated. First, an RTG test laboratory has been planned to evaluate the compatibility of the radioisotope power source and its inherent radiation field with space-science experiments and sensitive subsystems. Second, radiation shielding computer programs and basic nuclear data, such as criticality and fuel spectrum data, are being generated.

Radiation Analysis

Because of the increased application of the RTG as a primary source of electric power for advanced space-science missions, studies on the potential interference with nuclear-radiation science instruments have been pursued to define the nuclear-radiation spectrum and some modes of radiation interference. These studies have indicated the need to integrate the RTG into the system and to use more sophisticated computer programs to continue the evaluations.

The Livermore photon-evaluated library, after being integrated into the JPL computer system, was used to calculate 20 group photon cross sections for elements found in a typical RTG design. Errors were found both in the energy intervals which define the Compton edges and in the method used to integrate the inelastic transfer matrices. These errors were corrected and new photon group constants were calculated.

Photon group constants were recalculated with a photon flux spectrum given in report DP-984, Savannah River Laboratory, 1965. The 20 group constants were recalculated for 17 elements consistent with the SNAP-19, Martin Cronus, and SNAP-27 generator designs.

The JPL computer nuclear programs were augmented with the following operational computer programs:

(1) DOT. This is a bidimensional Boltzmann transport program which calculates both neutron and photon transport in two symmetrical dimensions. This is a very fast program and typically runs for five minutes as opposed to three minutes with ANISN, a one-dimensional Boltzmann Transport program. This new computer program will be used to define more carefully the flux in the region between the axial and radial directions.

(2) FASTER. This is a Monte Carlo computer program which will calculate either neutron or photon flux with built-in random number generators. No calculations have been made with this program to date. Since the RTG instruments and space-science capsules are heterogeneous in material and geometry, the FASTER computer code

will calculate a more realistic radiation flux and dose at various selected detector points.

(3) Boeing Monte Carlo Charged-Particle Codes. These are a series of Monte Carlo programs developed for the charged-particle (electron and proton) penetration in various shield slab materials. These programs are being used to calculate the energy deposited in silicon detectors.

Photon-production cross sections were recently acquired and will be used to calculate the neutron-induced photon production in high-Z shield materials. A literature search revealed only the thermal neutron-capture gamma spectrum, but newly acquired photon-production cross sections show a definite threshold of energy over which the (N, 2, N, γ), (N, 3, N, γ), etc., cross sections predominate over the previously assumed neutron-capture gamma cross sections.

RTG Radiation Laboratory and Experimental Program

Effort has continued in those tasks necessary for: (1) the structural modification of Building 247 for use as a radiation laboratory, (2) documentation of the necessary plans and procedures to obtain approval to use the radiation laboratory and, in particular, to receive a SNAP-27 fuel capsule assembly under the AEC-NASA Interagency Agreement, and (3) initiation of the experimental program.

Tasks completed during this period for the laboratory construction are as follows:

(1) NASA approval for construction of the radiation facility.

(2) NASA-critical procurement approval.

(3) Construction contract sent out for bid, bids received, and low-bid contractor chosen.

(4) NASA approval of supplemental service request.

Portions of the standard operating procedure for the radiation laboratory have been completed. The health and safety section has been written and approved by the JPL Radiation Safety Committee. Other sections covering the receipt and storage of a SNAP-27 fuel capsule assembly have been completed.

The planned experimental program has been reviewed for potential problem areas. Additional equipment has been ordered in three areas: (1) standard gamma-ray and neutron sources, (2) health physics monitoring, and (3) spectral measurement and readout. Initial steps have been taken to amend the state license so that small Pu-238 sources may be obtained under it. These sources would be used in initial experiments prior to the receipt of a SNAP-27 fuel capsule.

PLANNED ACTIVITIES

The RTG radiation laboratory will be completed, the building occupied, and the initial experiments begun during the next report period. Documentation necessary for the receipt of a SNAP-27 fuel capsule assembly will be completed and approved by AEC OSD/ALO.

Experimental programs are being developed to ascertain the following urgently needed information:

(1) Nuclear detector intrinsic efficiency as a function of incident neutron and photon spectral fluxes.

(2) Nuclear detector accidental count rates induced by absorbed dose rates caused by the incident neutron and photon spectral fluxes. Typical detectors to be studied will include the silicon surface barrier detector whose sensitive thickness varies from 50 to 500 microns, the G-M tube in which the stainless steel wall varies in thickness from 2 to 200 mils, the Bendix Channeltron analyzer (electron multiplier) in which the incident view angles will vary and, finally, plastic scintillators.

The intrinsic efficiencies of all the basic detectors will be used to predict the interferences in typical space-science particle flux experiments from a mixed spectrum of radiation. The results of these calculations will be verified by irradiating the components with a mixed spectrum. Semiempirical equations will be derived which interrelate the science-instrument interference modes.

PUBLICATIONS DURING REPORTING PERIOD

Meetings and Symposia Papers

1. Gingo, P. J., and Bermanis, H., "Nuclear Properties of Plutonium 238 Fueled Sources," Intersociety Energy Conversion Engineering Conference, Boulder, Colorado, August 13-17, 1968.

NUCLEAR REACTOR AND LIQUID METAL SYSTEMS ENGINEERING

NASA Work Unit 120-27-06-02-55

JPL 320-70201-0-3830

J. P. Davis
G. M. Kikin
H. G. Gronroos
M. L. Peelgren
W. M. Phillips

OBJECTIVE

To further the understanding of the dynamic and steady-state characteristics of high-temperature Rankine cycle powerplants with nuclear reactor heat sources, a two-loop (lithium-boiling potassium) test loop was designed, fabricated, and operated at JPL. The test loop contained all of the essential components of a Rankine cycle power plant, including an analog computer for simulation of neutron kinetics. The loop operated with velocities, temperatures, pressures, transient times, and many other important parameters in the range of actual system interest.

TEST LOOP STATUS

Lithium-Boiling Potassium Rankine Cycle Test Loop

Final Phase III operations of the Rankine cycle loop were concluded April 23, 1968. Approximately 900 hours of additional loop operation were accumulated in this final test phase. The highlights and the excellent performance of the new shell-side boiling cross-flow boiler were described in the previous semiannual report. Some results for the dynamic response with the nuclear reactor simulator on-line are described in JPL Space Programs Summary 37-52, Vol. III, pp. 121-127, August 31, 1968.

The loop has been dismantled and the various parts subjected to analysis. Results of the analysis are described here. The planned analog and digital computer simulation studies of the JPL test loop had to be cancelled due to budget cutbacks. However, reduction of data taken during the final third phase of operations will continue during the rest of FY 69.

TEST LOOP MATERIALS STUDIES

Disassembly of the Rankine cycle test loop and evaluation of the effects of operation have been completed. The potassium side of the loop displayed essentially no corrosion. Erosion was detected, however, in bends and nozzles which had been in the system for all three phases of operation, but not in piping which had been in the loop only during Phase III. Therefore, it was concluded that the 250 hours of low vapor quality operation during Phases I and II had a far greater erosive effect on the Cb-1Zr alloy than did the 500 hours of high-quality and high-temperature operation of Phase III.

Operation of the lithium part of the system during Phases I and II with an yttrium hot trap resulted in superficial corrosion, slight transfer of oxygen and nitrogen to the cold portions of the Cb-1Zr alloy, and no mass transfer deposits. Removal of the yttrium hot trap for Phase III operation resulted in orders of magnitude increase in corrosion of the Cb-1Zr containment alloy. This is attributable to the buildup of impurities in the lithium from the argon cover gas over the lithium in the sump. Almost complete penetration of the containment wall tubing occurred in many areas. Mass transfer deposits were present in all except the hottest areas of the loop.

The flow channels in the lithium centrifugal pump impeller had the highest lithium flowrate in the system (50 ft/sec). As shown in Figure 1, damage took place in these flow channels after a 90° bend indicating primary erosion and/or cavitation.

ALKALI METAL STAINLESS STEEL CORROSION STUDIES

The effect of additions of the gettering elements (beryllium, hafnium, samarium, titanium, thorium, yttrium, and zirconium) to an alkali liquid-metal system constructed of type 321 stainless steel was evaluated. Tilting capsules were used in conjunction with lithium and reflux capsules in conjunction with potassium in the 500-hour tests at a maximum temperature of 1750°F. Test results indicate that dioxide forming elements (hafnium, thorium, and zirconium) will eliminate the preferential transfer of nickel in a lithium stainless steel system. Of these, hafnium and thorium also eliminate subsurface porosity formation and improve tensile test behavior, as compared to ungettered test specimens.

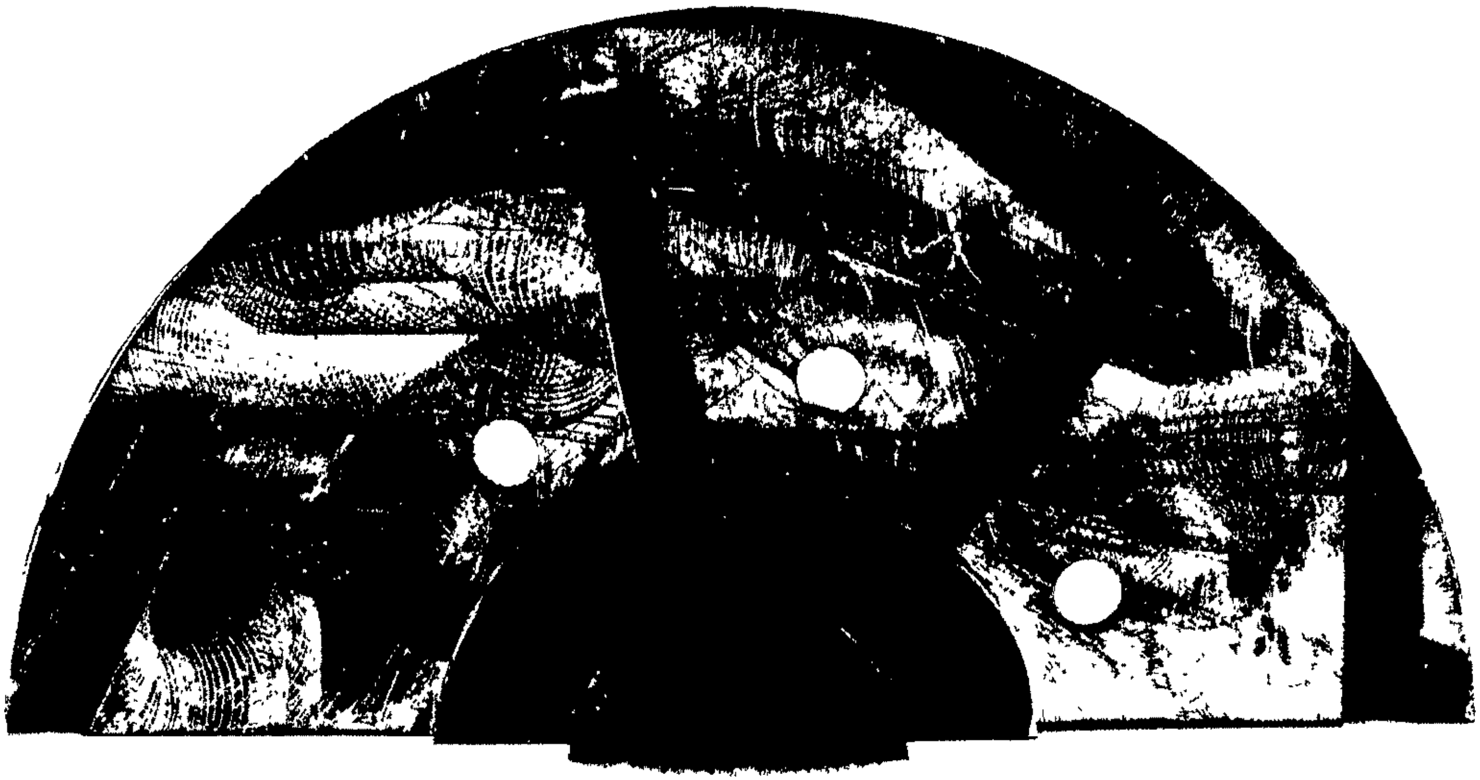

Figure 1 Impeller Section

PUBLICATIONS

SPS Contributions

1. Gronroos, H. G., and Kikin, G. M. "Lithium-Boiling Potassium Test Loop Runs with Reactor Simulator," SPS 37-52, Vol. III, pp. 121-127, August 31, 1968.

JPL Technical Reports

1. Phillips, W. M. "Effects of Alkali Metal Gettering Agents on Stainless Steel Corrosion," TR 32-1239, April 1, 1968.

MHD CONVERSION SYSTEMS

NASA Work Unit 120-27-06-03-55

JPL 320-70301-1-3830

D. G. Elliott
D. J. Cerini
L. G. Hays

OBJECTIVE

Liquid-metal magnetohydrodynamic (MHD) power conversion is being investigated as a power source for nuclear-electric propulsion. A liquid-metal MHD system would have no moving mechanical parts and would operate at heat-source temperatures between 1600°F and 2000°F. The system has the potential of high reliability and long lifetime using readily-available containment materials such as Nb-1%Zr. Liquid lithium would be heated at about 150 psia in the reactor or reactor-loop heat exchanger; mixed with liquid cesium at the inlet of a two-phase nozzle, causing the cesium to vaporize; accelerated by the cesium to about 500 ft/sec at 15 psia; separated from the cesium; decelerated in an alternating-current MHD generator; and returned through a diffuser to the heat source. The cesium would be condensed in a radiator or radiator-loop heat exchanger and returned to the nozzle by an MHD pump.

NaK-NITROGEN CONVERSION SYSTEM

Hydraulic and electrical problems are being investigated in a room-temperature conversion system, employing NaK in place of lithium and nitrogen gas in place of cesium. The generator for the system is a 400-volt, 400-Hz ac induction generator of 50 kW nominal output power. The first generator assembly underwent empty-channel electrical tests to determine current and voltage settings, verify proper magnetic field waveform, and measure core (iron) losses. The results were in accord with design predictions except for the core loss which was several times higher than the published values for the iron-cobalt alloy employed. The high core loss, which would reduce output power by 10 kW, will be reduced through material and fabrication modifications in subsequent assemblies. The conversion system is now being assembled for testing with NaK and nitrogen during the first half of 1969.

INDUCTION GENERATOR STUDIES

The reduction in efficiency of an MHD induction generator due to departure from pure sinusoidal waveform resulting from a finite number of slots was analyzed, and the use of 24 slots per wavelength (12 phases) was found to provide 96 percent of the ideal, continuous-winding, efficiency.

A $14,000 contract for research on end losses in MHD induction generators was awarded to the University of Illinois, Chicago (Contract No. 952453).

CESIUM-LITHIUM EROSION LOOP

The test section of the cesium-lithium loop, consisting of a two-phase nozzle and a target cone for thrust and erosion measurements, was operated with water and nitrogen as a final flow check. The test section is now being welded into the loop. The 100-kW NaK heat rejection system for removing the heat from the cesium condenser was installed.

TEST FACILITIES

A digital data system was installed. Paper tape output can be fed to a time-sharing computer terminal. The high-speed data system originally planned was not delivered due to other priorities in the instrumentation section and had to be deferred.

The 4800-kW dc motor-generator set for heating lithium in future large-scale conversion system tests is being installed and will be operational in 1969.

PUBLICATIONS

Meetings and Symposia Papers

1. Cerini, D. J., "Circulation of Liquids for MHD Power Generation," Paper No. SM-107/40, Symposium on Magnetohydrodynamic Electrical Power Generation, Warsaw, July 24-30, 1968.

2. Elliott, D. G., "Performance Capabilities of Liquid-Metal MHD Induction Generators," Paper No. SM-107/41, Symposium on Magnetohydrodynamic Electrical Power Generation," Warsaw, July 24-30, 1968.

3. Hays, L. G., "Effect of High Velocity Lithium on Structural Materials," Paper No. SM-107/42, Symposium on Magnetohydrodynamic Electrical Power Generation, Warsaw, July 24-30, 1968.

Open Literature

1. Elliott, D. G., "Variable-Velocity MHD Induction Generator with Rotating-Machine Internal Electrical Efficiency," AIAA Journal, Vol. 6, No. 9, September 1969, pp. 1695-1702 (Reprints issued as JPL TR 32-1328), and IEEE Proceedings, Vol. 56, No. 9, pp. 1449-1458, September 1968.

SPS Contributions

1. Elliott, D., and Hays, L., "Liquid-Metal MHD Power Conversion," SPS 37-52, Vol. III, pp. 113-119, August 31, 1968.
2. Cerini, D., "Liquid-Metal MHD Power Conversion," SPS 37-54, Vol. III, December 31, 1968.
3. Elliott D., Cerini, D., and Hays, L., "Liquid-Metal MHD Power Conversion," SPS 37-54, Vol. III, December 31, 1968.

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NUCLEAR THERMOELECTRIC POWER SOURCES

NASA Work Unit 120-27-06-08-55

. JPL 320-70801-2-3420

P. Rouklove
S. Bain

OBJECTIVE

The objective of the program is the evaluation of advanced-design isotope thermoelectric power sources. The task involves the procurement and evaluation of thermoelectric elements, multielement modules, and thermoelectric generators. The units under investigation are subjected to parametric environmental and life testing. The modes of abnormal behavior are examined.

ACTIVITIES

Several thermoelectric generators and modules were tested. A brief description of each follows:

SNAP 11

Generator model QN-3 was subjected to environmental tests after extensive parametric evaluation at room ambience. It sustained several thermal-vacuum cycles simulating lunar day and lunar night conditions, and successfully withstood vibration and acceleration tests in two axes. At present it is being prepared to be subjected to long-term life-testing at room ambience. As of December 1968, the generator has operated for approximately 21,000 hours with very slight degradation in its output power.

SNAP 19

Two SNAP-19 generators (Models SN-20 and 21) were subjected to tests. Model SN-20, built with 3P-2N thermoelectric elements, was subjected to extensive parametric tests at room ambience and in vacuum. In support of the Nimbus mission, data were obtained on the behavior of the generator during launch and orbiting conditions. Power output was measured for different fin root temperatures ranging from 160°F to 360°F. The generator was subjected to a thermal-vacuum test simulating the mission conditions. Future plans for the generator are to expose it to a long-term life test in a thermal vacuum, simulating the solar exposure or occultation expected during the Nimbus mission.

Generator Model SN-21, assembled with 2P-2N material, but with cups at the hot and cold end contacts, is presently being subjected to parametric evaluation and in the future will be operated at room ambience for long-term life evaluation.

Westinghouse Tubular Module

A TEM-10 tubular generator with an integral heat pipe and an unidirectional radiator has been tested over 1300 hours. Initially, a power output of 108.8 watts was observed with an overall efficiency of 4.82%. The output power of the generator sharply decreased after two shutdowns and restarts. Preliminary indications showed the possibility of internal short circuits between individual couples, caused by a possible misalignment of components during the fabrication. Diagnoses are now in progress, and a change in the design is being evaluated.

A cascaded generator composed of a first stage of silicon-germanium coupled by a sodium heat pipe to a second stage of lead-telluride (TEM-10 configuration) is now in construction at Westinghouse Astro Nuclear and is scheduled to be delivered in August 1969. It will be tested at JPL.

MODULE LIFE AND PERFORMANCE EVALUATION

The tests and performance evaluation of individual modules are continuing. A TEM-8 series Westinghouse tubular module has exceeded 20,000 hours of operation. The module now produces 32 watts of power at an efficiency of 1.85%. This represents a 55% decrease in power since the 10,000-hour mark. It appears that the degradation may be the result of thermal cycling rather than life.

Two 10-couple lead-telluride modules from Minnesota Mining & Manufacturing have accumulated a combined time of 22, 500 hours. They are producing 1. 5 watts each at an approximate efficiency of 2. 4%. Problems have been encountered with leakage of gas through the hermetic seals of the container.

A 24-couple silicon-germanium module of the "air-vacuum" type built by RCA has accumulated 7, 600 hours. The unit produces 12.8 watts at 2.7% efficiency.

An RCA silicon-germanium module having couples metallurgically bonded to a Hastalloy heat pipe has been on test for 11, 300 hours. The unit produces an output power of 3. 5 watts with an efficiency of 1. 4%.

PUBLICATIONS DURING THE REPORTING PERIOD

SPS Contributions

1. Bain, S., "Integrated Heat Pipe/Tubular Thermoelectric Generator," SPS 37-54, Vol. III, December 1968.

2. Rouklove, P., "Testing of Thermoelectric Generators," SPS 37-54, Vol. III, December 1968.

NUCLEAR THERMIONIC CONVERTER DEVELOPMENT

NASA Work Unit 120-27-06-09-55

JPL 320-70901-2-3420

P. Rouklove

OBJECTIVE

The objective of this program is to support the nuclear reactor thermionic project. It consists of the procurement and evaluation of out-of-pile nuclear thermionic converters developed under several nuclear thermionic programs and studies of different phenomena related to the in-pile operation of thermionic converters. The task involves the design and construction of test equipment, parametric and life testing of the converters, evaluation of converters operating in an abnormal mode, and the examination of the failure modes of the converters.

ACTIVITIES

Converter Testing

Two cylindrical converters have been procured from Thermo Electron Corporation. These units are similar to those developed by this manufacturer for the AEC and are representative of the latest application of nuclear thermionic converter technology. Both converters have been received at JPL and are awaiting the availability of test stations. Four additional converters of the same type have been obtained from the Marine Engineering Laboratory at Annapolis, Maryland, as part of a residual inventory from a terminating program.

The simulated converter (SIMCON) computer code formulated by General Electric Company predicts an instability in the performance of cylindrical thermionic converters operating with fixed cesium-reservoir pressures. At emitter temperatures above that for which the reservoir pressure is optimized, the desorption of cesium from the emitter causes a reduction in emitter current and a corresponding loss of electron cooling, resulting in a rise in emitter temperature and further desorption of cesium. This condition progresses until a new thermal equilibrium is achieved in which the bulk of the heat rejection from the emitter occurs by radiation. In this situation, the emitter may be several hundred degrees centigrade above its design temperature.

Using planar-type converters, it was intended to simulate the cesium desorption processes at constant cesium pressure by increasing the power input to the converters. However, due to excessive thermal end losses from the electrical heaters, the experiment was unable to duplicate the theoretically predicted thermal runaway.

TEST EQUIPMENT CONSTRUCTION

The frames for four test stands have been received, and the heavy items of equipment (vacuum-ion pumps and vacuum chambers) have been installed. The design of the electronics has been completed. The first station is about 70% assembled. After completion and checkout of the first station, the assembly of the remaining three stations will proceed.

PUBLICATIONS DURING REPORT PERIOD

Meetings and Symposia Papers

1. Rouklove, P., "Metallography of Thermionic Converters," Thermionic Specialist Conference, Boston, Mass., October 1968.

SMALL CYLINDRICAL DIODE DEVELOPMENT

NASA Work Unit 120-27-06-11-55

JPL 320-71101-2-3420

P. Rouklove

OBJECTIVE

The objective of this program is the development of a thermionic diode which, when used in series-parallel arrays, can provide adequate reliability for spacecraft power systems on the order of a few hundred watts total capability. The small (approximately 15-watt) diode concept obtains the required reliability by means of the redundancy provided by an array of diodes.

PROGRESS

Diode Development Contract

An 18-month contractual effort was negotiated with Electro-Optical Systems, Inc. (JPL Contract 952255) for development of small, cylindrical thermionic converters. The goal of this effort is to demonstrate the feasibility of producing converters of cylindrical configuration capable of operating with a heat pipe as the heat-transmitting medium. The converters are to be operated at an emitter temperature of 1400°C and will demonstrate a minimum power output of 15 watts at an efficiency of 8-10 percent. The converters will be assembled to outline the problem areas in design and fabrication. An iterative design approach is planned, with the possibility of seven design iterations. Because of difficulties in procuring chemically vapor-deposited (CVD) rhenium, the contract was modified to direct the use of solid polycrystalline rhenium as the emitter and deposited rhenium only on the collector surface. The increase in cost resulting from this modification reduced to seven the number of deliverable converters.

The design of the first converter was approved by JPL as well as the design of the electron-bombardment gun to be used in the testing of converters. The first converter is now in the assembly process.

System Studies in Isotope Thermionics

Studies performed to determine the optimum diode sizes for isotope thermionic systems were continued. The studies include the consideration of different power-level requirements, redundancy or reliability arguments, and dc-conversion requirements. Part of the study was presented at the Fifth Space Congress, Cocoa Beach, Florida, March 11-14, 1968.

PUBLICATIONS

None

NUCLEAR SYSTEM STUDIES

NASA Work Unit 120-27-06-14-55

JPL 320-71401-0-3830

J. P. Davis
J. F. Mondt
N. K. Simon

OBJECTIVE

The objective of this work unit is to develop the information and analytic techniques needed to design and evaluate nuclear electric propulsion spacecraft.

DESIGN INVESTIGATIONS

Three computer codes are being adapted for use in JPL work on nuclear thermionic power plants. They are:

(1) Heating-II, a two-dimensional heat transfer code originally developed by Atomics International.

(2) M091, a JPL-developed integrated code for radiator micrometeoroid protection and thermal design.

(3) A thermionic converter heat transfer code, using in tabular form results from General Electrics SIMCON converter performance code.

Codes 1 and 2 are working and have been used to obtain some preliminary results for power plant design.

A small effort has evolved to update meteoroid protection information for use in radiator design. Some calculations have been performed and will be reported during FY 69.

Preliminary component arrangements for a nuclear thermionic 300 kW electric propulsion spacecraft on the Titan III booster were investigated. The arrangement was used to estimate the launch vibration environment of a thermionic fuel element.

The planned activities for the next six months are:

(1) Vibration testing of a fueled emitter and collector thermionic diode assembly.

(2) Investigation of component arrangement for a 50 kWe spacecraft.

(3) Preparation of preliminary structural designs for the 300 kWe spacecraft.

HEAT-PIPE RADIATOR TESTING

The Jet Propulsion Laboratory has accepted a request from the AEC to test a heat-pipe radiator during calendar year 1969. Arrangements are currently being made to have the radiator shipped from storage at Wright-Patterson Air Force Base.

PUBLICATIONS

Meetings and Symposia Papers

1. Simon, N. K., and Stearns, J. W., "Evaluation of Nuclear Electric Propulsion for Planetary Exploration by Graphic Analysis Techniques," AIAA Joint Propulsion Specialist Conference, Cleveland, Ohio, June 1968.

INSULATOR BREAKDOWN

NASA Work Unit 120-27-06-20-55

JPL 320-72001-0-3830

J. P. Davis
G. M. Kikin

OBJECTIVE

Proposals have been received and evaluated for an experimental test to determine effects on the thermionic diode tri-layer structure of sustained electrical breakdown conditions.

The need to consider the phenomena of sheath insulator arcing results from the series connections of nuclear thermionic converters. In the flashlight concept of in-core converter assemblies, the arcing problem is due to a voltage across a thin, cylindrical, ceramic insulator which separates the collector from the liquid-metal cooled outer metallic sheath. This insulator is exposed to cesium vapor and any small cracks in the ceramic may have electrical breakdown potentials which are less than the maximum potential developed from the series connected (flashlight) thermionic converters.

Arcing across the crack may cause substantial degradation and puncture of the tri-layer structure allowing liquid-metal coolant to leak into the cesium vapor space. Failure of the punctured diode, plus loss of liquid-metal coolant, may cause further diode failures resulting in partial or complete failure of the nuclear-thermionic powerplant.

Under this one-year contract,the contractor will experimentally investigate arcing on the liquid-metal cooled tri-layer and the possible subsequent effects on the nuclear thermionic power plant.

Total contract funding is $96, 995 with incremental funding of $55, 000 for FY 69.

PUBLICATIONS

None

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EXTERNALLY FUELED DIODE

NASA Work Unit 120-27-06-21-55

JPL 320-72101-0-3830

J. P. Davis
J. F. Mondt

OBJECTIVE

The objective of this task is the design and fabrication of a prototype externally fueled diode of the uninsulated type conceived at JPL.

PROGRESS

A contract in the amount of $288, 380 (with incremental funding of $198,000 for FY 69) has been awarded to Fairchild Hiller for design and fabrication of this unit. Preliminary design is underway.

PUBLICATIONS

None

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THERMIONIC SPACE POWERPLANT SYSTEM STUDY

NASA Work Unit 120-27-06-23-55

JPL 320-72301-0-3830

J. P. Davis
N. K. Simon

OBJECTIVE

The objective of this work unit is to design a 300 kWe nuclear electric propulsion spacecraft for unmanned missions to the planets. A contract is being let to perform a detailed design study of the nuclear power plant. The detail is expected to be sufficient to allow evaluation of weights and extrapolation over the 70-to-500 kWe range. General Electric, Valley Forge, has been selected as contractor and the contract is in the final stages of preparation.

The total funding is $122,000 with increments of $63,000 for FY 69 and the remainder planned for FY 70.

PUBLICATIONS

None

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NUCLEAR POWER SYSTEM DESIGN FOR PLANETARY MISSIONS

NASA Work Unit 120-27-06-24-55
JPL 320-72601-2-3420
R. G. Ivanoff

OBJECTIVE

This program provides the overall power subsystem configuration and integration analysis required to assure the development and compatibility of a power subsystem to the spacecraft design for the Thermoelectric Outer-Planet Spacecraft (TOPS) project. Specifically, the effort involved is directed toward solutions of problems associated with the definition of the interfaces between the elements of the power subsystem and between the power subsystem and the other spacecraft subsystems. In addition, this task includes the development of high-efficiency, ultrareliable power conditioning electronics (PCE) to convert the voltage from the power source to voltages and regulation levels compatible with spacecraft electrical subsystems. This equipment will be designed to meet a 12-year life requirement for the power subsystem using the most advanced techniques to assure minimum weight.

PROGRESS

A power subsystem has been defined to support the TOPS project. This subsystem will consist of multiple radioisotope thermoelectric generators (RTGs) and the required power conditioning electronics. The RTGs, which are the power sources, utilize the decay of radioisotopes to provide the electrical power required by the electrical subsystems. The PCE conditions the RTG voltage to match the source to the electrical subsystems. Also, the PCE must provide the capability to perform any required switching and control functions for the effective management and distribution of the available power.

Accomplishments during this report period include the support of design team activities, project planning to define the extent of program support and development of a joint program between NASA/JPL and the Atomic Energy Commission for the development of RTGs for the TOPS project. Design team support has consisted of definition of the power system and tradeoff analyses on system size and effects with various subsystem interfaces. Preliminary data on RTG size as a function of power required have been developed. Radiation dose rates from a single RTG have been distributed to the design team to initiate a radiation-effect study by design team members.

Initial negotiations have been made with the Nuclear Space Power Division of the Atomic Energy Commission to solicit support on the planned development of RTGs for the TOPS project. They have tentatively agreed to provide a two-phase support. During the first phase, to be initiated in the next report period, the AEC will start an intensive study effort to evaluate the performance of existing RTG components to determine the types of components and technologies required to develop RTGs meeting the requirements of the TOPS project and the Grand Tour mission in the 1976-1979 period.

The second phase of the AEC support, which has not been formally approved, consists of a technology program and RTG development effort to provide power sources for the TOPS project. Two specific tasks are being performed on the power conditioning electronics during this report period. A work statement and requirements document is being prepared to initiate the design of the PCE. The work statement will define a two-phase program in which the first phase will consist of a design and configuration analysis. This first phase effort will define the type of distribution to be adopted, the redundancy and switching requirements, and the PCE configuration design. The second phase will provide the final design, breadboard models, and final engineering models to be delivered for the TOPS spacecraft.

The second task being performed in the PCE area is the design and development of a dc-dc converter for a 100-watt communications traveling-wave-tube (TWT) transmitter. The TWT requires four regulated voltages of which one, the helix voltage, requires critical voltage control. Because of the technologically advanced capabilities of high-power TWTs, high efficiency with high voltage regulation is required in the dc-dc converters. During this report period, the converter preliminary design has been completed and a breadboard model has been started.

Planned activities in the next report period include negotiating with the AEC for the Phase II RTG development program, initiating a contract for the detail design of power-conditioning electronics and system design and integration analysis. During this period, the method of power distribution (ac or dc) will be selected based on a detailed analysis of the spacecraft requirements. In addition, studies will be initiated to determine the power subsystem redundancy requirements to assure mission success for a 12-year mission. Design team support will continue with major emphasis on interface problems which occur due to the RTG (such as safety, radiation analysis, thermal control, and mechanical configuration). Additional analyses will be performed, where required, to predict mission capability and limitations of power subsystem capabilities.

The communications converter design and breadboarding will be completed in the next report period. This unit will then undergo thorough testing to evaluate its performance and its interface with the communications TWT.

PUBLICATIONS

None

RADIOISOTOPE THERMOELECTRIC GENERATOR (RTG) DESIGN FOR MULTIPLANET MISSIONS

NASA Work Unit 120-27-06-25-55

JPL 320-72701-2-3420

O. S. Merrill

OBJECTIVE

The twofold objective of this effort is: (1) to develop an RTG to be used on the thermoelectric outer-planet spacecraft (TOPS) project, and (2) to investigate and attempt to solve the problems associated with integrating a radioisotope thermionic generator (RTG), or multiple units, if required, into the TOPS.

APPROACH

Specific activities in support of the objective have been defined, and some of them were started during this report period. They are: (1) technical monitoring of contractor RTG development program (this effort has not yet begun), (2) technical evaluation of various RTG designs, (3) performing RTG/spacecraft integration studies and tradeoff evaluations (including RTG radiation/science experiments interaction; RTG-radiation/electronics interaction; RTG thermal/spacecraft interaction; RTG reliability, weight, size, lifetime, configuration, cost, etc.), (4) investigation of the safety and launch operational problems and writing of operation procedures, (5) procurement and evaluation of thermoelectric modules of the type being developed for the RTG power source, (6) testing of prototype generators and interpretation of test results, and (7) assisting in the integration of the RTG power system into the prototype spacecraft, and performance of system tests.

PROGRESS

During the second quarter of FY 69, active support of the TOPS project was begun. The principal effort has been the preparation of a document entitled, "Study Guidelines and Performance Requirements for the Development of an RTG Power Source for the JPL-TOPS Project and Subsequent Missions to the Outer Planets." This document has been prepared for submission to the Atomic

Energy Commission to be used by them and by one or more contractors in the preliminary design study to evaluate the current state thermoelectric materials technology and to select the thermoelectric generator concept which offers the greatest promise of meeting the TOPS and the 1977 multiplanet mission requirements. This document outlines the philosophy of the TOPS program, which is to utilize advanced technology in demonstrating the capability of building a second-generation spacecraft. It further delineates those factors in the project which may have an influence on the design of the RTG, principally mission considerations (including launch vehicle, launch constraints, trajectories, spacecraft and interplanetary environments, and nuclear safety) and spacecraft considerations (configuration, weight, altitude control, payload, etc.). In addition, the power source requirements (such as power level, lifetime, voltage output, weight, size, etc.) are stipulated. Finally, the manner in which the preliminary design study is to be performed is specified in the "Study Guidelines." This portion stipulates four tasks to be performed:

(1) Evaluation and comparison of existing and advanced-development thermoelectric materials.

(2) Preliminary design and comparison of generator concepts using selected thermoelectric materials.

(3) Preliminary design and evaluation of alternate fuel capsule concepts.

(4) Recommended RTG power source design and proposed development program to satisfy the TOPS and multiplanet mission requirements.

It is anticipated that the preliminary design study contractors will be selected by February 1969, and that a selection of a contractor for the design and development of the RTG hardware for TOPS will follow approximately six months thereafter, based upon the evaluation of the results of the study (or studies).

A continuing effort has been pursued as part of the overall preliminary design of the spacecraft. Thermal, mechanical, and radiation interfaces are being given primary concern, especially the interactions between RTG radiation and the science experiments. Only preliminary results have been obtained to-date, but a refined definition of the problems to be resolved has developed out of the investigations.

PUBLICATIONS

None

LIQUID-METAL MHD POWER SYSTEM UTILIZATION STUDY

NASA Work Unit 120-27-06-26-55

JPL 320-72801-0-3830

D. G. Elliott

OBJECTIVE

The objectives of Phase I (first year) are to provide size, weight, and mission performance estimates for liquid-metal MHD power systems employing a cesium-lithium separator cycle for a range of power levels, temperatures, numbers of loops, component efficiencies, containment material strengths, and launch conditions. The objectives of Phase II (second year) are (1) to provide a detailed study for a selected power system reference design of the configuration, structure, reliability, and operational problems; (2) to determine the startup, shutdown, coast, partial power, and general operational characteristics; (3) to provide the lifetime, power profile, redundancy, and auxiliary equipment requirements; and (4) to provide a conceptual design of the system including the reactor, shield, conversion unit, radiator, power conditioning equipment, and auxiliary equipment such as pumps and cooling systems.

The contract is being negotiated.

PUBLICATIONS

None

SOLAR POWER GENERATION SYSTEM (120-33)

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20 WATT/LB SOLAR ARRAY DEVELOPMENT

NASA Work Unit 120-33-01-02-55

JPL 320-30801-2-3420

D. W. Ritchie

OBJECTIVE

The object of this effort is to develop the technology for the design and fabrication of a high-power, 1,250-ft^2 solar panel exhibiting a power density of 20 w/lb minimum. Depending on future funding, the fabrication, assembly, and qualification testing of 20 w/lb solar arrays of up to 50 kWe may be realized.

INTRODUCTION

In FY 66, feasibility studies were completed using the Atlas/Centaur and Saturn/Centaur for an electrically propelled Mars flyby mission, and the application of large-area, high-power-density, photovoltaic arrays to these missions. The encouraging results of the feasibility study have led to optimism concerning the application of these large arrays for future spacecraft missions. Additional efforts have been initiated to investigate the problems associated with the detail design, fabrication, and testing of a 1,250-ft^2 prototype section of the 50-kW solar array. The present program was originally planned as a three-phase effort to accomplish these goals. The Phase I and Phase II efforts have been completed under JPL Contracts 951653 and 951934. The Phase II contract was a cost-plus-fixed-fee contract, with the award fee based on cost effectiveness.

ACTIVITIES

The Phase I effort, completed in November 1967, included a thorough evaluation of the preliminary design established earlier in the feasibility study. This analysis resulted in the complete detail design of a 1,250-ft^2 solar panel.

The Phase II effort of this program, now completed, provides an important milestone in developing confidence in the ability to assemble large-area lightweight solar panels. Activities during Phase II included assembly and testing of prototype mechanisms, installation and checkout of a simulated zero-g deployment fixture, and manufacture and assembly of a 100-ft^2 beryllium subpanel. In the course of the mechanisms test program, prototype units have been tested in scale-model assemblies in a limited-system aspect through a thermal-vacuum test program. These tests resulted in satisfactory performance of the mechanisms and identified minor design deficiencies. These deficiencies are mainly in the boost tiedown system. No major problems have been identified in the mechanism design or test area which would preclude obtaining program objectives.

The deployment demonstration test program yielded important data associated with the ability to predict the performance of the complete beryllium assembly (MTA-4) originally planned in Phase III. Also, these deployment tests have given insight into problems associated with handling and assembling large arrays. Analysis of the test results indicated conformance with predicted characteristics.

A major undertaking of the Phase II program was the manufacture and assembly of the 100-ft^2 beryllium structure and fiber-glass tape system (MTA-1). This portion of the effort was initiated in November 1967. Several problems were encountered in the manufacturing portion of this effort; most of these problems were associated with the transition from the 16-ft^2 assembly built in Phase I and scaling-up of production tooling and general shop workloads to handle the 100-ft^2 assembly. All forming has been completed and no major problems have been directly attributed to the beryllium material. The MTA-1 panel was completely assembled during the last weeks of May.

Major damage was experienced during the final bond assembly of the MTA-1 panel. Analysis revealed that loads experienced during the bond operation reached failure levels of the adhesive material at bonding temperatures. Correction of assembly procedures and tooling were necessary to complete the assembly. The panel was successfully completed and subjected to a vacuum-vibration test program. The Phase II effort has been satisfactorily completed. The originally planned Phase III program has been delayed pending definition of a more realistic end-item use.

PUBLICATIONS DURING REPORT PERIOD

SPS Contributions

1. Ritchie, D. W., "Development of 20 Watt/Lb Solar Array Technology," SPS No. 37-49, Vol. III.

2. Moss, R., "Material and Process Development for a 20 Watt/Lb Solar Panel," SPS No. 37-50, Vol. III.

Publications

1. Haynie, T., and Krieger, A., "Application of Mechanisms for Restraining and Deploying a 50 kWe Solar Array," ASME.

SOLAR CELL STANDARDIZATION

NASA Work Unit 120-33-01-03-55

JPL 320-31201-2-3420

R. F. Greenwood

OBJECTIVE

The principal program objective is to provide applicable standards for (1) procurement and evaluation of solar cells, and (2) predicting the space performance of solar arrays. Standard solar cells are also provided for use in calibrating solar simulators.

ACTIVITIES

Three successful high-altitude (80,000 ft) balloon flights were conducted during the months of July and August 1968. The balloon flights were under JPL Contract 952223 with the Applied Science Division of Litton Systems, Inc., of Minneapolis, Minnesota.

The planned improvements to the balloon flight system for increasing the payload capacity were successfully completed prior to the first flight of the series. Data-handling capabilities were also upgraded during this report period.

Standard solar cells submitted by NASA and government agencies under the cooperative calibration effort were balloon-calibrated and then postflight calibrated in the JPL X-25L solar simulator. The standard cells and the data obtained have been returned to the respective agencies. Participating agencies in the cooperative effort included the NASA/Goddard Space Flight Center, NASA/Langley Research Center, Air Force Aero Propulsion Laboratory, and Johns Hopkins University Applied Physics Laboratory. The third balloon flight of the 1968 series carried two JPL-designed and -built radiometers. The radiometers, designed to measure total sun radiation, performed well. A filter-wheel system was used in conjunction with the radiometers to permit measurement of selected energy bands. Good data were returned from this experiment, and a formal report is presently in progress.

PLANNED ACTIVITIES

Plans are being formulated for another series of balloon flights during the first quarter of FY 70. Solar cells calibrated would include those to support the Mariner Mars 71 flight program, newly developed solar cells to support advanced development programs, and previously flown standards to evaluate their long-term stability as standard solar cells. Also being considered is a flight with an improved and simplified version of the JPL radiometers to provide additional confidence in the data obtained during FY 69.

PUBLICATIONS

SPS Contributions

1. Greenwood, R. F., "Solar Cell Standardization," SPS 37-51 Vol. III, June 1968.
2. Greenwood, R. F., "Solar Cell Standardization," SPS 37-57 Vol. III, Sept. 1968.

Contractor Reports, Interim and Final

1. Conlon, R. D., "Solar Tracker Balloon Flights 3048, 3049, and 3050," Applied Science Division, Litton Systems, Inc., Report No. 3269, November 1968, JPL Contract 952223.

PHOTOVOLTAIC SUPPORTING DEVELOPMENT

NASA Work Unit 120-33-01-06-55

JPL 320-31601-2-3420

R. K. Yasui
J. D. Sandstrom

OBJECTIVE

The objective of this program is to develop the technology necessary to aid the solar panel engineer in solar panel design for deep-space missions. This effort is accomplished by testing and analyzing individual cells or matrices of cells (submodules) under conditions which simulate the actual temperatures, solar intensities, and space environment to which the panel will be exposed. Experience over the past years has shown this technique to be a valid method for predicting the performance of a solar panel within heliocentric distances equivalent to Mars/Venus missions.

Assembly techniques will be investigated emphasizing minimum weights consistent with cell contacts and assembly materials. This program will also include the evaluation of manufacturing control and electrical and mechanical performance characteristics of advanced-type solar cells. It is intended that the program will be conducted in a manner which will allow evaluation of the present capability of integrating the cells into flight program planning.

The interconnection of solar cells into series and parallel assemblies represents one of the most important fabrication steps in the design and development of solar panels. The ohmic contact to the cells is relatively fragile, and necessitates strict design considerations. Interconnection of these ohmic contacts with metal bus bars must be so designed as not to aggravate this weakness by putting unnecessary strain on the contacts during mechanical vibration or thermal cycling. It is the objective of this program to investigate bus bar materials and designs, interconnection techniques, and solar cell electrical and mechanical characteristics. This information will then be used to develop improved solar-cell assembly and submodule configurations.

GENERAL

Present solar-cell assemblies used on spacecraft arrays demonstrate approximately a 10-W/lb power output capability in near-earth space. Anticipated future spacecraft missions will require solar arrays to operate over a wide range of intensities and temperatures with a high specific power capability. Future programs such as Mercury and Jupiter flyby missions and Mars surface operation will require solar cells to operate at environments never before encountered. It is important to continue the solar-cell developments to keep abreast of the expanding demands on solar systems.

To enable JPL to meet its immediate and long-term objectives, several photovoltaic evaluation systems are currently in operation to measure the electrical and mechanical characteristics of the various solar cells in use today.

To perform temperature intensity parametric studies on solar cells, a thermal-vacuum test facility has been developed (Fig. 1). Test programs have been continued during the report period to evaluate the performance characteristics of a number of different photovoltaic devices. The cells tested in these studies have been tested over a wide range of temperature and solar flux levels. Test reports have been written on all the cells tested to date, describing their performance characteristics as a function of temperature and solar intensity. Work has progressed in the design and fabrication of a multicell thermal test chamber, Mars-environment test chamber and in the incorporation of a computerized solar-cell test data acquisition system. The above systems will improve JPL's testing capability and increase the overall output efficiency of the test facility. The Mars test chamber is required to study the effects of surface erosion and contamination that may affect the performance of solar arrays on a Mars-like planet surface. The present schedule indicates that these investigations will commence during the first quarter of FY 70.

A computer program was developed at JPL to predict the performance of solar cells over the heliocentric distances. This computer program was slightly modified to depict the standard deviations of a 95% confidence limit derived from empirical data. Very good correlation to empirical solar-cell performance characteristics has been achieved on a limited number of cells

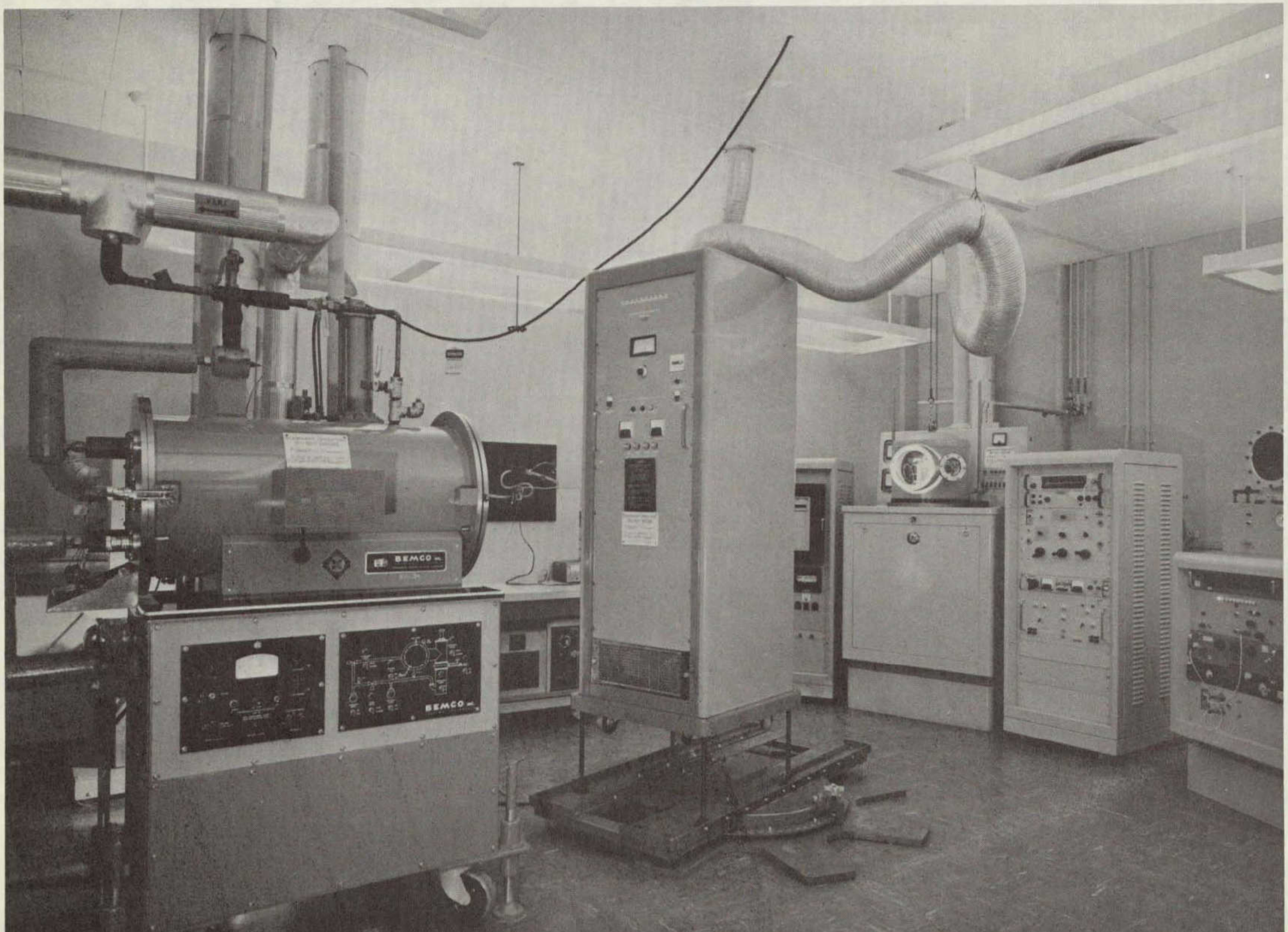

Figure 1. Photovoltaics Power Sources Test Facility

over a cell temperature range of -120° to +130°C, and over an intensity range of 5 to 250 mW/cm^2. Redesign of the thermal-vacuum test chamber and data-acquisition system has progressed, resulting in an increase in solar-cell test capability and more efficient handling of test data. However, additional measurements are being conducted on the computer data-acquisition system in order to compare the computer data-acquisition technique with the manual method used earlier. The manual measuring technique will be maintained as a backup to the computerized system.

Work is also progressing in the measurement of solar-cell characteristics of much wider temperature and intensity ranges utilizing the present solar simulator and thermal-vacuum system. However, the redesigned system will enable the processing of larger quantities of existing cell types in a more efficient manner. Significant progress has been made during the second quarter of FY 69 in control of operational test parameters and refinement of the test procedures. Future plans are to continue improving the measurement of cell parameters in simulated space environments. Further it is anticipated that some previously tested solar cells as well as cells purchased during FY 69 will be measured in larger quantities so that confidence in prediction of cell characteristics can be enhanced and the characteristics correlated to predict specific types of solar arrays anticipated for future spacecraft missions.

A portion of the work unit also encompasses the development of narrow-bandpass filters for thermal control of solar panels intended for near-sun missions. Three sample panels previously reported were fabricated and tested using the JPL thermal equilibrium chamber and solar simulator. The results of the test, conducted at three intensities (70, 140, and 250 mW/cm^2), are presently being evaluated. The purpose of the tests is the generation of empirical data necessary to develop optimized filtered coverglasses for near-sun missions.

A detailed review of available solar-cell submodule designs, materials, and fabrication techniques being used throughout the industry has been in process since January 1968. The information derived will serve as the foundation for subsequent programs that will require laboratory tests and analysis of the more promising designs. This program will then attempt to develop improved submodule designs which will enhance the mechanical integrity of the solar-cell assembly. The resultant design will be evaluated relative to reliability, producibility, cost, and ease of integration into a solar panel. Submodules will be subjected to extreme thermal cycling, deflection, and contact pull-strength during the program. The final report will describe in detail the material and fabrication techniques presently used throughout industry in solar-panel fabrication.

In the future, emphasis will be placed on the evaluation of solar cells (as to composition, thickness, configuration, and comparative performance). The data obtained from these investigations will be utilized to determine design parameters necessary to optimize solar cells and, ultimately, the composite solar panel for application to specific mission environmental conditions.

PUBLICATIONS

Meetings and Symposia Papers

1. Sandstrom, J. D., "Electrical Characteristics of Silicon Solar Cells as a Function of Cell Temperature and Solar Intensity," Intersociety Energy Conversion Engineering Conference, Boulder, Colorado, August 13-16, 1968.

ADVANCED ROLLUP SOLAR ARRAY CONCEPTS

NASA Work Unit 120-33-01-07-55

JPL 320-31701-2-3420

W. A. Hasbach

OBJECTIVE

The objective of this program is to extend the concept of a rollup solar array technology into a multikilowatt system. A program was initiated in 1967 to investigate the feasibility of developing a 10-kW solar array which would have a specific power capability of 30 W/lb and could be deployed after launch through a rollout technique similar to that used in a window shade.

CONTRACTED EFFORT

The three contractors below performed advanced design studies related to solar array development.

(1) Fairchild-Hiller Corp., Contract 951969, $161,000.00

(2) General Electric Co., Contract 951970, $162,240.00

(3) Ryan Aeronautical Co., Contract 951971, $164,033.00

Studies performed by the three contractors indicate that a 30 W/lb power-to-weight ratio can be achieved in a solar array. The total array will consist of four rollout panels, each containing 250 ft^2 of active surface area. The four rollout panels will be mounted symmetrically about the base of the spacecraft and will deploy uniformly with minimum disturbance of the center of gravity of the vehicle.

A summary of the weights and the specific power yielded by each of the three competing designs is shown in Table I. These were based on meeting the objectives of 30 W/lb at the environmental loads specified in JPL Specification SS 501407A.

During the study of deployment methods, it was noted by the three contractors that none of the extensible boom systems was clearly the preferred

Table I. Comparison of Contractor Designs

Characteristic	Fairchild Hiller	General Electric	Ryan
Estimated weight	78.6 lb	75.6 lb	74.7 lb
Allowance for growth	4.7 lb	7.7 lb	8.6 lb
Specified total weight (2500 watts)	83.3 lb	83.3 lb	83.3 lb
Present specific power	31.8 W/lb	33.0 W/lb	33.5 W/lb

choice to achieve the desired objective of this program. This is further emphasized by the fact that each contractor has selected designs which differ broadly in concept yet still achieve the 30-W/lb weight requirement. The various approaches have also shown by analysis that they will survive the environments defined by the applicable specifications.

PLANNED ACTIVITIES

A contract will be executed with one contractor of the three who participated in the feasibility study of Phase I, to continue in the design, fabrication, and test of a full-size solar array. The environmental restraints will be established based upon a hypothetical Jupiter flight. The primary objective of a Phase II effort will be to determine from test the dynamic characteristics of the solar array.

PUBLICATIONS

SPS Contributions

1. Hasbach, W. A., "Advanced Rollup Array Concepts," SPS 37-53, Vol. III, September 1968.

Contractor Reports, Interim and Final

1. "Feasibility Study of a 30 Watt Per Pound Rollup Solar Array," Quarterly Reports, General Electric Co., Report No. 68 SD 4301, June 21, 1968, Final Report.

2. "Feasibility Study of a 30 Watt Per Pound Rollup Solar Array," Quarterly Reports, Fairchild-Hiller Corporation, Report No. 652-00101 FR, August 15, 1968, Final Report.

3. "Feasibility Study of a 30 Watt Per Pound Rollup Solar Array," Quarterly Reports, Ryan Aeronautical Co., Report No. 40067-4, June 21, 1968, Final Report.

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PLANETARY SOLAR ARRAY DEVELOPMENT

NASA Work Unit 120-33-01-08-55

JPL 320-32101-2-3420

W. A. Hasbach

OBJECTIVE

The objective of this program is the development of solar arrays suitable for use as landable power source on the planet Mars. This will be accomplished by analysis of mission requirements, generation of conceptual designs for landed solar arrays, and fabrication and test of selected components of the best conceptual designs.

INTRODUCTION

Tradeoff studies of weight, power capabilities, and structural integrity versus exposure to the Mars environment have resulted in the selection of a preferred design for a "soft lander" configuration. Although studies have confirmed three possible approaches with the potential of meeting the program objectives, one is felt to be more worthy of further investigation. The chosen concept (Fig. 1) is the system which was optimized for the best compromise in power versus weight, but without the encumbrance of complicated orientation or tracking mechanisms. This system, once released from its locked flight position, will require no power from the lander system for deployment or continuous operation for the mission life of one year.

This system, as recognized initially in its concept, will not meet the desired goal of 20 W/lb at 1 astronomical unit. Under worst-case conditions, it will be under the minimum requirement of 200 watts of electrical power at solar noon. The worst-case minimum power is 5% low (190 watts). The best-case condition is 35% high (256 watts). The average noon power output for the limiting conditions is 17 percent high (223 watts). At the higher solar intensities occurring at spring and fall seasons, the power level is above 200 watts for all conditions.

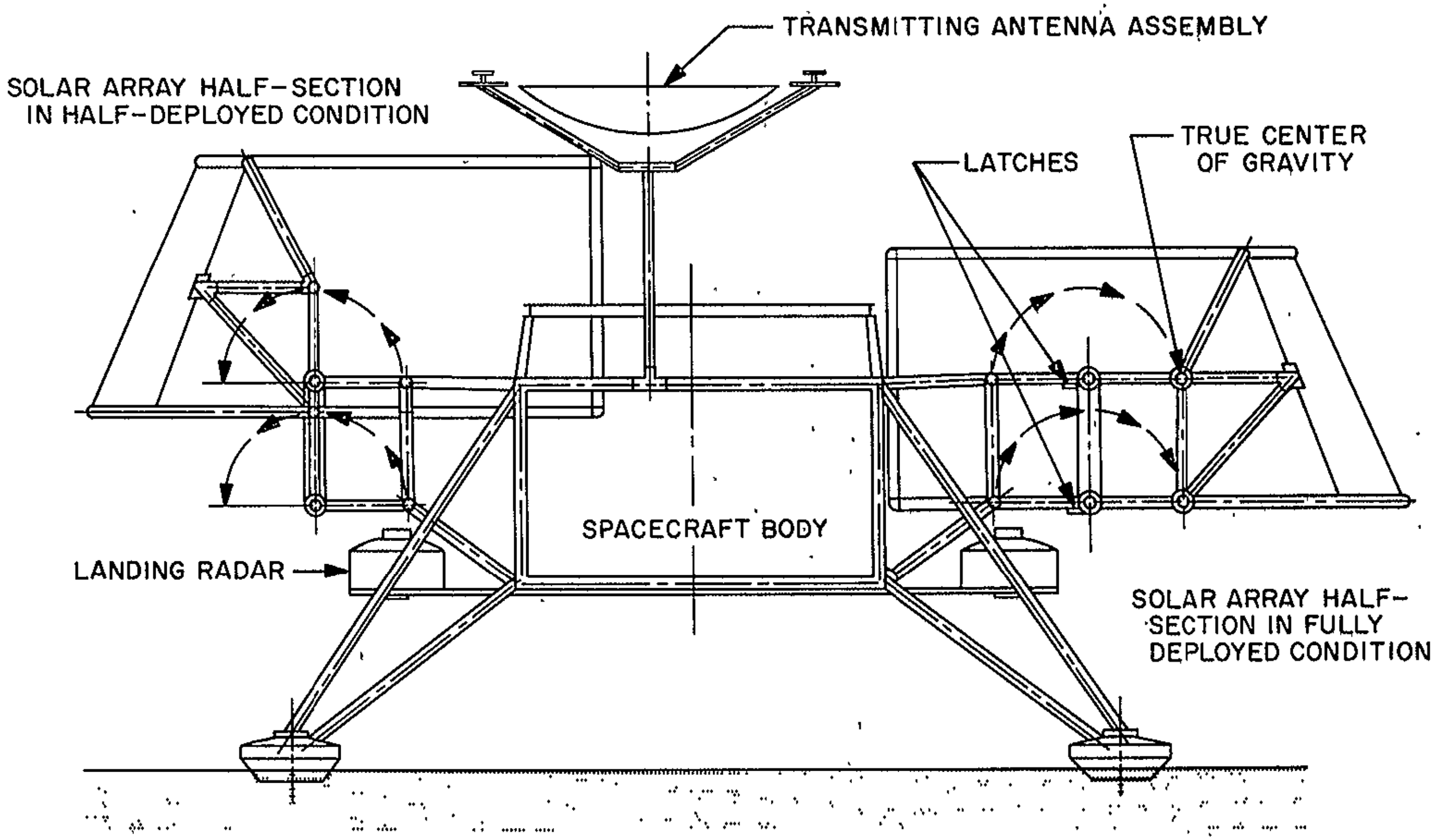


Figure 1. Non-Oriented Conical Truncated-Cone Mars Soft Lander

Figure 2 is a two-panel oriented-array system designed to minimize the antenna shadow problem, without combining the antenna with the solar panels. This system will meet the desired goal of 20 W/lb at one astronomical unit and exceed the minimum power of 200 watts at solar noon for the worst-case conditions. The actual power output will vary dependent upon the number of circuits shadowed at noon.

A third concept is illustrated in Figure 3, which has orientation capability and no shadowing restriction. To accomplish this, it is mandatory that the antenna and solar array be mounted to a common vertical boom elevated above the spacecraft body. Combining the antenna and solar array mounting presents a problem in maintaining the pointing accuracy of the antenna when the system is buffeted by wind gusts. This design requires the least number of solar-cell circuits to achieve the required power output of 200 watts under worst-case conditions, and will meet the desired goal of 20 W/lb at one astronomical unit.

The three array concepts have been reviewed, and the nonoriented conical truncated cone was selected as the most favorable. Because of its higher reliability factor, absence of electrical-motor gear drives, no power requirement necessary for operation, and its design growth potential, this choice appeared to be most suited to the program objectives.

Emphasis was then placed upon development of a computer program that would estimate a solar-panel power capability under the varying effects of cloud cover, atmospheric attenuation, temperature, and dust. This program is in the final phase of checkout and will be complete within the next report period.

In addition to the computer program to estimate electrical power, a high-impact test program has been performed to determine the effects of shock levels up to 5,000g upon solar cells and their electrical interconnections. Both static and dynamic testing indicate that survival up to 5000 g is within present solar-cell and panel-fabrication technology. Final reduction has been completed, and will be reported in the next period.

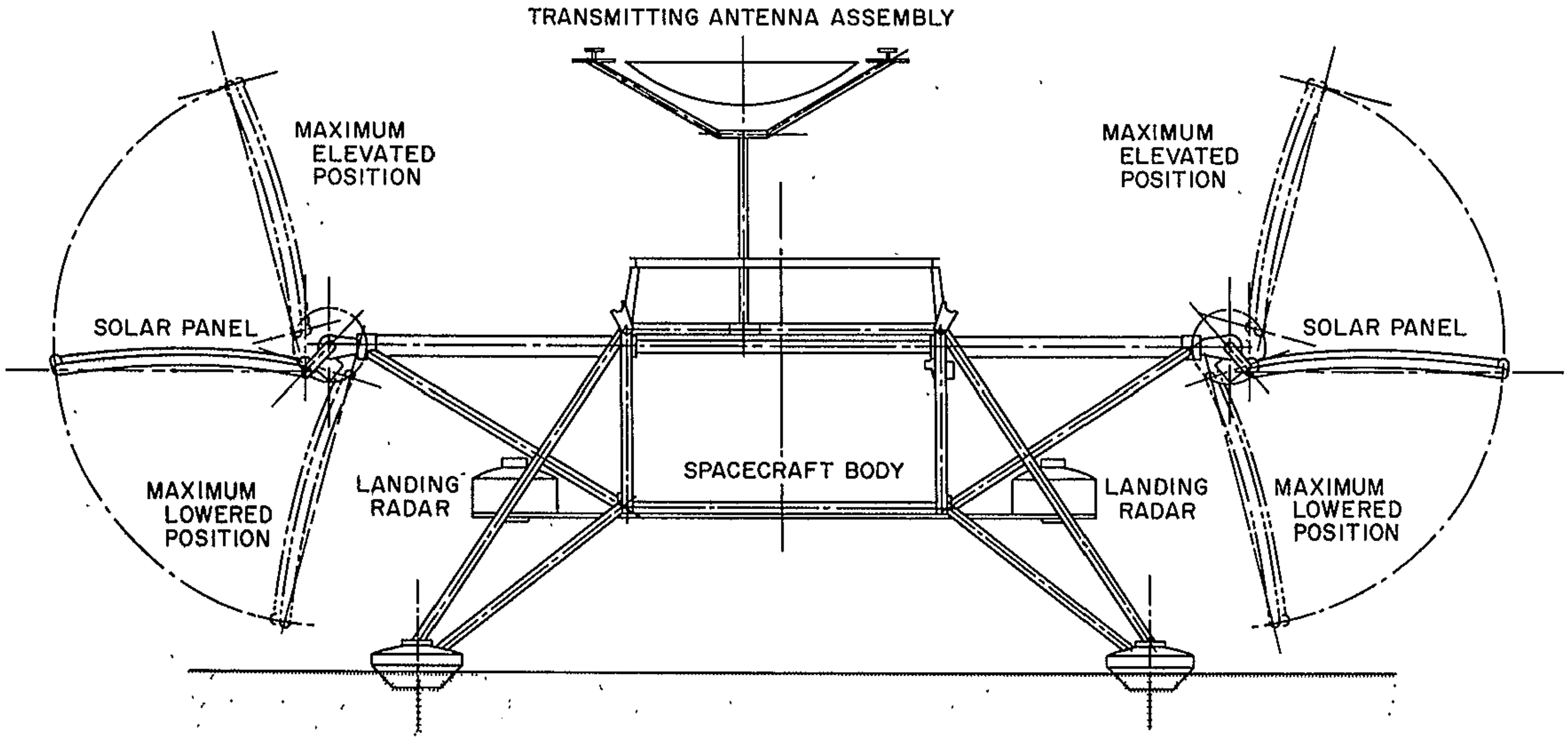


Figure 2. Two-Panel Oriented Array

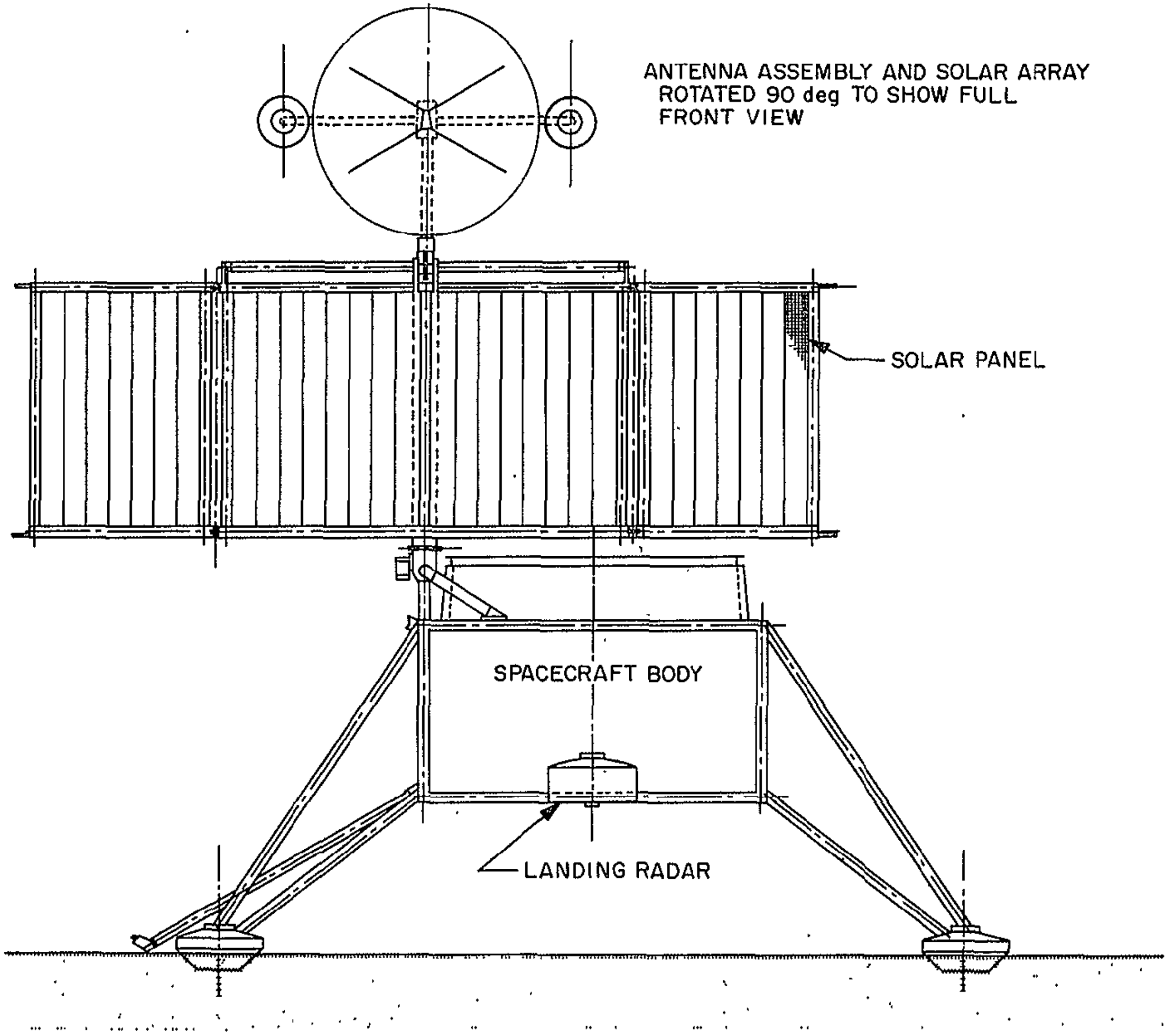


Figure 3. Oriented Solar Array and Integrated Antenna System

PLANNED ACTIVITIES

A preliminary structural design of a solar panel capable of "rough landing" on the surface of Mars will be reported. Tradeoff studies were concluded between a flat-plate design and a folding-arm panograph, extending-element design. These results will be reported.

Data reduction resulting from the high-impact testing will be reported in the next semiannual report; the tests will verify that solar cells can be used to supply electrical power for impact-type missions.

PUBLICATIONS

SPS Contributions

1. Hasbach, W. A., "Planetary Solar Array Development," SPS 37-51, Vol. III, June 1968.
2. Hasbach, W. A., "Planetary Solar Array Development," SPS 37-53, Vol. III, October 1968.

EFFECTS OF IONIZED PARTICLE RADIATION ON SOLAR CELLS

NASA Work Unit 120-33-01-09-55

JPL 320-32301-2-3420

B. E. Anspaugh
P. A. Berman

OBJECTIVE

The objective of this program is to obtain experimental data on the effects of proton irradiation on the electrical characteristics of various types of silicon solar cells. These data will eventually be used in conjunction with theoretical considerations to predict the effect of solar proton flares on the electrical characteristics of the cell types being considered for flight use. Cells to be investigated will be representative of Mariner and Surveyor hardware, as well as advanced technology silicon solar cells of 0.008- and 0.004-in. thickness.

ACTIVITIES

Work has been continued to make the JPL Dynamitron operational this reporting period. During the next period, we expect to complete the determination and optimization of beam uniformity and proceed with the irradiation program. This machine is capable of producing electrons or protons with energies up to 3 MeV. The Dynamitron will provide a much better source of protons for the low-energy portion of this program, and will produce the 1-MeV electrons that have been used as a standard radiation source throughout the field.

An investigation was undertaken to determine if low-energy protons incident on an M 69 solar cell/coverslide system could cause significant power degradation. Divita (Ref. 1) has estimated that the M 69 spacecraft could encounter fluxes from a single solar flare proton event as large as those shown in Table 1.

Table 1

E > 0.2 MeV	1.5×10^{12}	$< \phi < 2.4 \times 10^{13}$
E > 1.0 MeV	1.2×10^{11}	$< \phi < 1.8 \times 10^{12}$
0.2 < E < 1.0 MeV	1.3×10^{12}	$< \phi < 2.2 \times 10^{13}$

Some existing data (Ref. 2) has shown that proton fluxes of this magnitude and energy range can cause very serious cell power loss even though only 1 to 2% of the cell area was exposed to the radiation. Therefore, a cell irradiation program at the NASA/Ames proton accelerator facility was conducted with the following objectives:

(1) Determine the effect of low energy protons on various uncovered solar cell areas.

(2) Determine if protection by RTV-602 of exposed cell areas is adequate, or will it cause other problems equally severe.

(3) Determine if gap position affects cell output.

(4) Determine the effect of low energy protons on the spectral transmission characteristics of antireflection coatings, coverslides and filters.

Preliminary results of this program show that cells with unprotected areas are quite susceptible to low energy protons, but that RTV-602 applied to such areas affords adequate protection.

Figure 1 defines the gap areas investigated. The experimental matrix is shown in Figure 2. Five cells were irradiated at each level of the matrix. I-V curves were obtained for all cells, both before and after irradiation, using the Spectrolab X-25L solar simulator at an intensity of 140 milliwatts/cm^2 with the cells maintained at a temperature of 28 ±1°C. In general, it was found that I_{sc} did not change appreciably as a result of these irradiations, but V_{oc} did decrease somewhat.

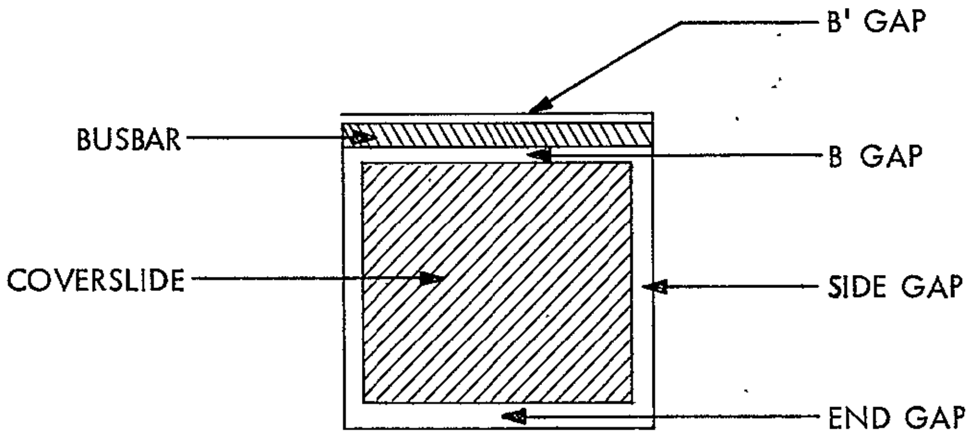
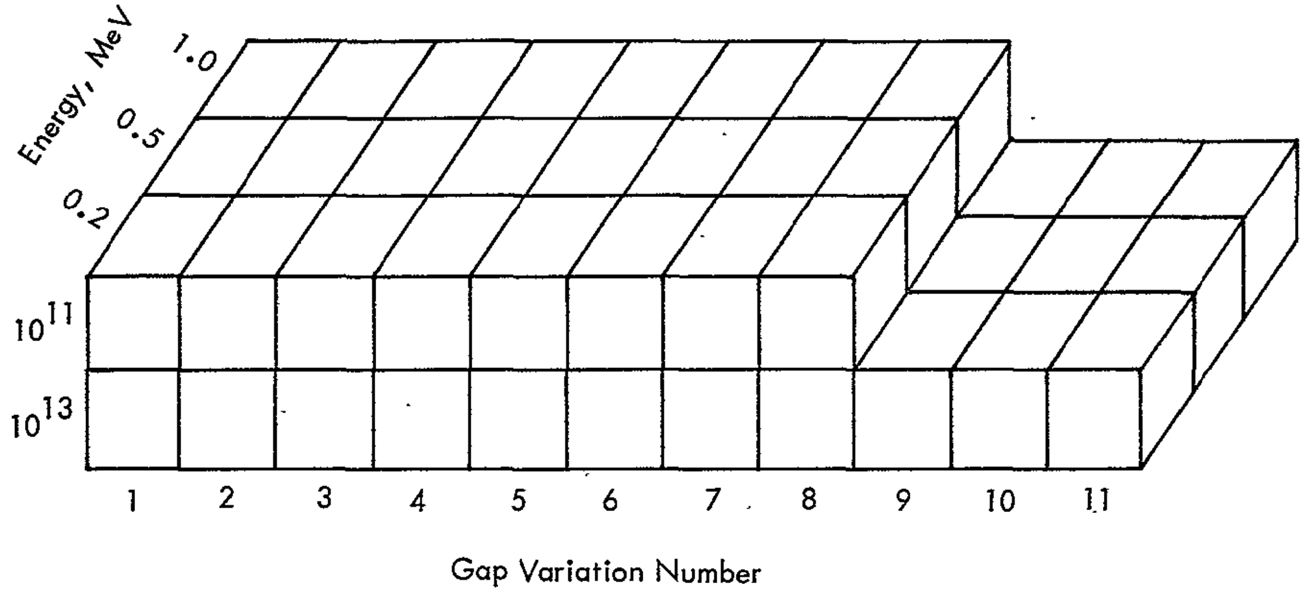


Figure 1. Solar Cell/Coverside Gap Terminology



1. Coverslides only
2. All gaps = 0
3. B = 7 mils, S = E = B' = 0
4. B = 15 mils, S = E = B' = 0
5. B' = 10 mils, S = E = B = 0
6. B = 15 mils, B' = 10 mils, S = E = 0
7. S = 15 mils, B = B' = E = 0
8. E = 15 mils, B = B' = S = 0
9. B = 15 mils, B' = 10 mils (B and B' covered with RTV 602)
   E = S = 0
10. Same as 9 but B and B' covered with SS 4044 primer + RTV 602
11. Same as 9 but B and B' covered with DC 93-500

Figure 2. Experimental Design Matrix

The conclusions may be briefly summarized as:

(1) A comparison of the results for the cells with protected gaps with the cells having unprotected gaps indicate that any of these materials give substantial protection from protons in the flux and energy ranges of this investigation.

(2) For each gap variation examined, the 0.2 MeV protons were more damaging than the 1.0 MeV protons. The 0.2 MeV protons have a range of 2.2 microns in silicon, and the 1.0 MeV protons have a range of 18 microns. Junction depth is approximately 0.3 micron in these calls. The lower energy protons clearly lose a greater amount of their energy in the vicinity of the junction, thereby causing this enhanced damage.

(3) Adding the fractional power degradation to the 15-mil B gap to that of the 10-mil B' gap at $\phi = 10^{13}$ p/cm^2 gives the fractional power degradation of the combined 15-mil and 10-mil B' gap irradiation at $\phi = 10^{13}$ p/cm^2. This is true for both the 0.2 and 1.0 MeV irradiations.

(4) Irradiations to fluences of 10^{11} p/cm^2 gave no significant power degradation in any of the gap variations tested.

(5) An ordering of the gap variations from least to most power degradation gives different results for the 0.2 and 1.0 MeV irradiations. No explanation is offered.

0.2 MeV				1.0 MeV			
Gaps	=	0	0.99	Gaps	=	0	0.98
B'	=	10	0.91	S	=	15	0.97
S	=	15	0.90	E	=	15	0.97
B	=	7	0.89	B	=	7	0.96
E	=	15	0.86	B	=	15	0.96
B	=	15	0.84	B'	=	10	0.95
B'	=	10,	0.77	B'	=	10,	0.90

Exposed edge and side gaps are seen to be quite important at 0.2 MeV, but not at 1.0 MeV.

REFERENCES

1. Divita, E. L., "A Summary of the Estimates of Time-Integrated Proton Flux in Low Energy, High Flux Solar Events," JPL IOM No. 2947-310, March 10, 1968.

2. Brown, W. D., et al, "ATS Power Subsystem Radiation Effects Study, Phase I/Final Report," Hughes Aircraft Company Report No. SSD 80089R, February 1968.

3. Jensen, W. M., "Protection of Exposed Solar Cell Edges," JPL IOM No. 351:68:176, June 12, 1968.

PUBLICATIONS

None

SOLAR CELL CONTACT STUDIES

NASA Work Unit 120-33-01-11-55

JPL 320-33001-2-3420

P. A. Berman

OBJECTIVE

The purpose of this work unit is to study and analyze the characteristics of solar cell contacts as a function of exposure to various environmental conditions. Many problems exist with present-day, state-of-the-art titanium-silver contacts with and without solder coating. Solar cell manufacturers have not analyzed their contacts sufficiently to determine what characteristics the cells will have as a result of exposure to environmental extremes. This information is needed to assure the success of any space mission.

ACTIVITIES

Cells having plated nickel-copper-gold contacts were procured from Ferranti Electric Incorpoated. Thirty-five cells were subjected to a 48-hour exposure at 60°C with a relative humidity of 95%. The cells were then temperature-cycled five times from -196°C to +135°C with a one-hour soak at each of the temperature extremes. The cell contacts were then subjected to pull tests performed perpendicular to the cell face. Two such pull tests were made on each of the two cell faces on the N and P contacts, utilizing Kovar ribbons soldered to the contacts. The results are shown in Table 1.

It is interesting to note that, in the case of the top or "N" contact, the primary cause of failure was the pulling of the silicon while on the bottom or "P" contact, the primary cause or failure was the plating separation. The average pull strength value does not appear to present any advantage over titanium-silver contacted cells with solder coating for these environments since Mariner 69 type cells survive these exposures with a minimum pull strength of 500 grams.

Ferranti cells having nickel-copper-gold contacts, and Heliotek cells having solderless titanium-silver contacts, were exposed to an extreme humidy-temperature environment of 95% relative humidity at a temperature of 80°C for

Table 1. Pull Strength of Ni-Cu-Au Contacts After Environmental Exposure

Ribbon Position Identification	Average Pull Strength (gms)	σ (gms)	Primary Cause of Failure
N_1	540	294	82% samples pulled silicone
N_2	504	301	85% samples pulled silicone
P_1	475	237	91% samples pulled plating
P_2	491	271	100% samples pulled plating
Note: N_1 + N_2 refer to top contact, P_1 + P_2 refer to bottom contact			

thirty days, and were compared electrically with Ion Physics cells having high-vacuum sputtered aluminum contacts. The results are shown in Table 2. The cells were tested at a cell temperature of 28 ±1°C in a tungsten simulator having a color temperature of 2800°K, and an equivalent solar intensity of approximately 100 mW/cm^2.

It can be seen that there are no significant differences between the pre-exposure and post-exposure electrical characteristics of the cell types. This was surprising because it was expected that the titanium-silver contact cells would degrade severely under these conditions since it is known that titanium reacts significantly under conditions of high temperature and high humidity environments. All cells were then mechanically peel-tested by utilizing Scotch 810 tape pressed to the cell top and bottom contacts. In this case, a drastic difference was observed between the titanium-silver contact cells and the other cell types. The sputtered-aluminum contact cells and the nickel-copper-gold contact cells exhibited no mechanical degradation of the contact, while severe contact delamination occurred on the titanium-silver contact cells. In several cases, the entire titanium-silver contact was found on the tape. These results point out a very significant aspect of contact degradation; namely, mechanical and electrical degradation mechanisms can operate entirely independent of one another. It should be noted that even the cell series resistance, which should

Table 2. Electrical Characteristics of Cells Before and After Thirty Day Exposure to 80°C at 95% Relative Humidity

Cell Type	No. of Cells Tested	Exposure	I_{sc} (mA)	V_{oc} (Volts)	I_{mp} (mA)	V_{mp} (mV)	P_{max} (mW)	CPF	R_s (ohms)
Ion Physics Sputtered Al	10	Pre-Test	95.7	0.541	87.7	0.430	37.7	0.728	0.54
		Post-Test	96.7	0.541	87.8	0.429	37.7	0.714	0.63
Ferranti Ni-Cu-Au Contacts; 1 Ω-cm Si Resistivity	12	Pre-Test	97.8	0.586	88.6	0.487	43.17	0.74	0.36
		Post-Test	98.3	0.579	89.5	0.475	42.56	0.75	0.25
Ferranti Ni-Cu-Au Contacts; 10 Ω-cm Si Resistivity	12	Pre-Test	98.7	0.545	90.9	0.442	40.26	0.74	0.40
		Post-Test	100.6	0.536	92.4	0.430	39.7	0.74	0.45
Heliotek Ti-Ag Contacts (Solderless) 8-Mil Thick Cells	10	Pre-Test	85.2	0.565	80.0	0.468	37.44	0.77	0.29
		Post-Test	87.4	0.557	81.4	0.460	37.43	0.77	0.26

I_{sc} = Short Circuit Current

V_{oc} = Open Circuit Voltage

I_{mp} = Current at Maximum Power

V_{mp} = Voltage at Maximum Power

P_{max} = Maximum Power

CPF = Curve Power Factor = $\frac{I_{mp} \times V_{mp}}{I_{sc} \times V_{oc}}$

R_s = Cell Series Resistance

increase significantly as a result of contact degradation, showed no adverse effects due to the environment.

PUBLICATIONS

SPS Contributions

1. Berman, P. A., and Rolik, G. P., "Solar Cell Contact Studies," SPS 37-53, Vol. III, October 1968.

IMPROVED SOLAR CELL CONTACT DEVELOPMENT

NASA Work Unit 120-33-01-12-55

JPL 320-33101-2-3420

P. A. Berman

OBJECTIVE

Solar panels for space applications are environmentally limited in many cases as a result of solar cell contact restrictions, and it can be expected that significant improvements in solar panel reliability will result from improvements in solar cell contacts and interconnection techniques. The objective of this program is the development of silicon cell electrical contacts and interconnection techniques which are less susceptible to mechanical and electrical degradation resulting from exposure to extremes of earth and space-type environments.

A major objective is the development of cell electrical contacts and interconnection techniques that do not require the use of solder. Contact strength and electrical characteristics will be optimized with regard to minimization of degradation after exposure to thermal shock, humidity-temperature, vacuum-temperature, high-temperature, and low-temperature environments. Also, the solar cell contact and interconnection techniques will be improved with respect to the following:

(1) Effects on solar cell current-voltage characteristics

(2) Series and/or contact resistance

(3) Stresses due to fabrication procedure

(4) Compatibility with requirements for fabrication into submodules

(5) Reliability

(6) Handling and manufacturing characteristics and restraints

(7) Repair or rework capability

(8) Reproducibility

(9) Production cost

(10) Ease of production

(11) Weight

(12) Compatibility with large-area cells

(13) Requirements for special equipment and tooling

(14) Compatibility with inorganic, integral protective coatings.

ACTIVITIES

Contracts were awarded to two vendors to perform the work outlined in the preceding paragraph. One contract was awarded to Ion Physics Corporation (JPL Contract No. 952144), and one contract was awarded to General Precision Systems Incorporated, Librascope Group (JPL Contract No. 952145).

The contract awarded to General Precision Systems Inc., Librascope Group, was cancelled at the convenience of the Laboratory. The principal investigators assigned to this program terminated their employment with Librascope, and it was the opinion of JPL that further progress would be difficult. At the time of termination, Librascope had not yet really succeeded in depositing low-resistance aluminum contacts on N- and P-type silicon.

Ion Physics Corporation has completed its contract with JPL. Solar cell contacts were fabricated utilizing Ion Physics' high vacuum sputtering technique. Contacts evaluated were aluminum, nickel, and copper. It was found that the most efficient cells were obtained through the use of aluminum contacts, and that these cells ranged in efficiency primarily between 8 and 10%, at air mass zero spectrum and intensity, and a cell temperature of 28°C. State-of-the-art titanium-silver contact cells normally have air mass zero efficiencies of 11 to 11.5%.

The high-vacuum sputtered-nickel was highly stressed, especially for film thicknesses greater than 0.7 micron, which usually resulted in a spontaneous splitting of the nickel. This resulted in a high cell series resistance in nickel-contacted cells due to the very thin conducting layer. Open-circuit voltages were approximately 10% lower than those obtained from titanium-silver contacted cells. Attempts to fire the nickel at a temperature of 400°C for 20 minutes resulted in flaking of the nickel contact. Air mass zero efficiencies of nickel-contacted cells were approximately 6%.

Cells produced with sputtered-copper contacts exhibited poor mechanical and electrical characteristics. The contacts tended to peel easily, and produced very low short circuit currents and open-circuit voltages.

A heat treatment at 450°C for one hour significantly reduced the series resistance of aluminum-contacted solar cells, and gave a slight increase in open-circuit voltage. Aluminum-contacted cells exhibited series resistances of approximately 0.5 ohm, and a curve power factor of 0.735, compared to a series resistance of 0.4 ohm, and a curve power factor of 0.75 for titanium silver-contacted cells.

$$\text{Curve power factor} \equiv \frac{I(\text{max power}) \times V(\text{max power})}{I_{sc} \times V_{oc}}$$

The finger resistance of sputtered-aluminum cells with 2 microns of aluminum was slightly greater than 6 ohms, compared to the finger resistance of less than 5 ohms for normal titanium-silver cells. The contact resistance to the front and rear surface of the sputtered-aluminum contact cells was approximately 0.08 ohm/cm^2, compared to a contact resistance for silver-titanium contact cells of approximately 0.05 ohm/cm^2. These cells were exposed to an environment consisting of 95% relative humidity at 82°C for 15 days. No significant electrical or mechanical degradation was observed.

Ultrasonic welding was successfully utilized to achieve aluminum bonds. Some problems in repeatability were encountered and were attributed to differences in the silicon surface characteristics. Soft aluminum ribbons, 3 mils thick and 320 mils wide, were ultrasonically bonded to aluminum contacts, two microns thick, by means of three ultrasonic bonds. These have withstood pull tests perpendicular to the cell face of 1750 grams which was the limit of the particular pull tester used. The area was approximately 62 mils in diameter.

More efficient cells (up to 11% for air mass zero) were obtained from evaporated aluminum contacts. The mechanical characteristics of evaporated aluminum contacts appeared to be as good or better than the sputtered-aluminum contacts. Ultrasonic bonds were successfully made to evaporated aluminum-contact cells.

CONCLUSIONS

It appears that aluminum can be successfully used for contacts to silicon solar cells, and that ultrasonic bonding can be utilized to fabricate interconnections.

PUBLICATIONS

None

LARGE AREA SOLAR ARRAY INTEGRATION

NASA Work Unit 120-33-01-13-55

JPL 320-32901-2-3420

D. W. Ritchie
R. E. Oliver

OBJECTIVE

The objective of this study is to investigate the feasibility of applying large area solar array technology to various future spaceflight missions. The study is a continuation of the effort initiated in FY 68. Whereas the FY 68 effort was limited to consideration of the foldable array concept developed by the Boeing Company under JPL Contract 951934, the FY 69 study effort encompasses both foldable and rollout array concepts.

STATUS

The study of applications of the foldable array concept has been completed. This study includes a fixed array for use on the SIV-B orbiting space station, and a steerable array for the Basic Subsystem Module mission.

The parametric study computer program developed during FY 68 was extended to provide plotted results useful in preliminary application studies. This program was then used to produce a catalog of parametric data curves. The computer program was also adapted to the Tymshare remote terminal computer system. This version of the program was applied to obtain performance characteristics and scale factors of arrays considered for the Grand Tour mission study, the SIV-B space station, and the Basic Subsystem Module.

A collapsible beam concept was pursued to the extent of designing a test beam and a test frame composed of collapsible beams. This concept is being pursued as a means of alleviating the stowed volume problems associated with the foldable array concept.

A preliminary design of a rollout array for use in a solar electric propulsion test flight mission was completed.

PLANNED ACTIVITIES

A parametric study of variations in properties of rollout arrays due to changes in size, aspect ratio, loads, and materials will be completed. This study will include a computer program similar to that developed for the foldable array study. Reports will be written describing the application of foldable and rollout arrays to SIV-B and Basic Subsystem Module missions. The collapsible beam concept test items will be fabricated and tested to determine strength and stiffness characteristics.

PUBLICATIONS

None

SUB-PANEL TECHNOLOGY USING ADVANCED SOLAR CELLS

NASA Work Unit 120-33-01-16-55

JPL 320-33501-2-3420

J. D. Sandstrom

OBJECTIVE

The practicality of advanced concept solar cells, such as 1 x 30-cm dendritic, and 3 x 3-in. cadmium sulfide type cells, must be evaluated relative to the techniques required to integrate these cells into complete solar panels. This program will evaluate the fabrication problems involved in developing lightweight solar panels using advanced concept cells, evaluate the electrical-mechanical performance characteristics of these panels, and compare these problems and characteristics to the problems and characteristics of panels fabricated from conventional 2 x 2-cm cells. The program will be oriented to evaluate such factors as fabrication ease, cost, reliability and specific power.

APPROACH

Advanced concept solar cells procured in the Evaluation of Advanced Solar Cells program (NASA Work Unit 120-33-01-15) will be used in performing this effort. These cells will be integrated into a solar panel assembly of lightweight design. The details of fabrication and mechanical configuration will be controlled in a manner representative of flight panel development. The complexity and effective cost in fabricating and reproducing these panels will be evaluated. After fabrication, the panels will be electrically and mechanically tested, and the relative reliability, ruggedness, handling requirements, and electrical characteristics will be studied. Preliminary solar panel design configurations have been completed using cadmium sulfide and 1 x 30-cm dendritic-type solar cells. The available solar cell area used in these designs was based upon a subpanel concept such as that proposed in the LASA (Large Area Solar Array) program being directed by JPL.

ACTIVITIES

Efforts on this program have been delayed pending evaluation and future efforts of the 120-33-01-22 program. An effort has been defined, and initiation of a contract has been delayed due to funding allocation. Anticipated contract release is now scheduled for March 1969.

PUBLICATIONS

None

ANALYSIS OF SOLAR CELL RADIATION DAMAGE

NASA Work Unit 120-33-01-17-55

JPL 320-33901-2-3420

P. A. Berman

OBJECTIVE

One of the primary considerations in the design of photovoltaic power systems for spacecraft is the effect of exposure to ionized particle irradiation on the silicon solar cells used to convert solar energy to electrical energy. The damage mechanisms for high-energy electrons and protons are fairly well understood, and it appears that they lend themselves quite readily to simple analysis. Low-energy protons, however, require far more complex analysis since the damage is not uniformly generated throughout the cell. The fact that electron-hole pairs are also not uniformly generated throughout the cells by space-sunlight complicates this analysis still further. Moreover, the amount of damage done by low-energy protons is far greater than high-energy protons, and is approximately proportional to the reciprocal of the proton energy. The effect of low-energy protons on the operating characteristics of silicon solar cells is especially important with regard to solar flare protons (since the preponderance of protons are of low energy), and also with regard to thin cover glasses which do not attenuate many of the low-energy protons. The objective of this work unit is to construct a mathematical model, suitable for machine programming, which will accurately predict the amount of degradation as a function of proton energy, and enable optimization of the cover glass thickness for a given radiation environment.

ACTIVITIES

A contract has been awarded to Exotech Incorporated (JPL Contract No. 952246) for $41, 034 for a theoretical study and analysis of radiation damage in silicon solar cells, and for the development of a mathematical model to predict silicon solar cell performance degradation resulting from exposure to proton and electron radiation environments.

The literature concerning proton-induced radiation damage to silicon solar cells and their coverslides has been collected and reviewed by Exotech. A summary of the state of the art has been presented in the first quarterly report. This summary strongly indicates that the localized damage in the silicon solar cell depends upon the proton energy at the point being considered. Thus, it is quite likely that for protons having insufficient energy to pass entirely through the body of the cell, nonuniform damage is induced. An equation is presented which yields the proton spectrum incident on the solar cell due to an isotropic fluence of a particular energy penetrating a shield of a given thickness. Figures are presented showing the number of displacements per centimeter of proton track for proton energies between 10^{-3} to 10^{3} MeV. The energy range of 5 to 10 MeV is a transition region between strongly nonuniform damage and nearly uniform damage to the solar cell base region. At some energy above this transition region, uniform damage to solar cells is experienced. At very low energies of about 100 keV, significant junction damage occurs. Low energy proton damage below 10 MeV is partially annealed at temperatures near 150°C, whereas for high energy proton damage, a temperature of at least 300°C is required for significant annealing. Investigation into the diode effects shows that I_o, the reverse saturation current, tends to increase with fluence for protons of energy of 100 keV while it remains comparatively constant for protons of 500 KeV.

A theoretical analysis of published data on silicon solar cells was performed, and reasonable values of the photovoltaic current density at the cell junction were obtained as a function of the minority carrier diffusion length in the base region. A numerical technique was utilized which appears applicable to a nonuniform profile of diffusion length across the base region which would occur as a result of low energy proton damage.

The minority carrier concentration as a function of distance from the junction has been calculated for three different assumed values of diffusion length. The photovoltaic current was calculated for each of these values of diffusion length. The calculated current seems somewhat high compared to normally obtained short-circuit currents.

The analysis suggests that the characteristic voltage, defined as the coefficient in the exponential of the diode equation, is independent, both of temperature and radiation penetrating exposure. (The characteristic voltage is defined as $V_o = AkT/q$.) These results are in agreement with past experiments which show A to vary as the reciprocal of T, thereby making V_o independent of T. An analysis of published data shows that the reverse saturation current, I_o, tends to increase with radiation exposure, temperature, and light intensity. The temperature dependence is exponential, and appears to be independent of the irradiation history according to the published literature. The characteristic voltage appears to be also unaffected by radiation exposure.

PUBLICATIONS

Contractor Reports, Interim and Final

1. Barrett, M. J., and Straud, R. H., "Exotech First Quarterly Report, Proton-Induced Damage to Silicon Solar Cell Assemblies, a State-of-the-Art Survey," July 10, 1968.
2. Barrett, M. J., and Straud, R. H., "Exotech Second Quarterly Report, Effects of Uniform Damage to Silicon Solar Cells," October 10, 1968.

STUDIES OF RADIATION DAMAGE UNIVERSITY GRANTS

NASA Work Unit 120-33-01-18-55

JPL 320-34401-2-3420

E. C. de Wys

OBJECTIVE

JPL has been recently assigned the prime responsibility for administration of the NASA solar cell university development programs. The objective of this program is to stimulate university participation in the photovoltaic power source development effort. It is the intent of this program to contract work with universities which will contribute to both the educational and research activities of the university.

APPROACH

Contracts will be initiated with approximately seven universities during FY 69. Several of these programs will be essentially continuation of work initiated in past years when the responsibility for the program was with another NASA Center.

Programs will be primarily concerned with study of radiation degradation of solar cell power source assemblies, and improvement in the power conversion efficiency of solar cells.

STATUS

This is a new JPL program. All university contracts are administered under this work unit.

PUBLICATIONS

None

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RADIATION EFFECTS ON SOLAR CELLS WITH LITHIUM DOPING

NASA Work Unit 120-33-01-20-55

JPL 320-32001-2-3420

P. A. Berman
B. E. Anspaugh

OBJECTIVE

One of the major concerns in the use of silicon solar cells for space is that significant decreases in power can occur when the cells are subjected to irradiation by electrons and protons that exist in the Van Allen belts surrounding the earth, and proton flares that occur in deep space as the result of solar activity. For the past 10 years, considerable effort has been expended to develop solar cells with improved resistance to radiation exposure. Within recent years, work on cells with lithium doping has indicated that cells can be fabricated which exhibit considerable annealing from radiation damage at temperatures of 28°C or greater. This phenomenon could be of great significance if the effect can be reproducibly controlled, stabilized, and accurately predicted JPL is presently establishing an extensive program in the area of lithium-doped solar cells that involves many contracts with industry. To direct these programs effectively, it is mandatory that JPL maintain an intimate knowledge of the cell characteristics by means of an internal experimental program. The objective of this program is the determination of the radiation characteristics of lithium-doped silicon solar cells, with emphasis on annealing characteristics as a function of cell design.

ACTIVITIES

An extensive and continuous review of work in the field of lithium-doped silicon solar cells is presently being carried out. It is becoming increasingly apparent that, because of the effects of lithium-dopant concentration and the starting material on the resultant cell characteristics, it is quite likely that the optimum cell for a particular mission will have to be custom designed on the basis of the expected total fluence, flux density, and composition of the radiation (particle types and energy spectra). Hence, no one combination of crystal type and lithium concentration appears to be optimum when evaluated in terms of relative recovery rate, relative cell efficiency, and tendency to re-degrade. Highly-doped, float-zone material has the fastest recovery rate (which is most desirable), but yields the lowest relative cell efficiency, and has the highest tendency to re-degrade (both of which are undesirable characteristics). The medium-doped, crucible-grown cell design has the slowest recovery rate, but the highest relative cell efficiency, and the smallest tendency to re-degrade. The lightly-doped, float-zone cell is moderate in all three of these categories.

Approximately 600 lithium-doped silicon solar cells, having various concentrations of lithium introduced into the base region and being fabricated from silicon grown by various methods, have been measured at JPL in the X-25L solar simulator. The measurements were taken at an intensity and spectrum corresponding to air mass zero conditions at a cell temperature of 28° C. It appears that cells fabricated from crucible-grown material have higher efficiencies for similar lithium diffusion schedules than cells fabricated from either float-zone, Monex, or Lopex material. In general, it has been observed that the greater the lithium concentration in the base region of the cell, the lower the cell efficiency obtained.

A very considerable effort during this period has been expended towards making the JPL Dynamitron operational, and determining the uniformity of the beam.

PUBLICATIONS

Meetings and Symposia Papers

1. Berman, P. A., "Status of Lithium Solar Cell Development," Seventh Photovoltaics Specialist Conference, Pasadena, California, November 19-21, 1968.

RESEARCH AND DEVELOPMENT OF LITHIUM SOLAR CELLS

NASA Work Unit 120-33-01-21-55*

JPL 320-34601-2-3420

P. A. Berman

OBJECTIVE

One of the major concerns in the use of silicon solar cells in space is that significant decreases in power can occur when the cells are subjected to irradiation by electrons and protons that exist in the Van Allen belts surrounding the earth, and proton flares that occur in deep space as the result of solar activity. For the past 10 years, considerable effort has been expended to develop solar cells with improved resistance to radiation exposure. Within the past few years, work on cells with lithium doping has indicated that cells can be fabricated that exhibit considerable annealing from radiation damage at temperatures of 28°C or greater. This phenomenon could be of great significance if the effect can be reproducibly controlled, stabilized, and accurately predicted. The objective of this program is to develop and fabricate radiation-resistant, high-efficiency, lithium-doped silicon solar cells for space use.

ACTIVITIES

Three contracts have been awarded, one to each of the three major suppliers of solar cells, Texas Instruments Inc., Heliotek Division of Textron, and Centralab Division of Globe Union Inc., to perform this program. The use of three contractors will provide greater flexibility, opportunities for a greater number of experiments, opportunities for analysis of the effects of process and equipment variables, and assurance that successful cell designs can be duplicated by all three major solar cell manufacturers. These contracts were awarded to develop a program to determine the effects of process parameters upon solar cell electrical and mechanical characteristics, and to fabricate a minimum of 600 lithium-doped silicon solar cells. The investigation of process parameters that may influence solar cell performance will include such variables

*Note: The three contracts reported on in this review were initiated last year under Work Units 120-33-01-25-55, 120-33-01-26-55, and 120-33-01-27-55.

Methods of lithium vapor diffusion are also being investigated. Some problems which have been encountered has been to provide a suitable container for the heated lithium, and to protect the furnace tube from lithium vapor attack. Also, there is an uneven lithium distribution across the silicon surface due to flow patterns.

Introduction of lithium into the base region of the silicon solar cell is accomplished by heating the lithium-coated silicon in a furnace with an inert carrier gas flowing through the heated furnace tube. The carrier gas commonly utilized for this purpose is nitrogen. Heliotek has attempted to use helium as a carrier gas, and Centralab has attempted to use argon. In both cases, the cell efficiencies were found to be lower than those obtained when nitrogen was used as the carrier gas. In the case of argon, the surface concentration and penetration of the lithium was similar to nitrogen, but it was found that the brittleness of the silicon was increased which gave rise to greater cell breakage. In the case of helium, a rounding of the characteristic knee of the current voltage curve was found, giving rise to cells of lower efficiency.

Centralab has determined lithium concentration profiles for various lithium diffusion schedules by beveling the silicon slice, and utilizing two-point probe measurements in conjunction with empirically derived relationships between the measured resistivity and the majority carrier concentration. In general, the lithium profiles were not constant as a function of distance from the P/N junction. Generally, redistribution resulted, in a decrease in the lithium concentration near the back surface, the loss of lithium being more severe for higher redistribution temperatures. Attempts to minimize the back surface decrease in lithium concentration by utilization of a barrier layer of titanium-silver or silicon monoxide proved unsuccessful. However, the average lithium concentration within the body of the cell was slightly higher when such layers were utilized.

Heliotek was able to achieve more uniformity in cell efficiency by utilizing dummy slices during the boron junction diffusion operation, and dummy runs in the lithium diffusion operation to pre-condition the diffusion tube. They have also investigated the effects of a sintering operation on the titanium-silver contacts on solar cell power output. After the first sintering operation, a six percent decrease in short circuit current, and a drastic increase in series resistance as crystal-growth method, crystal resistivity, method of lithium introduction, and pre- and post-diffusion treatment.

Lithium solar cells have been fabricated by diffusing the lithium into N-type silicon. Prior to the introduction of the lithium, a P/N junction is formed in the silicon blank by diffusion of boron to a depth of approximately 3000 Angstroms, thus giving a P/N cell configuration. One of the original problems encountered with lithium-doped solar cells was an initial efficiency so low that, even when irradiated cells completely recovered their pre-irradiation electrical characteristics, they had lower power outputs than state-of-the-art cells similarly irradiated. Recently however, lithium-doped cells have been fabricated which have efficiencies approaching state-of-the-art N/P cells; namely, approximately 11% at air mass zero at 28°C.

One of the methods of introducing the lithium into the silicon is to utilize a paint-on source which consists of lithium powder suspended in an oil. After the lithium is deposited on the back surface of the cell, the cell is subsequently heated in a furnace to alloy the lithium and drive it into the silicon. The cell is then removed from the furnace, the lithium alloy region removed by etching, and the cell re-introduced into the furnace for additional heat treatment. This is termed redistribution since it redistributes the lithium within the base region, and changes the lithium concentration profile. The technique for painting the lithium-oil suspension onto the back surface of the cell is quite critical since thick layers can form spheres of lithium which cause the formation of large alloy pits when the lithium-coated cells are heated in the diffusion furnace. These alloy pits can yield large stresses which, in extreme cases, are of a sufficient magnitude to break the cell. Even when the paint-on layer is kept thin, it is still possible to get conglomerations of lithium, small pits, and possible stressing of the cell.

Some investigators have found that evaporation of the lithium onto the silicon works quite well as a diffusion source, while others have had difficulties with this process. Some of the problems encountered were leakage of the lithium to the front surface (i.e., the boron-doped diffused region), oxidation of the lithium during transfer of lithium-evaporated slices from the evaporator to the diffusion furnace, and a disappearance of the lithium from the back cell surface.

occurred. After a second sintering operation, a slight short circuit increase, and a large decrease in the series resistance were obtained. The cell maximum power, prior to sintering, was 24.3 mW, dropped to 21.5 mW after the first sintering operation, and increased to 24.7 mW after the second sintering operation. A third sintering operation resulted in an additional short circuit current increase, and an increase in series resistance. Thus, there appears to be some optimum sintering schedule which might improve cell characteristics beyond the unsintered case. An increase in short circuit current after sintering has also been observed on P/N cells when no lithium is present, and has been attributed to a gettering action.

In general, for similar lithium diffusion schedules, cells fabricated from crucible-grown material exhibit higher maximum power outputs than cells fabricated from either Monex or float-zone material.

PUBLICATIONS

Contractor Reports, Interim and Final

1. Payne, P., "Heliotek First Quarterly Report, Development of Lithium-Diffused Radiation Resistant Solar Cells," 15 July 1968.

2. Payne, P., "Heliotek Second Quarterly Report, Development of Lithium-Diffused Radiation Resistant Solar Cells," 15 July 1968.

3. Iles, P., "Centralab Semiconductor First Quarterly Report, Study of Lithium Doped Solar Cells," 15 August 1968.

4. Kendall, D. L., Fisher, J. K., "Texas Instruments First Quarterly Report, Lithium-Diffused Solar Cells," July 1968.

RADIATION DAMAGE IN LITHIUM-DOPED SOLAR CELLS

NASA Work Unit 120-33-01-22-55

JPL 320-34101-2-3420

P. A. Berman

OBJECTIVE

One of the major concerns in the use of silicon solar cells for space is the fact that significant decreases in power can occur when the cells are subjected to irradiation by electrons and protons that exist in the Van Allen belts surrounding the earth, and proton flares that occur in deep space as the result of solar activity. For the past 10 years, considerable effort has been expended to develop solar cells with improved resistance to radiation exposure. Within the past few years, work on cells with lithium doping has indicated that cells can be fabricated that exhibit considerable annealing from radiation damage at temperatures of 28°C or greater. Some major problems, however, exist with the lithium-doped cells, mainly in the area of long-term stability. The lithium ion is highly mobile in silicon, even at room temperature, and thus storage at room temperature and above can result in a redistribution of the lithium, especially near the P-N junction, and at the back surface. Cells stored for periods of time have shown changes in electrical characteristics and, in the case of irradiated cells which have exhibited annealing from radiation damage, re-degradation has occurred in some instances. The objective of this program is to study the properties of lithium-doped silicon, and to investigate the applicability of lithium and other dopants in the radiation hardening of silicon solar cells.

ACTIVITIES

JPL contracts have been awarded to RCA, TRW Systems, and Northrop Corporation, Northrop Corporate Laboratories. It has been found by RCA that lightly-doped lithium cells, having approximately 2×10^{15} lithium atoms/cm^3 near the junction, exhibit slow recovery (to approximately 4.5 mW/cm^2 after irradiation at a fluence of 10^{16} electrons/cm^2), while fast recovery is obtained from cells having 2 to 5×10^{15} lithium atoms/cm^3 near the junction (to a value of 5.2 mW/cm, which is typical of 10 ohm-cm N/P cells). Highly-doped lithium cells having concentrations at the junctions of 7 to 10 x 10^{15} lithium atoms/cm^3 show fast recovery, but exhibit re-degradation. Re-degradation simply means that the cells recover all, or a portion of their electrical characteristics after irradiation, but, subsequently, the electrical characteristics degrade once again during post-irradiation storage.

Generally, RCA has found that lithium-doped cells fabricated from float-zone material recover 80 to 90% of their electrical power within several hours to several days after irradiation with a slower recovery of about 10 to 20% over a period of several weeks to several months. A period of three to six months storage at room temperature after irradiation appears to be a critical time for cells fabricated from float-zone material, after which the cells either remain stable or re-degrade. A similar sequence of events is also found for cells manufactured from Lopex material which is essentially float-zone material with a low dislocation content. Lithium-doped solar cells, diodes, and bulk material are being irradiated at temperatures from 79°K to 180°K. This should be very useful in observing the interaction of the radiation-induced defects with lithium as the samples are raised in temperature. The lattice vacancy induced by radiation (Frenkel defect) is mobile at approximately 77°K, while the lithium should be relatively immobile at temperatures below 260°K. After room temperature annealing, new carrier removal defect energy levels are formed. The production rate of carrier removal defects is reduced at low irradiation temperatures, the ratio of carrier removal at 250°K to 79°K being approximately 13. The carrier removal defect in float-zone material appears to be unstable at room temperatures, and exhibits spontaneous annealing approximately 2 hours after irradiation. Results of these investigations show that in float-zone material, the defect contains lithium but no oxygen while in crucible-grown material, the carrier removal defect contains lithium and oxygen. TRW has also observed significant differences in the nature of the carrier removal process between irradiated float-zone and crucible-grown lithium-doped silicon. There is a difference in both the annealing behavior and the majority carrier removal rate. Float-zone material, heavily doped with lithium, exhibits changes in majority carrier concentration which are exponentially related to the fluence. Lithium-doped, crucible-grown silicon exhibits majority carrier concentrations which are linearly related to the fluence. The production rate of defects for lithium-doped, crucible-grown material appears to be constant and independent of the lithium concentration in contrast to the defect production rate in lithium-doped float-zone material which appears to be proportional to the remaining ionized concentration. These observations might indicate that defects formed in crucible-grown material involves oxygen rather than lithium.

Isochronal annealing studies performed by TRW indicated a rapid annealing stage in lithium-doped float-zone material having a resistivity of 0.1-ohm centimeters at 175°C. It was possible to fit the data by assuming a first order process, the time constant of which is limited by an activation energy of 0.32 Ev. This annealing stage restored approximately 40% of the carrier removal damage, the remainder being stable to a temperature of 350°C. Attempts to anneal at higher temperatures were inconclusive due to the out-diffusion of the lithium at these temperatures. A negative annealing stage, that is the formation of additional carrier removal defects, was observed on samples of lithium-doped, crucible-grown, and float-zone silicon at a temperature of 100°C. This reverse annealing damage was removed after annealing at 150°C.

Raising the temperature of lithium-doped silicon above 300°C with a subsequent cooling to room temperature results in an increase in resistivity. This could be caused by either precipitation of the lithium, or lithium out-diffusion. To more fully investigate this, TRW has used Lang X-ray topography to search for stressed areas which would increase X-ray reflection. These stressed areas might be indicative of lithium precipitation. The resolution obtained by this technique is less than 10 microns. Hence, no strained areas have been observed as a result of heating and cooling lithium-doped silicon samples. It is still possible, however, that lithium could precipitate at dislocation sites which are already strained, thus resulting in little change in X-ray reflection.

Investigations into the applicability of lithium-aluminum hydride as a diffusion source for lithium are being pursued by TRW. There is a difficulty in getting a uniform coat of the lithium on the cell surface, and the lithium aluminum hydride easily oxidizes. Hence, surface concentrations of greater than 10^{17} lithium atoms/cm^3 have been unattainable. The lithium-aluminum hydride, however, exhibits no physical attack on the silicon surface which is normally observed with the oil-based paste oftentimes used by solar cell manufacturers as a lithium diffusion source. Moreover, the residue is easily removable.

Studies by RCA have indicated that re-degradation seems to be most severe after a fluence of 10^{14} electrons/cm^2. Fluences of 10^{15} and 10^{16} electrons/cm^2 give rise to poorer (i.e., slower and possibly incomplete) recovery, but less re-degradation. The magnitude of re-degradation can range from negligible to very severe. At this time, cells fabricated from float-zone material seem to be somewhat less prone to re-degradation than cells fabricated from Lopex material while cells fabricated from crucible-grown material show negligible re-degradation after 18 months. Cells with good, long-term stability after an irradiation of 10^{14} electrons/cm^2 are usually very lightly doped with lithium. Thus, it appears that for cells fabricated from float-zone and Lopex material, the greater the lithium concentration, especially in the region near the P/N junction, the greater the probability of re-degradation.

A literature survey has been made by Northrop Corporate Laboratories to survey the practicality of using dopants other than lithium for improving the radiation resistance of silicon. Prime emphasis was placed on factors such as solid solubility, diffusibility, and action as a recombination center. The dopants surveyed were lithium, sodium, potassium, beryllium, magnesium, calcium, sulphur, fluorine, bromine, chlorine, oxygen, and aluminum. In many cases, little or no information was available. This was especially true for fluorine and bromine. Likely candidates for silicon dopants were sodium, beryllium, and oxygen for N-type silicon, and aluminum chlorine and oxygen for P-type silicon. All of the crystals to be used in this study have been received by Northrop and preliminary minority carrier lifetime measurements have been made.

The silicon samples containing excess oxygen, in addition to the normal phosphorus and boron dopants, sodium-doped samples and aluminum-doped samples having high and low oxygen contents, exhibited reasonably long minority carrier lifetimes and would be suitable for further study. The chlorine and beryllium-doped silicon ingots were unsuitable, the beryllium-doped crystal having a very low minority carrier lifetime (of the order of 0.2 microsecond), and the chlorine-doped sample having an extremely high resistivity (2.8×10^4 ohm/cm). Attempts were made to heat treat the beryllium-doped ingot at 700°C to increase the resistivity (which was 0.86 ohm-cm) and minority carrier lifetime. While large resistivity changes were obtained, the desired lifetime improvement was not forthcoming.

Samples from seven of the crystals were irradiated with 2 MeV electrons to study lifetime degradation and recovery. Greater degradation was observed on samples containing excess oxygen as an added impurity. This is in direct contrast to results previously obtained on samples irradiated with 10 MeV electrons which showed greater minority carrier lifetime degradation in oxygen-lean samples. The silicon samples doped with aluminum, and having a low oxygen concentration (float-zone material), exhibited much less lifetime degradation than any of the other samples, including boron-doped, crucible-grown material which is commonly used in the fabrication of solar cells. These results are extremely encouraging, although more samples must be investigated to provide some measure of statistical validity to the apparent superiority of aluminum-doped, float-zone silicon. Six of the samples were isochronally annealed between temperatures of 72°C and 253°C. The results indicated that lifetime recovery, subsequent to exposure to 2 MeV electrons, is strongly dependent upon the impurities in the sample. Phosphorus and boron-doped samples containing excess oxygen exhibited little or no lifetime recovery after annealing at 253°C while samples containing the same dopants, but less oxygen, exhibited partial recovery. One aluminum-doped oxygen-lean (float-zone) sample exhibited almost complete recovery.

Samples were exposed to gamma rays obtained through utilization of a Co^{60} source, annealed and re-irradiated. The samples were then re-annealed, and it was observed that the residual damage was dependent upon the dose received in the first irradiation (e.g., the total dose). Less than 1% of the lifetime damage produced in the first irradiation was evident after the first anneal. These results might indicate that attempts to provide moderate temperature annealing cycles for solar cells in a radiation environment may have limited success.

PUBLICATIONS

Contractor Reports, Interim and Final

1. Brucker, G. J., Faith, T. J., and Holmes-Siedle, A. G., "RCA First Quarterly Report on Action of Lithium in Radiation Hardened Silicon Solar Cells," August 15, 1968.

2. Brucker, G. J., Faith, T. J., and Holmes-Siedle, A. G., "RCA Second Quarterly Report on Action of Lithium in Radiation-Hardened Silicon Solar Cells," November 15, 1968.

3. Faith, T. J., Brucker, G. J., Holmes-Siedle, A. G., and Wysocki, J., "Long Term Stability of Lithium-Doped Solar Cells Irradiated with Electrons, Protons or Neutrons," 1968 IEEE Photovoltaic Specialist Conference, Pasadena, California, November 19-21, 1968.

4. Brucker, G. J., "Electrical Studies of Electron-Irradiated Lithium-Containing N- Types Si," 1968 IEEE Photovoltaic Specialist Conference, Pasadena, California, November 19-21, 1968.

5. Brucker, G. J., "Injection Level Effects in Irradiated, Lithium-Containing Solar Cells," IEEE Photovoltaics Specialist Conference, Pasadena, California, November 19-21, 1968.

6. Carter, J. R., and Scott, R. E., "TRW Systems First Quarterly Report, Study of Radiation Effects in Li-Doped Silicon Solar Cells," August 15, 1968.

7. Downing, R. G., Carter, J. R., and Van Atta, W. K., "TRW Systems Second Quarterly Report, Study of Radiation Effects in Li-Doped Silicon Solar Cells," November 15, 1968.

8. "Northrop Corporate Laboratories Quarterly Report, Effects of Impurities on Carrier Lifetime in Bulk Solar-Cell Material," August 1968.

9. "Northrop Corporate Laboratories Quarterly Report, Effects of Impurities of Impurities on Carrier Lifetime in Bulk Solar-Cell Material," November 1968.

LOW FLUX RATE RADIATION DAMAGE IN LITHIUM SOLAR CELLS

NASA Work Unit 120-33-01-23-55

JPL 320-34501-2-3420

E. C. de Wys

OBJECTIVE

Lithium-diffused solar cells offer a potential technique to improve the radiation resistance of photovoltaic power sources. Early and preliminary investigations have indicated that the degree of radiation resistance is a function of cell construction, type of damaging particle, and radiation rate sensitivity. It is the purpose of this program to investigate the rate sensitivity of radiation degradation to lithium solar cells.

APPROACH

Lithium solar cells of various configurations will be exposed to low flux-rate exposure to energetic particles. The performance of the solar cells will then be evaluated as functions of temperature of the cell under irradiation and cell physical characteristics. It is proposed that initial experiments be conducted using a radioactive isotope as a source of Beta particles, and the flux rate will be representative of that experienced by spacecraft in near-earth orbit.

STATUS

This is a new program and work has not been formally initiated.

PUBLICATIONS

None

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FILTERS FOR NEAR-SUN MISSIONS

NASA Work Unit 120-33-01-24-55

JPL 320-31501-2-3420

D. W. Ritchie

OBJECTIVE

The objective of this program is the development of partially reflecting filters to be employed on solar cell panels for spacecraft destined for near-sun missions. The purpose of the filters is to limit the effective incoming intensity so that the resulting maximum equilibrium panel temperature at Mercury encounter of 0.44 AU will be less than 120°C. Since this approach to panel thermal control is passive, the reliability of such missions is judged to be much greater over approaches using mechanical concepts such as window shades, louvers, etc.

INTRODUCTION

A method for controlling the operating temperature of a photovoltaic array at a sun-probe distance of 0.44 AU is the use of selective control coatings. At present, the thermal properties of the solar array have been optimized for only back-side emittance. Absorbence and reflectance of the front side emittance has been optimized for electrical and filtering mounting adhesive considerations. This effort is being directed to attempt filter optimization for electrical and thermal considerations. Narrow-band-pass filters are being considered in this approach.

The narrow-band-pass filter operates on the principle of rejecting light wavelengths to which the solar cell is not, or only slightly, sensitive. Light to which the cell is most sensitive is transmitted. The rejection of light to 5000 mu is necessitated by the fact that, at the present mission parameter (Mercury encounter at aphelion, 0.44 AU), 165 mw cm^{-2} of light energy with wavelengths from 1100 to 5000 mu impinges on the panel surface. This light contributes nothing to cell power conversion, only to panel temperature, and must be rejected to comply with the 120°C panel temperature limitation. The rejection of violet and UV radiation from the UV limit of the sun's spectrum to 500 mu is necessary to prevent darkening of the filter adhesive.

PROGRESS

Sample quantities of narrow-band-pass type filters have been procured. These filter types are similar in design to the band-pass filters used on the NASA-Ames program. The filters have not been optimized for the constraints of this program. These sample filters were obtained to perform tests in an equilibrium chamber to substantiate or amend the theoretical temperature equation. To date, three sample assemblies have completed testing, and data is being analyzed. Preliminary results substantiate theoretical equations.

PUBLICATIONS

None

SOLAR CELL RADIATION FLIGHT EXPERIMENT

NASA Work Unit 120-33-01-31-55

JPL 320-35301-2-3420

B. E. Anspaugh

OBJECTIVE

The objective of the Solar Cell Radiation Flight Experiment, scheduled for launch on the ATS-E spacecraft, is to determine the effect of the synchronous orbit radiation environment on selected solar cell/coverslide configurations. The experiment is designed to provide high accuracy data on the entire I-V curve of each solar cell. A supplemental extensive ground test program is concurrently in progress which is designed to predict the behavior of the cells on the experimental package, and to furnish information which will allow an optimization of the experimental design.

ACTIVITIES

Hughes Aircraft Company (HAC) has been contracted (JPL Contract 952351) to build the experimental apparatus, and to assume a large portion of the effort in implementing the ground test program and flight data analysis. HAC is the prime contractor for building the ATS-E satellite, and interfacing the experiment with the spacecraft has proceeded smoothly.

The experiment consists of the following components: (A total of 80 solar cells (2 x 2 cm) will be flown. Twelve I-V pairs will be obtained from each cell upon activation of the experiment by ground command.)

(1) A rigid solar panel tangentially mounted to the spacecraft containing five each of 13 types of solar cells (total of 65 cells), and 13 thermistors.

(2) A flexible solar panel mounted radially to the spacecraft. Panel substrate will be a kapton-fiberglass sandwich 2 mils thick. Five each of three types of solar cells (total of 15 cells), and three thermistors will be mounted. This panel is designed to investigate

the effect of radiation on the back cell surface, and to discover the potential problems which will be encountered in the design of large area flexible arrays.

(3) Two signal processor units which sequentially select the solar cells and load resistors, and process the signal into the format for telemetry via the ATS-E encoders. Each processor handles half the cells.

(4) A spacecraft payload regulator.

ACCOMPLISHMENTS

The following project milestones have been passed:

(1) Completion of signal processor breadboard fabrication and evaluation testing.

(2) Completion of the ultraviolet and thermal cycling phases of the ground test program.

(3) Completion of solar cell fabrication and calibration tests prior to electron and proton radiation tests.

(4) Completion of solar panel, installation design, and interface specification.

(5) Receipt of all critical components.

As scheduled, the experiment will be acceptance tested and delivered to the spacecraft assembly area on January 31, 1969.

PUBLICATIONS

None

LUMINESCENT AND TUNNELING PHENOMENA IN IRRADIATED SILICON

NASA Work Unit 120-33-01-32-55

JPL 320-35401-2-3420

E. C. De Wys

OBJECTIVE

The objectives of this program are (1) a study of the type and nature of electron transitions in the energy band structure of single crystalline, lightly-doped silicon, and (2) a study of the behavior of electrons in the impurity bands in heavily-doped silicon. Both of these studies will be performed as a function of irradiation, and as a function of types of impurities. It is anticipated that, by a more thorough understanding of electron behavior in irradiated silicon, a better understanding of the interactions of radiation induced defects with the silicon lattice and existing impurities will be obtained.

APPROACH

The intended approach will be the detailed examination of the luminescent spectra that are observed in irradiated silicon. The investigations will include the following:

(1) The influence of lithium as the sole impurity upon the luminescent spectra that are observed in irradiated silicon.

(2) The nature of the luminescent spectra at high spectral resolution and its dependence upon lithium and oxygen, and donor or acceptor impurities in combination.

(3) The correlation of the annealing temperature for the loss of luminescence in silicon with the measurements of minority carrier lifetime and Hall effect in lithium-doped and pure silicon.

(4) Interpretation of the luminescence spectra with the object of determining the type of electron transitions causing the photon or phonon emissions in the spectra.

(5) The use of uniaxial stress for the determination of the symmetry of the defects involved in the recombination process in lithium-doped, or in pure silicon.

In highly-doped silicon, the investigation of the use of high electron density tunneling as a feasible technique for the examination of the properties of the impurity band states will be performed. The work will include the following:

(1) A detailed study of the tunneling conductance between a superconductor and silicon with the intent of determining the density of states of the impurity band.

(2) Irradiation of the semiconductor to determine the effectiveness of the above technique for measuring the properties of radiation-induced defects in the barrier region.

PROGRESS

A contract (952383) has been awarded to the University of Illinois, and the research has just begun.

PUBLICATIONS

None

RADIATION KINETICS IN ELECTRONIC MATERIALS

NASA Work Unit 120-33-01-33-55

JPL 320-35501-2-3420

E. C. De Wys

OBJECTIVE

The objective of this work unit is to achieve theoretical understanding in mathematical terms of the nature, and the rate of production and annealing, of radiation damage in doped and undoped silicon.

APPROACH

The approach consists of the following:

(1) Mathematical formulation of models on the basis of the published Waite's equations for defect production and annealing with physical interpretation of the consequences.

(2) The theoretical treatment of the effect of lithium and oxygen, as well as clustering, on the annealing rate. Consideration of the charge state of the reactant will be included. In addition, the effects of irradiation of dose rate will be investigated.

The final results will be compared with the Tanaka equation and published actual experimental results.

STATUS

This program is new and presently is in the final contract negotiation stage.

PUBLICATIONS

None

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EFFECTS OF SUB-THRESHOLD HIGH ENERGY ELECTRONS ON SILICON CELLS

NASA Work Unit 120-33-01-34-55

JPL 320-35601-2-3420

E. C. De Wys

OBJECTIVE

The objective of this task is to study the effects of high energy (> 50 KeV) electrons on the properties of silicon.

APPROACH

The experiments will be performed in an organic vapor-free vacuum provided by sorption pumps and ion pumps.

The first purpose of the investigation will be to establish the effects of electrons, whose energy is too low to produce bulk displacements, on the surface recombination properties of silicon. An attempt shall be made to separate those effects which are caused by changes in surface potential from effects which are caused by changes in the concentrations of recombination sites on the surface. In this part of the program, radiation-induced changes of surface conductance will be used to determine the changes in surface recombination velocity. Silicon samples, both n- and p-type with various concentrations of donor or acceptor impurities (10^{15}, 10^{16}, and 10^{17}/cc) with ohmic contacts, will be the subjects of these experiments. The samples will be thin ($\gtrsim$0. 010 in.). Their shape will be such as to produce a large ratio of surface conductivity to bulk conductivity. These samples will be irradiated by 50, 100 and 140 KeV electrons to test the dependence of these effects on electron energy.

These experiments shall be repeated on n-type lithium-doped silicon samples with lithium concentrations in the range 10^{15} to 10^{17}/cc. Differences in behavior between lithium-containing and lithium-free samples and, in particular, changes in bulk properties which may result from displacement of lithium ions will be investigated. Lithium is much lighter than silicon (lithium has an atomic weight of ~6; silicon, ~14) and, therefore, it is possible that bulk effects associated with displacement of lithium atoms may be observable when the lithium-doped silicon is irradiated with electrons whose energy is substantially below the energy electrons needed to displace a silicon atom, namely 150 keV. Special effects of radiation on surface properties of lithium-doped samples will also be evaluated.

If the experiments based on conductivity show that the threshold for bulk damage in silicon containing lithium differs from the threshold of silicon without lithium, experiments on lithium-doped silicon photovoltaic cells would be performed to determine whether the lower thresholds also apply to the defects which control lifetime in silicon. An analysis of variance will be performed on this design of experiments to carefully prove significance of any observed differences. At least 5 repeat samples will be in each design of experiment matrix.

PROGRESS

Contract negotiations are in the final phase.

PUBLICATIONS

None

INVESTIGATION OF THE OPTICAL PROPERTIES OF IRRADIATED SILICON

NASA Work Unit 120-33-01-35-55

JPL 320-35701-2-3420

E. C. De Wys

OBJECTIVE

The objective is to characterize the imaginary and real components of the complex index of refraction of the doped and undoped silicon substrate as well as the thickness and refractive index of the oxidation film on the silicon substrate.

APPROACH

The approach consists of the following:

(1) A study of the refractive indices n and k as well as the value for R for solar cell quality silicon in the region of 0.4 to 1.1μ wavelengths; i.e., the values of n, k, and R will be given for certain distinct wavelengths within this region.

(2) Determination of the changes in the above optical properties in silicon subjected to the conditions indicated by the matrix indicated in Table 1.

Table 1. Design of Experiments

Fluences Particles/cm^2	Particles	Electron Energies			Proton Energies.
		1 MEV	2 MEV	3 MEV	6 MEV
	10^{14}				
	10^{15}				
	10^{16}				

STATUS

This project is new, and is in the final contract negotiation stage.

PUBLICATIONS

None

SOLAR CELL RESEARCH

NASA Work Unit 120-33-01-36-55

JPL 320-35801-2-3420

P. Berman

OBJECTIVE

One of the major concerns in the utilization of silicon solar cells for space use is the fact that significant decreases in power can occur when the cells are subjected to irradiation by electrons and protons which exist in the Van Allen Belts surrounding the earth, and proton flares which occur in deep space as the result of solar activity. For the past ten years, considerable effort has been expended to develop and characterize solar cells with improved resistance to radiation exposure.

Another major concern is the prediction of solar cell performance in various space environments (e. g. , various combinations of temperature and solar intensity). This involves more complete characterization of solar cell parameters. The objective of this program is to determine the effects of space-type environments such as radiation, temperature, and solar intensity on the operating characteristics of state-of-the-art and developmental-type solar cells.

ACTIVITIES

A contract has been awarded to the Naval Research Laboratory in the amount of $200, 000 for a program to characterize solar cell parameters as a function of radiation environments, and also as a function of other space-type environments such as various temperature and solar intensity levels. Both state-of-the-art N/P-type silicon cells and developmental cells such as lithium-doped P/N silicon cells will be included in these investigations. A continuous evaluation of work being performed by others in the field will be carried out throughout the program.

In the course of this program, the contractor is (1) to investigate the non-uniform damage resulting from exposure to low energy radiation particles which come to rest within the solar cell, (2) to explore improved methods of characterizing solar cell parameters, (3) to develop radiation damage models for solar cells, (4) to investigate the characteristics of lithium-doped silicon solar cells as a function of irradiation, and the mechanisms involved in radiation damage annealing, (5) to study annealing effects in irradiated non-lithium-containing state-of-the-art solar cells, (6) to investigate improved silicon solar cell contacts, and (7) to update and modify the existing "Handbook of Space Environmental Effects on Solar Cell Power Systems" in order to make this document more directly applicable to the engineering design of space solar cell power systems.

An initial report indicating the milestones and defining the tasks to be performed will be prepared by the contractor. Work will be initiated on the investigations previously discussed.

PUBLICATIONS

None

INVESTIGATION OF THE STRUCTURE OF RADIATION DAMAGE IN LITHIUM DIFFUSED SILICON SOLAR CELLS

NASA Work Unit 120-33-01-37-55

JPL 320-35901-2-3420

E. C. De Wys

OBJECTIVE

The objective of this work unit is to study the radiation-produced defect structures in lithium-doped solar cells.

APPROACH

The experimental approach is indicated by the design of experiments indicated in the matrix table below. The electron fluences are also indicated.

The experimental testing will include infrared spectroscopy, 1 to 50 microns, and photoconductivity, 0.5 to 10 microns, with associated annealing experiments. The photoconductivity spectra will be measured at 87°K, the infrared spectra at 78°K and 300°K, and the annealing temperatures in the 50°C to 500°C range. The matrix will be subjected to a complete analysis of variance. The results will be interpreted in terms of actual lattice defects, energy gap characteristics, and the role of lithium concentrations with respect to the degree of radiation damage.

Table

Li conc.	F.Z.$^{+}$	Q.C.$^{++}$	1.5, 3 and 5 MeV Electron Fluences e/cm^2		
$\sim 10^{15}$ cm^{-3}	1 and 10 Ω-cm	1 and 10 Ω-cm	$\sim 10^{14}$	$\sim 10^{15}$	$\sim 10^{16}$ *
$\sim 10^{16}$ cm^{-3}	1 and 10 Ω-cm	1 and 10 Ω-cm	$\sim 10^{14}$	$\sim 10^{15}$	$\sim 10^{16}$ *
$\sim 10^{17}$ cm^{-3}	1 and 10 Ω-cm	1 and 10 Ω-cm	$\sim 10^{14}$	$\sim 10^{15}$	$\sim 10^{16}$ *

$^{+}$F.Z. = Floating-Zone silicon, phosphorous-doped
$^{++}$Q.C. = Quartz-Crucible silicon
$^{*}\geq 10^{17}$ e/cm^2 for IR Spectroscopy

STATUS

This program is new, and contract negotiations are in the final phase.

PUBLICATIONS

None

PHOTOVOLTAIC ARRAY STRUCTURE TECHNOLOGY

NASA Work Unit 120-33-01-38-55

JPL 320-36201-2-3420

D. W. Ritchie

OBJECTIVE

To provide potential growth to the Mariner spacecraft, a design, utilizing applicable lightweight solar array technology developed under NASA work unit 120-33-01-02-55, will be undertaken. The hardware designed and developed under this program will provide an important step toward the potential integration of lightweight solar array technology into the Mariner class vehicle.

INTRODUCTION

A detail design, fabrication, and test program will be initiated using design and specification requirements of the Mariner 71 spacecraft. Close coordination between development efforts and project requirements will be pursued to an extent that hardware substitution could be undertaken.

PROGRESS

This is a new task initiated in December. A statement of work has been initiated and awaiting contractor response. A contracted effort is expected to be initiated by March 1969.

PUBLICATIONS

None

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MERCURY-VENUS FLYBY SOLAR ARRAY

NASA Work Unit 120-33-01-39-55

JPL 320-36101-2-3420

D. W. Ritchie

OBJECTIVE

The objective of this program is to develop photovoltaic array technology for near-sun missions (sun-probe distance 0.6 - 0.3 AU) using realistic mission constraints.

INTRODUCTION

Present day technology limits solar array design to a maximum operating temperature of approximately 150°C at intensities of 400 mw/cm^2. This design limitation is imposed mainly by the upper operating temperature of the solar cell. Using constraints of a typical Mercury-Venus flyby mission, techniques of thermal control of array systems will be analyzed to establish feasibility of performing these type missions with conventional silicon cells. Limited testing will be performed to establish supporting data on potential approaches.

PROGRESS

This is a new program and plans are being finalized. Efforts are expected to be fully underway by February 1969.

PUBLICATIONS

None

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EFFECT OF SPACE PARTICLE BOMBARDMENT ON SOLAR CELL MATERIALS

NASA Work Unit 120-33-01-40-55

JPL 320-36301-2-3420

E. C. De Wys

OBJECTIVE

The objective of this task is to determine the nature of the surface and bulk defects in irradiated, doped and undoped, float-zone and pulled silicon.

APPROACH

The experimental approach is indicated by the following matrix:

PROTONS

Type of Silicon	Li-Doping Level (Li/cm^3)	100 eV			5 MeV			10 MeV			30 MeV			100 MeV		
		10^{12}	10^{13}	10^{14}	10^{12}	10^{13}	10^{14}	10^{12}	10^{13}	10^{14}	10^{12}	10^{13}	10^{14}	10^{12}	10^{13}	10^{14} P/cm^2
Float Zone	0				X		X	X		X	X		X			
	10^{15}															
	10^{16}															
	10^{17}				X		X	X		X	X		X			
Pulled	0				X		X	X		X	X		X			
	10^{15}															
	10^{16}															
	10^{17}				X		X	X		X	X		X			

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The irradiated samples will be subjected to various heat treatments to determine the thermally-induced recovery processes. The purchased solar cells in the as-received condition, and after irradiation, will be sectioned into samples of suitable size for X-ray diffraction and topography, electron metallography, transmission electron microscopy, and electron diffraction.

X-Ray Analysis

A determination of the average density of irradiation defects will be made by X-ray line broadening measurements. The point-to-point variation in the directions, or the intensities of X-rays diffracted from radiation-damaged solar cells, will provide an overall image of the defect structure of the specimens. Both the Berg-Barrett method for surface investigations and the Lang method for studies of lattice defects in the bulk of the specimens will be used.

Etch-pit Techniques

The samples will be etched according to procedures specifically suited for silicon semiconductors, and investigated by light microscopy and electron microscopy of replicas to determine the density and nature of surface defects.

Transmission Electron Microscopy

To determine the nature, distribution and interaction of radiation-induced defects in the bulk solar cell materials, high-resolution transmission electron-microscopy and electron diffraction will be used extensively. Thin films, suitable for this technique, will be prepared from the bulk samples by chemical etching and polishing. The profile of the defect damage will be determined by examining sections of specimens at different levels.

Electron Probe Microanalysis

Radiation-induced diffusion processes, particularly of the contact materials of the irradiated solar cells, will be studied by electron probe microanalysis using X-ray line and area scans.

Electrical Measurements

Bulk damage and defect production will be determined by measuring changes in electrical resistivity. A particularly promising approach would be to make measurements *in situ* while the sample is being bombarded. Post-irradiation annealing studies will permit further characterizing of the defects produced. Changes in the electrical properties of the surface will be measured using RF conductivity techniques. The diode characteristics of the irradiated solar cells will be evaluated with particular emphasis on minority carrier life-time, diffusion lengths, damage coefficient, and I-V curve characteristics.

Optical Spectroscopy

Further characterization of the bombarded solar cell materials will be made by optical spectroscopy (i. e., recording of absorption and emission spectra in the visible, infrared and ultraviolet regions). This would allow a determination of the band gap and impurity levels, and the detection of the electrical defect centers such as divancies, A centers and E centers.

PROGRESS

Contract negotiations are in the final phase.

PUBLICATIONS

None

SOLAR THERMIONIC DEVELOPMENT

NASA Work Unit 120-33-02-01-55

JPL 320-30201-2-3420

O. S. Merrill
P. Rouklove
G. Stapfer
F. de Winter

OBJECTIVE

The objectives of this program include the development and evaluation of improved thermionic converters, the design, procurement, and evaluation of multiconverter generators, the parametric evaluation of converters and generators, the evaluation of new converter accessories such as heat pipes and gas additives, and the life testing of converters and generators.

PROGRESS

Diode With Heat Pipe Collector

The effort, under JPL Contract No. 951263 with Thermo Electron Company which was redirected to develop converters using a heat pipe as a collector-radiator assembly and heat rejection medium, was successful. Converter No. T-210 developed a power density of 22 W/cm^2 of emitter area, or 50 watts total power output at 0.7 volt. The weight of the converter was reduced from 376 grams to 110 grams with the employment of the heat pipe. The design of the multiconverter generator, including the new type of converters, has been finalized. A final report on the effort is now in preparation.

Six Converter Generators, JG-4

The laboratory performance tests of generator JG-4 have been completed. Low resistance between the converter emitter and the mounting flange caused the mounting block to be directly bombarded by the electron gun. This resulted in excessively high seal and collector temperatures which prevented the achievement of the design performance goals.

After the completion of the laboratory tests, the generator was installed in the vacuum system of the Table Mountain Solar Facility. The instrumentation wiring of the generator had to be reworked to prevent the shorting of wires as the generator rotated during solar tracking. The initial outgassing and the testing of the generator is scheduled to begin January 1, 1969, and should be completed by April 7, 1969.

Converter Life Tests

Six life-test stations were operated during this reporting period. Converter SN-101 presently exceeds a total operating time of 12,000 hours at an average emitter temperature of 2,000°K. The metallurgical examination results of five previously life-tested converters were published by the Materials Section (351). A new solenoid coil, to operate the electrically activated viewport shutters, was designed and incorporated into the stations.

A fully-automated, multichannel data-recording system has been successfully incorporated to aid in the acquisition of the life-test data. The data, which is printed on cards, is inserted into a computer program for reduction and tabulation. A report on the operation of this computer program has been written and released.

Analytical and Experimental Description of Parabolic Solar Concentrators

Experiments were performed to determine the energy distributions close to the focal point which were produced by a 9-1/2 foot diameter, 69-inch focal length parabolic concentrator. This mirror, of electro-formed nickel, is to be used in conjunction with the 6-converter generator.

The heat flux close to the focus was determined by photographing a special propeller blade on which the energy was incident. By controlling the propeller configuration and surface finish, position, RPM, and film exposure and development parameters, the heat flux could be determined from film negatives with a densitometer device. The heat flux distributions obtained were in close agreement with the analytical description of the mirror, and with the Hartmann optical tests made on the mirror.

There is an optimum position, along the mirror axis, for the 6-converter generator, where the energy distribution inside of the generator cavity will provide the highest efficiency. Both the analytical and experimental work on the parabolic mirror indicate that this position is 69.6 inches rather than 69.0 inches (the focal length) from the mirror. Again agreement was excellent. Final reports and papers covering this work are in preparation.

Applied Thermionic Research

This effort was previously reported as a separate task (NASA Work Unit 120-33-02-05-55). However, for FY 69, it was supported under the Solar Thermionic Development task and is included under this heading. The reader is referred to the previous semi-annual report for a statement of the objective and approach.

The effort has been performed under JPL Contract No. 952184 with Thermo Electron Corp, Waltham, Mass. It was completed in December 1968, but the final report has not yet been published.

The principal results achieved during this reporting period were as follows:

(1) The obtaining of thermochemical and mass spectrometric data on cesium oxide to evaluate it as a source of oxygen to act as an electro-negative additive.

(2) A theoretical study resulting in a rigorous definition of the electronegativity of atoms and of atomic orbitals.

(3) The obtaining and analysis of parametric data using two variable-spacing, guard-ring laboratory test converters. One had a single crystal tungsten emitter, the other a chloride vapor-deposited tungsten emitter deposited over a fluoride vapor-deposited tungsten substrate. Both converters employed molybdenum collectors. The data were used to investigate the dependence of the voltage drop on the product of the cesium pressure and the interelectrode spacing, Pd, on the cesium pressure, P, and on the ion richness, β. A dependence on cesium pressure was observed at constant values of Pd and β.

(4) A continuing examination of the micro-structure and preferred orientation of vapor-deposited tungsten emitters after exposure to various heat treatments.

(5) The design, fabrication, and use of a device for measuring bare vacuum work functions of prospective cathode materials.

Advanced Thermionic Development

This effort was previously reported as a separate task (NASA Work Unit 120-33-02-06-55). However, for FY 69, it was supported under the Solar Thermionic Development task and is included under this heading. The reader is referred to the previous semi-annual report for a statement of the objective and approach.

This effort is being performed under JPL Contract No. 952217 with Electro-Optical Systems, Inc., Xerox Company, Pasadena, California. The principal results achieved during this reporting period were as follows:

(1) The single-crystal rhenium sample contained facets of several different crystal faces and was not suitable for its intended use. Consequently, the planned variable spacing test vehicle, and two planar converters with single crystal rhenium electrodes, were not built. Also, since the work function of the single-crystal rhenium sample was no better than that of poly-crystalline rhenium, no further effort is planned on the single-crystal rhenium. This effort has been replaced by the surface characterization of several exotic refractory alloys, (e.g., tungsten/rhenium, tungsten/osmium, tungsten/iridium, and tungsten/tantalum).

(2) A variable-spacing test vehicle with tungsten/20 to 25% rhenium electrodes is being fabricated. In addition, one planar converter and one cylindrical converter are being fabricated to demonstrate correspondence of performance among the three units. Both of the fixed-spacing converters are being built with a 10-mil spacing, and will be operated at an emitter temperature determined by the use of data from the variable spacing test vehicle, that will yield maximum performance.

(3) A fixed-spacing cylindrical converter, with a 6-mil interelectrode spacing and vapor-deposited rhenium electrodes, has been fabricated and tested. It has a 2.0 cm^2 emitter area and a 1.88 cm^2 collector area which is identical to a previously built fixed-spacing planar converter. Its performance at 1800°K agreed to within approximately 1% with its predicted performance. A second identical unit is being fabricated. Two additional units designed to operate at 1700°K emitter temperature, and with a 10-mil spacing, are also being fabricated. Their performance is to be that predicted by a variable-spacing test vehicle, and is to correspond with that of a planar converter with the same spacing.

PUBLICATIONS

Meetings and Symposia Papers

1. de Winter, F., and Merrill, O. S., "Analytical Characterization of Parabolic Solar Concentrator Performance," Solar Energy Society Annual Meeting, Palo Alto, California, October 21-23, 1968.

2. Jacobson, D. L., and Campbell, A. E., "Effective Work Function Determination of Rhenium and Molybdenum," 1968 Thermionic Conversion Specialist Conference, Framingham, Mass., October 21-23, 1968.

3. Lieb, D. and Rufeh, F., "Performance of a Duplex Vapor-Deposited Emitter," 1968 Thermionic Conversion Specialist Conference, Framingham, Mass., October 21-23, 1968.

4. Merrill, O. S., and de Winter, F., "Status Report on the Solar Energy Thermionic (SET) Program at the Jet Propulsion Laboratory," Solar Energy Society Annual Meeting, Palo Alto, California, October 21-23, 1968.

5. Merrill, O. S., Powell, C. E., and Gerber, W., "Experimental Characterization of Parabolic Solar Concentrator Performance," Solar Energy Society Annual Meeting, Palo Alto, California, October 21-23, 1968.

6. Rouklove, P., "Analysis of Failures of Thermionic Converters," ASME National Conference, Beverly Hills, California, June 1968.

7. Shefsiek, P. K., "Reproducibility of Thermionic Performance," 1968 Thermionic Conversion Specialist Conference, Framingham, Mass., October 21-23, 1968.

8. Stapfer, G., and Shimada, K., "Electrical Testing of a Six-Converter Generator," 1968 Thermionic Conversion Specialist Conference, Framingham, Mass., October 21-23, 1968.

9. Van Someren, L., and Sprenkle, E., "Partial Pole Figures from Cylindrical and Planar Tungsten Specimens," 1968 Thermionic Conversion Specialist Conference, Framingham, Mass., October 21-23, 1968.

SPS Contributions

1. Merrill, O. S., "Thermionic Converter Technology," SPS 37-52, Vol. III, August 1968.

2. Merrill, O. S., "Six-Converter Solar Thermionic Generator," SPS 37-53, Vol. III, October 1968.

JPL Technical Reports

1. Carne, Thomas, "Automatic Data Collection and Analysis for Life Tests of Thermionic Power Converters," JPL Report 900-218, October 25, 1968.

Contractor Reports, Interim and Final

1. Gyftopoulos, E. P., et al., "Applied Thermionic Research," Thermo-Electron Corp., Waltham, Mass., Second Quarterly Progress Report No. TE 4092/3-183-68, Covering the Period March 4, 1968 to June 4, 1968.

2. Jacobson, D. L. et al., "Thermionic Research and Development Program," Electro-Optical Systems, Inc., Pasadena, California. First Quarterly Progress Report, EOS Report 4006-Q-1, July 12, 1968.

3. Jacobson, D. L., et al., "Thermionic Research and Development Program," Electro-Optical Systems, Inc., Pasadena, California, First Quarterly Progress Report, EOS Report No. 4006-Q-1, October 12, 1968.

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SOLAR POWER SYSTEM DEFINITION STUDIES

NASA Work Unit 120-33-05-01-55

JPL 320-30901-2-3420

H. Wick

OBJECTIVE

The over-all objective of this effort is to investigate the problems associated with developing spacecraft electrical power systems for unmanned planetary missions. The effort stresses development of the technology required to solve system design problems associated with meeting JPL mission requirements. One task that is presently being undertaken is the investigation and development of computer programs for power system design and analysis.

ACTIVITIES

Recent activities have been directed toward the conversion of existing IBM 7094 Fortran IV power system computer programs for use on the Univac 1108 data processing system. The following computer programs have been successfully converted:

(1) Mariner Mars 71 Orbiter Power System Load Profile

(2) Ag-Zn Battery Design

(3) Shepherd's Equation - Single Discharge Curve

(4) Photovoltaic Power System Configurations

A reliability analysis computer program has been added to the power system computer program library. This program was written by General Electric, Missile and Space Division, as part of the over-all methodology developed for the optimum application of redundancy to the Voyager spacecraft. This program, in an updated form, has been recently applied by General Electric to improve the performance and reliability of Mariner-class power systems (JPL contract 952150).

The basic approach used in the computer analysis is the solution of differential equations associated with the state transition diagrams of the reliability models. Numerical integration is performed by using 4th-order Runge-Kutta methods. The state probabilities are combined by logic expressions which define the over-all subsystem states for a given model. Several unique features are incorporated into this computer program such as:

(1) The reliability model is encoded directly from the state transition diagrams and logic expressions. There is no need to define differential equations or matrix coefficients.

(2) Transition rates for the state diagrams are defined and encoded in terms of component reference numbers and associated failure rates.

(3) Individual failure rates can be varied as a function of mission phase through the use of stress factors applied to each component.

(4) The program has the ability to handle models combining both fixed probabilities and Poisson failure rates.

PLANNED ACTIVITIES

Planned activities during the next reporting period include documentation and updating of the reliability analysis program, review of power system computer programs presently used in the industry, conversion of these programs to meet JPL needs, and continued JPL effort to support the solution of spacecraft power system design problems.

PUBLICATIONS

SPS Contributions

1. Wick, H., "Solar Power System Definition Studies," SPS 37-53, Vol. III, October 31, 1968.

MARS SPACECRAFT POWER SYSTEM DEVELOPMENT

NASA Work Unit 120-33-05-04-55

JPL 320-32701-2-3420

H. Wick

OBJECTIVE

This program is directed toward the development of an optimum Mariner-class spacecraft power system to provide improved utilization of solar array power, greater reliability, and higher performance than the present Mariner Mars power system.

PROGRESS

The Phase I study effort, performed by General Electric's Missile and Space Division, and TRW Systems Group, has been completed. The contractor final reports have been published and distributed.

Results of the contractor effort for the Mars Spacecraft Power System Development program have been reviewed by JPL. A comparison of system characteristics between the present Mariner Mars 69 power system design and the contractors' recommended power system designs has been completed. The major characteristics of these power systems are shown in Table 1. A more detailed description of the recommended power system designs may be found in SPS 37-53 and the contractor final reports.

Table 1. Comparison of System Characteristics

	M 69	GE	TRW
Power System Weight (lb)	120.53	120.83	117.77
Reliability △1	0.830	0.860	——
△2	0.854	——	0.964
△3	0.854	0.903	0.964
Reliability Improvement	——	5.7%	12.9%
Array Power Margin Improvement	——	30 watts	None
Unregulated bus voltage swing	25-50 Vdc	25-38.2 Vdc	25-65 Vdc
Regulated bus voltage	56 Vdc	37.5 Vdc	50 Vdc
Regulation	±1%	±1%	±1%
Method of regulation	Boost	Shunt/Boost	Buck/Boost
Regulator efficiency	84-89%	98%	92%
Battery charge rate	600 mA max	2.0 A	300 ±50 mA/battery
Number of batteries	1	1	2
Battery charger cutoff voltage	34.6 ±0.2 Vdc	35.0/33.6 Vdc (2 step)	35.4 ±0.2 Vdc

△1 GE reliability estimate - 1 battery system (mission duration - 1 yr)

△2 TRW reliability estimate - 2 battery system (mission duration - 1 yr)

△3 JPL reliability estimate

Table 1 (Cont'd)

	M 69	GE	TRW
Array demand (TV Seq)	380 watts	350/334 watts △4	380/362 watts △4
Current limit of main power chain	None	1. 2.4 kHz inverter 2. Booster regulator	1. Buck-Boost regulator
Current limit set point	——	Adjustable	Nonadjustable
Ease of test on pad	Wide ground power limits	Limited ground power limits	Wide ground power limits
Reduction of input voltage swing @ input to PCE	——	Yes	No
Elimination of battery-array load sharing condition	——	Yes	No
Number of power handling units	1	2	1
Functional elements eliminated in recommended system design	——	1. Boost converter 2. Share mode detector 3. Array Zeners	1. Array Zeners
Functional elements (new)	——	1. Earth/Mars relay 2. Shunt regulator	1. Additional battery 2. Additional battery charger

△4 Second number represents array demand if TWT converter is improved ($\eta_{TWT} = 92\%$). First number represents array demand if present TWT converter design is used ($\eta_{TWT} = 75\%$).

Table 1 (Cont'd)

	M 69	GE	TRW
Battery charger design	Constant V, I limited series dissipative. Ground command turnoff	Same as MM69 with 2 step V limit control Ground command turnoff	Resistive I limit, V cutoff is automatic.

PUBLICATIONS

SPS Contribution

1. Wick, H., "Mars Spacecraft Power System Development," SPS 37-53, Vol. III, October 31, 1968.

Contractor Reports, Interim and Final

1. Kirpich, A., et al, "Mars Spacecraft Power System Development-Final Report," General Electric, Missile and Space Division, Valley Forge, Pennsylvania, GE Document 68SD4305, JPL Contract No. 952150, July 26, 1968.

2. Osugi, F., "Mariner Mars Power System Optimization Study-Final Report," TRW Systems, Redondo Beach, California, TRW Report 10247-6001-TO-00, JPL Contract No. 952151, November 11, 1968.

POWER CONVERSION CIRCUIT DEVELOPMENT

NASA Work Unit 120-33-08-04-55

JPL 320-34201-2-3420

D. J. Hopper

OBJECTIVE

The objective of this task is to increase reliability and efficiency and to reduce the weight of spacecraft power conditioning hardware. There are a number of circuit and functional element technology areas which, if improved, could greatly affect over-all power system performance. In particular, voltage regulator performance is a key factor in determining power system weight, efficiency and reliability. Much of the effort in this task will be directed toward improving regulator performance characteristics.

PROGRESS

One of the major items that was started during the previous reporting period under NASA Task 120-33-08-07, Capsule Power Conditioning Development, was the design and fabrication of an improved boost regulator. The work was carried out by Wilorco, Inc. of Long Beach, California. The program called for the design and breadboarding of 100 watt, 200 watt, and 400 watt regulators having significantly improved characteristics compared to presently available Mariner technology. The contract for these regulators was released late in FY 68, and as a result, the monitoring of the development and the verification testing of the regulators at JPL was accomplished under the current work unit. A summary of the results that were achieved in shown in Table 1.

In addition to the improvements shown in Table 1, the transient response characteristics of the new regulator are significantly better than those of the Mariner unit.

PLANNED ACTIVITIES

Other tasks planned, but not yet started, include the investigation and improvement of shunt regulators, switching regulators using SCR's, buck-boost regulators, and current limiting techniques for regulators and inverters.

Table 1. Regulator Characteristics

Function	New Regulator Actual Characteristic	Mariner Regulator Actual Characteristic
Efficiency	93 to 97%	87 to 93%
Regulation	±0.5%	±1%
Voltage	56 volts	56 volts
Output Power	200 watts	250 watts
Parts Count		
Magnetics	3	5
Transistors	13	11
Capacitors	16	13
Resistors	31	32
Diodes	3	13
Total	66	74

PUBLICATIONS

SPS Contributions

1. Hopper, Donald J., "Power Conversion Circuit Development," SPS 37-53, Vol. III, October 1968.

CHEMICAL POWER GENERATION SYSTEMS (120-34)

REACTION GEOMETRY OF ALKALINE ELECTRODES

NASA Work Unit 120-34-01-01-55

JPL 320-40101-2-3420

G. L. Juvinall
A. A. Uchiyama

OBJECTIVE

The long-range objective of this task is to obtain a more fundamental understanding of the electrode processes involved in batteries using silver, zinc, and cadmium electrodes. The immediate objectives include studies of: (1) the mechanism of the oxidation and reduction of the alkaline-silver electrode, (2) variation of the effective electrolytic surface area as a function of physical stress, (3) the nonuniformity of reaction of the alkaline electrode, and (4) conditions for the stabilization of silver III. These studies are directed toward the solution of problems which should permit the design of more versatile and reliable batteries for use in spacecraft.

ACTIVITIES

Tests performed on a coulometric potentiostatic method for surface-area determination have yielded promising results. The area of a sintered-silver electrode compared favorably with that measured by the constant-current technique developed earlier in this program. Results of the two methods agreed to within 7%. Further tests are under way in an effort to resolve these differences.

Additional work has been done on the cyclic current-step method of determining the exchange current density, transfer coefficient, and rate constant for the electrolytic oxidation of silver in ammoniacal solution. This apparatus will also be used in the direct measurement of the resistance of the silver oxide layer formed on the surface of a working electrode.

Studies of the effects of ultrasonic vibrations on the charging capacities of silver electrodes have been terminated. Charge recovery performance was found to be too poor to warrant additional work in this area. Consequently, the subtask concerned with the effects of physical stress on electrode performance will include studies of the effects of tensile stress in the near future.

Future work will include the investigation of promising methods of effective electrolytic-area determination, further studies of the effects of physical stress on the performance of electrodes, and techniques for the formation and stabilization of silver III.

PUBLICATIONS

Contractor Reports

1. Butler, E. A., and Blackham, A. U., "Studies of Reaction Geometry in Oxidation and Reduction of the Alkaline Silver Electrode," Brigham Young University, First Quarterly Report, August 15, 1968, JPL Contract 952268.

2. Butler, E. A., and Blackham, A. U., "Studies of Reaction Geometry in Oxidation and Reduction of the Alkaline Silver Electrode," Brigham Young University, First Quarterly Report, November 15, 1968, JPL Contract 952268.

SPS Contributions

1. Juvinall, G. L., "Electrolytic Determination of the Effective Surface Area of the Silver Electrode II," SPS 37-53, Vol. III, October, 1968.

HEAT-STERILIZABLE AG-ZN BATTERY DEVELOPMENT

NASA Work Unit 120-34-01-03-55

JPL 320-40301-2-3420

R. Lutwack

OBJECTIVE

This program is directed toward the development of heat-sterilizable batteries. The general objectives are to: (1) obtain basic information regarding battery components which have been subjected to heat sterilization, (2) develop technology for the design and fabrication of heat-sterilizable batteries, (3) test and evaluate components and batteries, and (4) produce batteries meeting flight program requirements. The program is comprised of two phases. Phase I includes studies of electrochemistry, case development, sealing techniques, cell design, cell fabrication, and cell testing. Phase II includes the design, fabrication, testing, and delivery of cells for heat-sterilizable batteries.

STATUS

The major effort is being done under JPL Contract 951296 with ESB, Inc.; this is supplemented by a JPL effort. Phase I, which is divided into tasks for electrochemistry, cell case development, and cell design and testing, was intended to provide information for the design of prototype cells; this phase is near completion.

Some of the recent results are listed here.

(1) Heat sterilization can be done after electrical cycling if special precautions are taken to completely discharge the zinc plate before sterilization. A procedure in which the cell is discharged so that no zinc remains and no mercuric oxide is formed leads to the practicality of electrically cycling after sterilization without causing large gas pressures and without incurring large capacity losses. This discharge is accomplished by a procedure in which the discharges are made through successively larger resistances until an open-circuit voltage between 0.75 and 0.81 volt is reached.

(2) Two batteries of six cells each, the cells having been sealed after sterilization, have been cycled at a depth of discharge of 60% of normal capacity. Failures have occurred as early as 33 cycles, but the usual cycle life was 120 to 130 cycles; one cell reached 200 cycles. The failure mode was by silver penetration through all of the separator layers, although there were also indications of zinc shorting over the top of the separator to the lead wires of the silver plate. It was concluded that additional layers of separator and a different zinc plate design are needed if the cycle life is to be extended.

(3) A component of the epoxy formulation which has been used to seal the case seems to cause gassing, loss of capacity, and nonuniformity of cells. Modifications of the sealing technique are being investigated in efforts to eliminate this problem.

Phase II is divided into tasks for the design, fabrication, and testing of cells for batteries with the following capabilities:

(1) Heat-sterilizable, impact-resistant 120 and 600 Whr primary batteries.

(2) Heat-sterilizable, 1200 W-hr, 90- and 400-cycle secondary batteries.

(3) Heat-sterilizable, impact-resistant 1200 Whr, 90-cycle secondary battery.

(4) Heat-sterilizable, 2000 Whr primary battery.

The design and development of the cells for these batteries are under way.

The work at JPL is directed primarily to separator and cell testing. This program is being used to complement the contractual efforts.

PUBLICATIONS

Meetings and Symposia Papers

1. Lutwack, R., "Progress in the Development of Heat Sterilizable Batteries," Intersociety Energy Conversion Engineering Conference, Boulder, Colorado, August 1968.

SPS Contributions

1. Lutwack, R., "Development of The Heat Sterilizable Battery," 37-52, Vol. III, August 1968.

2. Ibid, 37-54, Vol. III, December 1968.

STORAGE OPTIMIZATION AND DESIGN STUDIES

NASA Work Unit 120-34-01-04-55

JPL 320-40401-2-3420

R. S. Bogner

OBJECTIVE

The efforts of this work unit were directed towards reporting purposes only. This task was terminated during this period. The work resulting from continuation of prior activities is reported under NASA Work Unit 120-34-01-15-55, Advanced Battery System Development.

PUBLICATIONS

None

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STUDY OF SEPARATOR MEASUREMENTS

NASA Work Unit 120-34-01-05-55

JPL 320-40501-2-3420

R. Lutwack

OBJECTIVE

This program is for a study of separator materials which are candidates for use in heat-sterilizable silver-zinc batteries (described by NASA Work Unit 120-34-01-03). This study is required to establish a rational basis for the use of separator characteristics in the design of a battery. Since an additional set of chemical and physical requirements results from the heat-sterilization conditions, a section of the program is for the correlation of measurements such as tensile strength, resistivity, permeability, and wettability, with poststerilization capability as a separator. The final objective will be the use of optimum separator materials in the design of batteries.

STATUS

In one phase of this program, individual cell tests and measurements of resistivity, tensile strength, silver migration, and spectrophotometric spectra continue as the means to evaluate candidate separator materials and provide quality assurance for the polyethylene film being used in the silver-zinc cell development program. The separator products from JPL Contracts 951524 and 951966 (Monsanto Research Corp.) and 951525 (Westinghouse Electric Corp.) are being evaluated in this manner.

In a second phase a study is being made of the chemical and physical characteristics of membranes which are necessary for the desired transport properties in silver-zinc cells. From radiation grafted polyethylene, the first material to be examined, these results have been obtained:

(1) The separator was shown to be embrittled by dehydration. Since the conditions for reversing the dehydration are not present in a silver-zinc cell, the embrittlement may become a limiting factor in the use of polyethylene-based separator materials.

(2) The procedure of grafting with acrylic acid using cobalt-60 radiation causes extensive cross linking.

(3) Although the procedure for cross linking with divinylbenzene using cobalt-60 radiation after grafting with acrylic acid causes a marked increase in cross linking, the same procedure using ungrafted polyethylene does not yield measurable amounts of cross linking.

Cells have been fabricated using various separator materials, and attempts continue to correlate internal cell measurements with bench measurements.

PUBLICATIONS

Meetings and Symposia Papers

1. Lutwack, R., "Heat Sterilizable Separators," The Electrochemical Society Meeting, Montreal, Quebec, Canada, October 1968.

HEAT-STERILIZABLE REMOTELY ACTIVATED BATTERY

NASA Work Unit 120-34-01-06-55

JPL 320-40601-2-3420

R. Lutwack

OBJECTIVE

The objective of this program is to develop a heat-sterilizable, remotely activated battery capable of 200 W-hr capacity. This battery should supply sufficient current at an output voltage range of 26 — 30V dc for (1) a 1200W load for 10 min or (2) a 500W load for 24 min. The silver-zinc system is considered a first choice, but the study of other electrochemical systems has not been precluded. In addition to possessing the necessary electrical properties, the battery will be designed to be sealed and capable of:

(1) Shelf storage for a minimum of one year at temperatures between -10 and +25°C.

(2) Readiness for sterilization within 24 hr.

(3) A 9-month storage period in the dry-charged state at temperatures between -10 and +60°C.

(4) Being brought from zero to operating voltage at full load within 2 min and standing at open circuit prior to the application of the load for up to 30 min.

(5) Activation under a vacuum of 10^{-4} torr between 20 and 45°C.

The program comprises the design, development, fabrication, and testing of a heat-sterilizable, remotely activated battery capable of meeting these requirements.

STATUS

A research and development effort is being performed under JPL Contract 952214 by Eagle-Picher Co. Candidates for battery components are being tested under heat-sterilization conditions.

PUBLICATIONS

Contractor Reports

1. "Heat Sterilizable, Remotely Activated Battery Development Program," Eagle-Picher Industries, Inc., First Quarterly Report, October 1968.

GRAVITY EFFECTS ON BATTERIES

NASA Work Unit 120-34-01-07-55

JPL 320-40701-2-3420

G. L. Juvinall
A. A. Uchiyama

OBJECTIVE

The primary objective of this task is to investigate the effects of gravitational forces on the performance characteristics of batteries. Of special interest will be gravity conditions related to planetary encounter and landed operations on extraterrestrial bodies. It is anticipated that knowledge will be obtained by this program which will enable the design of batteries uniquely suited to mission requirements.

ACTIVITIES

The General Electric Research and Development Center has completed the design and fabrication of a breadboard unit to investigate the effects of low-gravity environments on batteries and battery electrodes. Testing is now in progress. The electrical capabilities of the unit include measuring and recording the limiting current-density characteristics of smooth zinc electrodes in alkaline electrolyte, which extends previous JPL high-g work in this area. Additionally, it is capable of recording similar data on commercial silver-zinc cells as well as discharge capacity as a function of charge-discharge cycling in a low-g environment. Finally, data can be obtained on the low-gravity behavior of silver and zinc electrodes operated under conditions designed to induce bubble formation. All measurements, including both electrical parameters and gas-liquid phase distribution within the cell are recorded. All measurements are carried out in the range of 0 to 1 g. Electrical data are recorded on magnetic tape and the gas-liquid phase distribution is recorded on photographic film.

Both the tape and film will be retrieved by an astronaut from an actual flight unit. Telemetry is not proposed, although the extension of the proposed system to permit telemetry of tape-recorded data could be done with moderate modification if required.

The next phase of the program will result in fabrication of a prototype unit. This phase will be performed in close coordination with the Apollo Applications Office.

The high-g portion of the program has been partially completed. Silver-zinc cells which have been subjected to charge-discharge cycling at selected g-levels at the U. S. Naval Ammunition Depot, Crane, Indiana, have been returned to JPL for examination. The electrodes will be checked for changes in shape or structure. Additional tests will be conducted on starved silver-zinc cells in the near future.

PUBLICATIONS DURING REPORT PERIOD

Contractor Reports

1. First Quarterly Report, "Reduced Gravity Battery Test Program," General Electric Research and Development Center, Contract 952121, July 1968.

2. Second Quarterly Report, "Reduced Gravity Battery Test Program," General Electric Research and Development Center, Contract 952121, October 1968.

SPS Contributions

1. Juvinall, G. L., "A Cell for the Direct Observation of Gassing Phenomena at Battery Electrode Surface in Low-Gravity Environments," SPS 37-52, Vol. III, p. 38, June 1 to July 31, 1968.

BATTERY ENGINEERING STUDIES

NASA Work Unit 120-34-01-09-55

JPL 320-40901-2-3420

W. L. Long

OBJECTIVE

The objective of this task was to determine optimum battery designs based on anticipated mission requirements. Although this task was terminated during this period, it was maintained as an active task for the purposes of obligating funds. The work resulting from the procurements are described under NASA Work Unit 120-34-01-15-55, Advanced Battery System Development.

PUBLICATIONS

None

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HEAT-STERILIZABLE NICKEL-CADMIUM CELLS

NASA Work Unit 120-34-01-10-55

JPL 320-41001-2-3420

R. Lutwack

OBJECTIVE

This program is for the development of the technology for a heat-sterilizable nickel-cadmium battery as a backup energy storage system for the heat-sterilizable secondary silver-zinc battery. The general objectives are to obtain basic information regarding battery components which have been subjected to heat-sterilization, develop the technology for the design and fabrication of heat-sterilizable batteries, test and evaluate components and batteries, and produce batteries meeting flight program requirements.

STATUS

A research and development effort is being performed (JPL Contract 951972) by Texas Instruments Inc. The tasks in this contract are in these categories:

(1) Electrochemistry (includes statistical experiments for characterizing and optimizing electrodes, electrolyte solution, and the separators).

(2) Design of hermetically sealed cell cases.

(3) Fabrication and evaluation of rectangular, heat-sterilizable 4- and 25-Ahr sealed cells.

(4) Fabrication and evaluation of heat-sterilizable, impact-resistant 25-Ahr cells.

The following observations and conclusions have resulted from this work:

(1) Two polypropylene materials were initially qualified for cell testing but only one performed satisfactorily in cells. The use of surfactants to increase wetting is being investigated.

(2) Cells made with glass-to-metal seals coated with Kel-F can be cycled after sterilization without leakage. However, Ziegler-type seals are also being studied.

(3) The end-of-charge voltage remains about 50 mV higher than normal when cycling is done after sterilization.

(4) Pack tightness is an important design factor.

(5) The capacities of 17- and 18-plate rectangular cells are improved continually by cycling after sterilization. The capacities for the 72nd cycle are 80% of theoretical for the nickel plate, which is the same as for a conventional, nonheat-sterilizable nickel-cadmium cell.

PUBLICATIONS

SPS Contributions

1. Lutwack, R , "Development of the Heat Sterilizable Battery," 37-52, Vol. III, August 1968.

2. Ibid, 37-54, Vol. III, December 1968.

Contractor Reports

1. Popat, P. V., "Heat Sterilizable Ni-Cd Battery Development," Texas Instruments Inc., Report for Third Quarter, April 1968.

2. Popat, P. V., and Crawford, R. L., "Heat Sterilizable Ni-Cd Battery Development," Texas Instruments Inc., Report for Fourth Quarter, July 1968.

HEAT STERILIZABLE BATTERY CASE DEVELOPMENT

NASA Work Unit 120-34-01-11-55

JPL 320-41101-2-3420

R. Lutwack

OBJECTIVE

This program is for the development of a heat-sterilizable separator and a sealed case for the heat-sterilizable silver-zinc battery described by NASA Work Unit 120-34-01-03. The sealed case development is a backup effort to that of Contract 951296 with EBS Inc., and is required to insure the success of this phase of the overall program.

STATUS

This effort was performed under Contract 951091 with the Narmco Division, Whittaker Corp. Tensile samples of poly 2, 2' — octamethylene — 5, 5' — bibenzimidazole were delivered to JPL and were evaluated by JPL as a potential case material. The properties of the material are comparable to those of the currently used polyphenylene oxide, and bonding can be done with an epoxy resin. The material will be considered as a backup to polyphenylene oxide.

PUBLICATIONS

None

HEAT STERILIZABLE SEPARATORS INCORPORATING CHELATING GROUPS

NASA Work Unit 120-34-01-12-55

JPL 320-41201-2-3420

R. Lutwack

OBJECTIVE

This is a program to develop a separator for the heat-sterilizable silver-zinc battery described by NASA Work Unit 120-34-01-03. The effort is for the investigation of films made from polymers containing chelating groups and includes a research and development phase and a phase for limited production.

STATUS

This investigation was done under JPL Contract 951524 by Monsanto Research Corp. Two types of ligand-containing polymers were developed, one being a tetrapolymer of styrene/maleic-anhydride/methyl-methacrylate/methyl-acrylate and the other being a 2-vinylpyridine/methyl-methacrylate copolymer. Portions of films prepared from a 31:69 composition of the copolymer using a paper-coating machine have been tested at JPL. The results to date are that the shrinkage caused by heat sterilization makes the film unusable for cell fabrication.

PUBLICATIONS

Meetings and Symposia Papers

1. Lutwack, R., "Heat Sterilizable Separators," the Electrochemical Society Meeting, Montreal, Quebec, Canada, October 1968.

SPS Contributions

1. Lutwack, R., "Development of the Heat Sterilizable Battery," 37-52, Vol. III, August 1968.

Contractor Reports

1. O'Connell, J. J. et al., "Separator Development for Heat Sterilizable Battery," Monsanto Research Corp., Final Summary Progress Report Supplement, June 1968.

COMPOSITE MEMBRANE DEVELOPMENT FOR HEAT-STERILIZABLE BATTERY SEPARATORS

NASA Work Unit 120-34-01-13-55

JPL 320-41301-2-3420

R. Lutwack

OBJECTIVE

This is a program to develop a separator for the heat-sterilizable silver-zinc battery described by NASA Work Unit 120-34-01-03. It is comprised of a research and development phase and a production phase.

STATUS

The techniques for the preparation of composite membranes (composed of a matrix of polypropylene, a binder of polysulfone, and a filler of zirconium oxide) were investigated under JPL Contract 951525 with Westinghouse Electric Corp. A modified commercial dip-coating procedure and a foil drying tower were adapted to fabricate films. The best specimens, which were prepared with a 3:1 oxide-to-polysulfone ratio, were shown to have low resistivities of less than 59 ohms-in. and to permit negligible silver and zinc transport over a 150-hr period. Several dozen feet of one-foot-wide material were delivered to JPL for testing.

PUBLICATIONS

Meetings and Symposia Papers

1. Lutwack, R., "Heat Sterilizable Separators," The Electrochemical Society Meeting, Montreal, Quebec, Canada, October 1968.

SPS Contributions

1. Lutwack, R., "Development of the Heat Sterilizable Battery," 37-52, Vol. III, August 1968.

Contractor Reports

1. Scala, L. C., and Dixon, G. D., "Separator Development for a Heat Sterilizable Battery," Westinghouse Electric Corp., Eighth Quarterly Report, July 1968.

HEAT-STERILIZABLE RADIATION GRAFTED POLYETHYLENE SEPARATORS

NASA Work Unit 120-34-01-14-55

JPL 320-41401-2-3420

R. Lutwack

OBJECTIVE

Tis is a program to develop a separator for the heat-sterilizable silver-zinc battery described by NASA Work Unit 120-34-01-03. It is comprised of a research and development phase and a production phase.

STATUS

The preparation of separator materials from polyethylene grafted with acrylic acid using radiation from a cobalt-60 source is being studied under JPL Contract 951718 with the Southwest Research Institute. Investigations of some of the parameters of the grafting and cross linking steps have led to these results:

(1) Acrylic, methacrylic, oleic, and maleic acids have been used for grafting, the best films being prepared from acrylic and methacrylic acids.

(2) Dimensional changes, which occur during sterilization, are dependent upon the temperature of the wash solution used during the processing of the film.

(3) Films with higher K content are produced when the grafting solution contains lower chain terminator concentrations.

(4) The apparatus for producing large continuous rolls of material has been developed and is being tested.

The studies of the grafting and cross linking procedures are continuing. A scaleup of the basic procedure is being developed. Southwest Reasearch Institute is also supplying JPL with the separator material used in the silver-zinc cell development program.

PUBLICATIONS

Meetings and Symposia Papers

1. Lutwack, R., "Heat Sterilizable Separators," The Electrochemical Society meeting, Montreal, Quebec, Canada, October, 1968.

SPS Contributions

1. Lutwack, R., "Development of the Heat Sterilizable Battery," SPS 37-52, Vol. III, August, 1968.

ADVANCED BATTERY SYSTEM DEVELOPMENT

NASA Work Unit 120-34-01-15-55

JPL 320-41501-2-3420

A. Uchiyama

OBJECTIVE

This task has two major objectives. The first is to develop batteries capable of meeting the life requirements for complex and long-duration missions; the second is to develop the battery system technology which will permit greater control over batteries used on these missions. Future missions -- especially those contemplated by the NASA/JPL to the outer planets -- will impose much more severe requirements on the flight batteries due to the complexities of the spacecraft and to the longer periods of the missions. Current model flight batteries and battery systems will not meet these requirements. Consequently, the overall purpose of this task is to develop the technology which will permit the design and fabrication of batteries and battery systems suitable for future missions. This task will be specifically directed toward obtaining cell and battery data simultaneously. The total system will then be capable of automatically sensing and analyzing impending failures in time to prevent or correct cell and battery malfunctions during the mission.

ACTIVITIES

Tests of the Mariner-type cells are continuing. Current results indicate that these cells lose capacity at a rate of 1% per month at 75°F and 5% per month at 100°F. There is no significant difference in the behavior of cells stored fully charged and cells stored 50% discharged. The vendor has developed ten formulations of epoxy resin which have passed gassing and vibration tests. The final choice will represent a trade off among the variables of low gassing characteristics, bond strength, and ease of fabrication.

The storage optimization studies are continuing at the U. S. Naval Ammunition Depot at Crane, Indiana. The automatic controller and data-acquisition system are installed, and programs are being written to reduce the data.

A series of 18 remotely activated silver-zinc batteries (Eagle Picher GAP 4184) is now under test at Crane. The batteries will undergo storage temperature tests at periods of two months to six years and at temperatures ranging from 68°F to 150°F. Activated stand life tests will also be performed.

A breadboard commutator unit for monitoring individual battery cells during flight has been fabricated and is now working. The design is under review at the present time to assess the reliability under flight conditions.

Electrolyte concentration studies of silver-zinc cells have shown that high concentrations (50% potassium hydroxide) are best for batteries where high rate discharge and charge performance is required at relatively low temperatures. Optimum electrolyte concentration depends on the ultimate application.

Future work includes studies of other systems, such as silver-cadmium, nickel-zinc, nickel-cadmium/hydrogen-oxygen, mercury-cadmium, rubidium-silver iodide, and lithium-copper fluoride. Life times of 2, 5, 10, and 12 years will be considered under varying conditions of wet and dry, low and high temperatures, and state-of-charge and conditioning.

PUBLICATIONS

SPS Contributions

1. Bogner, R. S., Patterson, R., "Effect of Electrolyte Concentrations on the Electrical Characteristics of AgO-Zn Cells," SPS 37-54, Vol. III, December, 1968.

STATE-OF-CHARGE INDICATOR FEASIBILITY
NASA Work Unit 120-34-01-16-55
JPL 320-41601-2-3420
S. Krause/A. A. Uchiyama

OBJECTIVE

For any space mission that uses batteries as one of its sources of power, it is highly desirable to know the exact amount of battery power available for use at any time, particularly during critical periods of spacecraft operation, such as: launch, maneuvers, encounter, landing, and data playback. The need for state-of-charge indicators cannot be overemphasized, since it is possible that the performance of these critical phases may depend upon a knowledge of available power from the battery. The prime objective of this task is to develop techniques whereby the available energy output of a battery may be determined at any time, and with particular emphasis on measuring devices which may be incorporated as a part of the battery. At the present time, emphasis will be placed on development of state-of-charge indicators and measuring techniques for silver-zinc batteries, but with JPL's current research and technology expanding into new battery types for new applications and missions, a commensurate effort will be made as a continuing development program for advanced state-of-charge measuring techniques which can be applied to many types of batteries now in existence or which will be developed in the future.

ACTIVITIES

Further definition of the problem was necessary prior to any outside work, primarily to assure that the approach of this study would result in the highest probability of meaningful information being generated. Technical discussions were held with personnel at various universities to add further information to the JPL compendium of available knowledge and various state-of-charge determination techniques.

As a result of these discussions, a number of tests at JPL were performed on silver electrodes of varying states of charge using attenuated-total-reflectance (ATR) spectroscopy. The preliminary data indicate a correlation between absorption in the 12 - 15 micron region and the electrode state of charge. Since these data do indicate some feasibility exists in the ATR approach, an extensive test program utilizing this technique will be continued to obtain a more statistically conclusive correlation between infrared absorption and electrode state of charge.

PUBLICATIONS

None

REACTIONS OF ZINC, CADMIUM, AND SILVER ELECTRODES

NASA Work Unit 120-34-01-17-55

JPL 320-41701-2-3420

G. L. Juvinall
A. A. Uchiyama

OBJECTIVE

The primary objective of this task is to obtain a more fundamental understanding of the electrode processes involved in silver, zinc, and cadmium electrodes. The studies included in this task are directed toward the solution of problems to pave the way for design of more reliable and versatile batteries and development of new battery systems. Immediate plans include further overpotential studies with particular emphasis on gassing. A major objective of this effort is the extension and expansion of studies on liquid-amalgam electrodes. The discovery of the liquid mercury-potassium electrode by the principal investigator during the earlier phase of this effort has made this area of study possible. Such electrodes appear to be particularly useful in applications where very high peaking currents are required. Obvious applications include squib batteries and land-based vehicles where high torque is required.

ACTIVITIES

Tracer studies, utilizing ^{110}Ag, have shown that the greatest reduction of Ag(1) from potassium hydroxide solutions saturated with argentous oxide occurs within the first 24 hours with little subsequent change. Chronopotentiograms at 147 mA/cm^2 of zinc plates upon which silver has been deposited show transition times of 24 to 50 seconds as compared with 69 seconds for untreated plates. The results, coupled with the fact that some of the silver was easily removed from the plate by electrolytic bubble formation, indicated that silver is deposited first as a strongly adherent layer followed by weakly held layers.

Amalgam electrodes with lithium, sodium, potassium, magnesium, calcium, barium, aluminum, copper, lead, zinc, and cadmium have been investigated. The most promising to date are the potassium amalgam, zinc amalgam, and cadmium amalgam.

Potassium amalgam electrodes have been discharged at 1200 mA/cm^2 without serious deterioration of discharge behavior. There is evidence that discharge capacity (defined as the percentage of recovery of charge during the discharge mode) is lower at low amalgam concentrations than at high concentrations. Discharge capacity seemed unaffected by charge or discharge rate when the total charge was constant. These capacities were generally in excess of 90 percent.

No loss in capacity in zinc-amalgam electrodes in 10 $\underline{N}$ potassium hydroxide was observed over a period of 28 days. At all potassium hydroxide concentrations, potassium-amalgam electrodes lost at least 20% capacity within 32 days. The stand life of the sodium-amalgam electrode was poor except in saturated sodium hydroxide, where no significant loss was observed after a stand of 71 days.

Future work includes an intensive investigation of the promising liquid amalgam electrode field, as well as a study of depth of electrode gassing phenomena.

PUBLICATIONS

SPS Contributions

1. Juvinall, G. L., "The Products of the Electrochemical Oxidation of Zinc Battery Electrodes," SPS 37-52, Vol. III, P. 44, August, 1968.

Contractor Reports

1. Arcand, G. M., "Investigation of electrode materials for alkaline Batteries," Idaho State University First Quarterly Report, August 25, 1968, JPL Contract 952265.

2. Arcand, G. M., "Investigation of Electrode Materials for Alkaline Batteries," Idaho State University Second Quarterly Report, November 25, 1968, JPL Contract 952265.

HEAT-STERILIZABLE, CHEMICALLY GRAFTED POLYETHYLENE SEPARATORS

NASA Work Unit 120-34-01-18-55

JPL 320-41801-2-3420

Ralph Lutwack

OBJECTIVE

This is a program to develop a separator for the heat-sterilizable silver-zinc battery described by NASA Work Unit 120-34-01-03. It is comprised of a research and development phase and a phase for limited production.

STATUS

The effort, which includes the synthesis of ethylene/methyl acrylate copolymers by high-pressure mass copolymerization, conversion of the copolymers to thin films, vulcanization of the film, and saponification to films of ethylene/acrylic acid, was performed under JPL Contract 951966 with the Monsanto Research Corp. The most promising films were prepared from a polymer composition of acrylate/ethylene in a ratio of 45:55. After consecutive hydrolyses for 24 hours at 65°C in alcoholic potassium hydroxide and then in aqueous potassium hydroxide these films were heat-sterilized and had resistivities of less than 20 ohms-in. The material is being evaluated by JPL.

PUBLICATIONS

Contractor Reports

1. Salyer, I. O., et al, "Ag-Zn Battery Separator Development," Monsanto Research Corp., Final Quarterly Report, July, 1968.

SPS Contributions

1. Lutwack, R., "Development of the Heat Sterilizable Battery," Space Program Summary 37-52, Vol. III, August, 1968.

Meetings and Symposia Papers

1. Lutwack, R., "Heat Sterilizable Separators," The Electrochemical Society Meeting, Montreal, Quebec, Canada, October, 1968.

STUDY OF PERMEABILITY CHARACTERISTICS OF MEMBRANES

NASA Work Unit 120-34-01-20-55

JPL 323-42001-2-3420

R. Lutwack

OBJECTIVE

This is a study of the permeability characteristics of membranes as a function of the application of different forces. It includes a detailed theoretical application of thermodynamics of the steady state to transport across membranes and experimental determination of the derived relationships.

STATUS

A method of transport parameter evaluation from the basic flux equations of linear nonequilibrium thermodynamics has been outlined. An apparatus has been designed and fabricated which will be used to measure osmosis, electro-osmosis, dialysis, transport number, membrane potential, streaming potential, and conductivity under uniform hydrodynamic conditions using feedback mechanisms to keep solution concentrations constant despite the mass transfer which occurs.

PUBLICATIONS

<u>SPS Contributions</u>

1. Lutwack, R., "Development of the Heat Sterilizable Battery," SPS 37-54, Vol. III, December, 1968.

<u>Contractor Reports</u>

1. Spiegler, K. S., et al., "Study of Permeability Characteristics of Membranes," University of California at Berkeley, Quarterly Progress Reports 1 and 2, April, 1968, Contract 952109.
2. Ibid. Quarterly Progress Report No. 3, August, 1968, Contract 952109.

SPACE VEHICLE SYSTEMS SRT (124)

SPACE VEHICLE AEROTHERMODYNAMICS (124-07)

PLANETARY ENTRY GAS DYNAMICS

NASA Work Unit 124-07-01-01-55

JPL 324-71401-0-3530

J. M. Spiegel

OBJECTIVE

This task has the general objective of reducing uncertainties in predicting heat transfer and aerodynamic behavior during planetary entry in areas where these factors are considered important to the science payload of an entry vehicle. During the present report period, primary areas of activity were approximate heat transfer techniques, low speed entry dynamics, simulation of Venus entry by earth re-entry, and shock-layer ablation-product interactions.

APPROXIMATE HEAT TRANSFER TECHNIQUES

The need for rapid, but validated, techniques for predicting entry heat transfer continues. In this report period, the approximate JPL Entry Trajectory and Heating Program has been modified to include the CO(4+) radiator (which occurs in heated CO_2-N_2 gas mixtures), molecular gaseous absorption, carbon and nitrogen atomic lines, and a simplified radiation cooling correction. Further improvement of the atomic line treatment is planned.

As a result of previous study contracts with the General Electric and Philco-Ford Companies to calculate Martian entry heat transfer distributions on a 60° spherically-blunted cone body by flow field techniques, it was found by comparison that simpler methods underpredict the heat transfer level by a considerable amount on the conical part of the body. However, available experimental data from various ground facilities favor the simpler approach. The reason for this is yet to be determined.

Discrepancies between various published predictions of stagnation point convective heating results have been resolved. When properly compared, these results are in reasonable agreement with remaining discrepancies attributable to differences in transport property data used in the various studies. Unfortunately, some authors did not reduce the results of other publications to their own form of presentation in a consistent manner thus causing resulting comparisons to show discrepancies that did not really exist. A detailed discussion of this problem is now being prepared for publication.

LOW SPEED ENTRY DYNAMICS

Near-terminal descent for certain rolling, high drag-coefficient bodies has been predicted to involve possible divergent motion during descent in the Venus atmosphere. The basis for this prediction and criteria for the phenomenon applicable to both Venus and Mars is presented in publication (Open Literature) 1, and was orally given at the Third Technical Workshop on Dynamic Stability Problems held at the NASA Ames Research Center, Moffett Field, California, November 4-7, 1968. Experimental verification of the basic phenomenon was qualitatively obtained in the LaRC spin tunnel in September by a joint effort with the JPL Aerodynamic Facilities Section. Personnel of this section will quantitatively analyze the results as their resources permit.

SIMULATION OF VENUS ENTRY BY EARTH RE-ENTRY

An earth re-entry test is a possible means of testing the design of a Venus atmospheric entry probe. Analysis of the simulation attainable indicated that a full-scale vertical earth re-entry flight test at 36,000 ft per sec should provide an acceptable simulation of deceleration, angle-of-attack envelope, and heat response for a Venus entry at a path angle of about 45°, despite large differences in the atmospheric composition of the two planets. A paper on this subject was presented at the AIAA Entry Vehicle Systems and Technology Meeting in Williamsburg, Virginia, on December 4, 1968. No further work is planned for this FY on this subject. (Refer to publications list, Meetings and Symposia Paper No. 1.)

SHOCK-LAYER ABLATION-PRODUCT INTERACTIONS

A potentially important observation made subsequent to the completion of meeting paper No. 1 was that the predicted char removal was due primarily to reaction between the char and hydrogen in the pyrolysis gases. To determine the influence of this reaction, the calculations were repeated, but with 25% of the hydrogen in the pyrolysis gases isolated (not permitted to react with the char). The predicted char removal was then observed to decrease by about 20%, and the surface temperature increased slightly, but overall ablation response was not significantly affected. It is possible, however, that this reaction could be much more important under more severe entry conditions and should be investigated further when missions involving such entry conditions are considered.

PUBLICATIONS

Meetings and Symposia Papers

1. Spiegel, J. M., Wolf, F., and Zeh, D. W.; "Simulation of Venus Atmospheric Entry by Earth Re-entry," AIAA Paper No. 68-1148, Williamsburg, Virginia, December 3-5, 1968.

Open Literature

1. Shirley, D. L. and Misselhorn, J. E.; "Instability of High-Drag Planetary Entry Vehicles at Subsonic Speeds," Journal of Spacecraft and Rockets, Vol. 5, No. 10, October 1968.

SPS Contributions

1. Spiegel, J. M., Wolf, F., and Zeh, D. W.; "Simulation of Venus Atmospheric Entry by Earth Re-entry," JPL SPS 37-53, Vol. III, August-September 1968.

PLANETARY ENTRY AEROTHERMODYNAMIC RESEARCH

NASA Work Unit 124-07-01-04-55

JPL 324-70800-2-3730

F. R. Livingston

OBJECTIVE

The objective of this work unit is to complete tasks in aerothermodynamic research required to understand and cope with the extremely hot environment encountered by a Mars, Venus, Jupiter, or earth entry vehicle.

STATUS

Several important milestones have been reached. Highlights of the period include:

(1) Completion of shock tube measurement of the vacuum ultraviolet continuum spectra of oxygen, nitrogen, and carbon combined with the successful self-consistent field calculations of the same spectra.

(2) First measurements of the total and spectral intensities of a simulated Jupiter atmospheric gas at temperatures of from 10,000 to 22,000°K.

(3) Completion of one of the first works attempting to explain deviations from ideal performance observed in a shock tunnel.

The lack of funds to proceed with the construction of a shock tube capable of producing the Jupiter entry vehicle environment has interrupted plans to advance our experimental study of total and spectral intensity from shock-heated Jovian gases. Other tasks are progressing as planned, however.

Current aerothermodynamic research tasks cover the many phases of experimental and theoretical analysis of planetary entry problems.

Vacuum Ultraviolet Spectra of Shock Layer Plasmas

The photoionization cross sections of carbon and oxygen were measured in the 500 to 1200Å spectral region. The vacuum ultraviolet spectrometer attached to the 6-inch D. electric-arc driven shock tube was used. The test gases, CO and O_2, were mixed with helium in order to reduce absorption, increase temperature, and, hence, improve data interpretation. The preliminary results were about a factor of 2 higher than our self-consistent-field (SCF) prediction. The previously measured cross-section of nitrogen was larger than the current SCF prediction.

The CO(4+) molecular spectrum will be measured next from a sidewall position on the electric-arc shock tube. Minor changes in the computer program enabled the making of SCF solutions for the important continuum radiation from the negative ions of nitrogen, oxygen, and carbon. Publication of all results will be done in the next reporting period.

Total and Spectral Intensity of Shock-Heated Jovian Gases

Thermodynamic conditions a Jupiter entry probe may encounter were simulated in a free-piston shock tube by bathing the atmospheric gas in argon. Radiation was measured from gas mixtures of 18% H_2-11% He-1% Ne-70% A and pure argon over the temperature range 10,000-22,000°K. Time-resolved measurements were made behind the incident shock wave and the bow shock of a model. Spectral measurements were made in the visible wavelength region and total radiation from 0.18 - 2.7 μ. Calculations were made of the equilibrium radiation, including effects of absorption and cooling and agreed within 40% of the measurements.

Future work here will only be concerned with the understanding of argon radiation and nonequilibrium relaxation. A paper will be presented at the January 1969 AIAA meeting describing the Jupiter work.

Planetary Entry Body Heating Rates in Air and Venus Atmospheric Gas

Convective plus radiative stagnation-point heating rates of air and Venus atmospheric gas to platinum calorimeters mounted on a 5-inch D hemisphere and on 1-1/4, 2, and 2-1/2 inch D flat-faced cylinders were measured in a dump tank attached to a 6-inch diameter free piston shock tube. Total heat flux in air was compared to theoretical calculations, and found to compare favorably at temperatures between 12,000-15,000°K. An attempt is being made to reconcile the excess heat flux measured at temperatures from 8000-12,000°K in air. There has been little success. Apparent radiative flux to the models in the Venus gas mixture is about 1-2/3 that encountered in air at T = 14,000°K and comparable pressure. A paper describing this work has been tentatively accepted for the AIAA 4th Thermophysics Conference to be held in June 1969.

Additional models have been completed for the continuation of these tests at higher pressures. In order to establish the convective heating data base, additional runs will be made a lower shock speeds in nitrogen. The radiative flux from the Venus atmospheric gas will be computed as will thermochemical shock tables for the 90% CO_2 - 10% N_2 mixture.

Convective Heating Distribution on 60° Half-Angle Blunted Cones in a Shock Tunnel

Distributed pressures have been measured on three 60-deg half-angle blunted cones in the hypersonic shock tunnel. The results of this pressure study were used to calculate distributed laminar convective heat transfer rates. Measurement of heat transfer rates to identical bodies has also been made by thin film gages in the shock tunnel. There is poor agreement with the calculated rates. However, the measured rates do compare favorably with measurements of Grumman, Ames RC, and the Martin Co.

One of the cone models will be equipped with thick film platinum calorimeter gages in order to check the thin film data. Future tests will be concerned with distributed convective and radiative flux on blunt models in the shock tube.

Blunt Body Inviscid Flow-Field Studies

A means was found to incorporate the JPL thermochemistry program into the real gas blunt-body flow field program. With this adaption, the linear flow-field program for equilibrium conditions will be solved as soon as the program is converted to the Univac System. A simple shock structure program was completed. This will be used in calculating the flow field of a blunt body at low density where a discontinuous shock wave cannot be assumed.

Future progress will be made in solving the radiative flux divergence equation within the shock layer for the uncoupled flow conditions.

Viscous Shock Layer Analysis

A method is needed for computing the laminar skin friction and heat transfer to a blunt body whose flow external to the boundary layer has variable entropy. A task was initiated in September to analyze the viscous shock layer on a blunt body. Assuming the shock layer to be thin, the Navier-Stokes equations were simplified in the usual manner, and the stream function was introduced as the independent variable. After certain assumptions, the shock layer equations were reduced to the boundary layer form and transformed to the boundary layer coordinates. Boundary conditions on the body surface include slip and temperature jump and on the shock the viscosity effect on the Rankine-Hugoniot conditions is considered. Further work has resulted in formulating the first nonlinear vorticity interaction theory for flow outside the stagnation region.

Future work will include solutions at lower Reynolds numbers, and at conditions where radiation effects must be considered in the viscous shock layer.

Hypervelocity Laboratory Development

Shock speeds and test times have been calculated and measured for the 3-in. D shock tube which supplies the hot gas for the JPL 43-in. D hypersonic shock tunnel. The pressures recorded at and near the end of the driven tube have been interpreted by use of the turbulent wall-boundary layer theory. Tailoring operation was observed for shock Mach numbers from 5.4 to 5.7 for cold H_2 driving N_2. The tailoring Mach number is limited by boundary-layer mixing in the reflected shock region. The hypersonic nozzle starting flow was surveyed and reconciled with unsteady flow theory.

The detail design and fabrication of the coaxial arc driver flow simulation and diaphragm evaluation section was completed. No additional component of the MAARC shock tube will be purchased this fiscal year. A new electric-arc driven shock tube and monorail suspension system has been completed. Now, two electric-arc shock tube experiments can be conducted simultaneously by alternately firing the two existing drivers from the capacitor bank.

Developmental work anticipated includes a re-evaluation of the ceramic lined electric-arc driver. There have been problems with insulation material failure. The MAARC driver flow simulation and diaphragm test rigs will be completed and evaluated through a series of tests.

PUBLICATIONS

JPL Technical Reports

1. Passamaneck, R., "Aerodynamic Characteristics of Spherically Blunted 45-deg Half-Angle Cones," TR 32-1327, Sept. 1, 1968.

JPL Section Reports

1. Blair, M. F., "A Study of Laminar Convective Heat Transfer to 60 Degree Blunted Cones in Hypersonic Flow," Report 900-192, Nov. 15, 1968.

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FLOW FIELD COMPUTER PROGRAM FOR PLANETARY ENTRY

NASA Work Unit 124-07-01-06-55

JPL 324-70601-0-3530

Z. Popinski

OBJECTIVE

This continuing task has the general objective of acquiring coupled flow field programs for the primary purpose of providing a basis of validating and improving rapid but more approximate heat transfer and pressure distribution methods. These coupled flow field programs are particularly important for evaluating the effects of real gases, radiation/flow field coupling, low density flows, and radiation reabsorption including ablation products.

ACCOMPLISHMENTS

The use of the time-dependent approach to the solution of shock-layer flow fields has been reviewed with the aid of Professor H. T Yang on a summer assignment from the University of Southern California. Within the time dependent approach, boundary conditions using the so-called "shock and body fitting" methods were selected because conditions at these locations are quasi one-dimensional and can be fitted to the finite difference technique in the smoother center portion of the shock layer.

In an effort to learn as much as possible from outside sources using the time-dependent approach, visits were made to the Langley Research Center, the Courant Institute of Mathematical Sciences at New York University, and the General Applied Science Laboratory, Long Island, New York. The trip resulted in much valuable information, but led to the conclusion that working computer programs appropriate, or even modifiable, to JPL needs are not available.

Detailed formulation of a system of governing equations, similar to that developed by Moretti at the General Applied Science Laboratory for an axisymmetric body, is proceeding satisfactorily. (it should be mentioned that the method of Moretti was presented for the two-dimensional case, Ref. 1, and with much less detail for the three-dimensional case, Ref. 2. Thus, the analysis for the axisymmetric case is actually not available.) For the inner part of the shock layer, these equations are transformed into a coordinate system which maps the shock layer into a rectangle. At the shock and at the body a body-oriented coordinate system is used. A quasi one-dimensional treatment of these regions leads to expressions for characteristic directions, and leads to the compatibility equations for pressure. Using the method of characteristics, the flow conditions in narrow regions at the shock and at the body will be matched to the conditions in the inner region of the shock layer.

PLANNED ACTIVITIES

The effort for the following six months will consist of formal derivation of detailed expressions for the axisymmetric case. This derivation will be verified as a special case of a three-dimensional analysis for zero angle of attack. The equations will be reduced to a form suitable for programming which, for the inviscid axisymmetric case, will be initiated as resources permit.

REFERENCES

1. Moretti, G., and Abbett, M.; "A Time-Dependent Computational Method for Blunt Body Flows," AIAA Journal, Vol. 4, No. 2, pp. 2136-2141, 1966.

2. Moretti, G., and Bleich, G.; "Three-Dimensional Flow Around Blunt Bodies," AIAA Journal, Vol. 5, No. 9, pp. 1557-1562, 1967.

PUBLICATIONS

None

SPACE VEHICLE STRUCTURES (124-08)

NASA GENERAL PURPOSE STRUCTURES COMPUTER PROGRAM

NASA Work Unit 124-08-01-03-55

JPL 324-81101-0-3530

R. M. Bamford

OBJECTIVE

The objective of this work unit is to assist Goddard Space Flight Center in the development and evaluation of the NASA General Purpose Structural Analysis Program (NASTRAN) being developed under NAS 5-10049.

STATUS

The statics portion of the NASTRAN program was delivered to JPL in July 1968.

ACCOMPLISHMENTS

Six demonstration problems were run using both the NASTRAN and the SAMIS computer programs. An evaluation of the NASTRAN program, as compared with SAMIS, was transmitted by letter to GSFC on 20 August, 1968.

PLANNED ACTIVITIES

None

PUBLICATIONS

None

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VEHICLE CONCEPTS FOR PLANETARY MOBILITY

NASA Work Unit 124-08-01-04-55

JPL 324-81201-0-3530

E. Heer

OBJECTIVE

The general objective of this work unit is to develop advanced structural technology of planetary mobility systems for planetary and lunar surface operations and exploration. A long-term plan is required involving extensive investigations into conceptual and detailed aspects of mobility systems and locomotion. Particular FY 69 objectives are to determine and identify the existing mobility concepts, to establish criteria for the evaluation of mobility concepts, to assess, in a morphological sense, the existing and newly created mobility concepts with respect to such criteria, to establish interface requirements with other disciplines, and to define advanced research areas for future investigations of the structural and mechanical aspects of planetary vehicles.

PROGRESS

Existing Mobility Concepts

Through contacts and visits at the various NASA centers, other government agencies, industrial organizations and universities, the mobility concepts for planetary and lunar surface operations and explorations under consideration up to the present time have been identified. The various concepts have been classified and grouped with respect to an empirical scale of increasing dependence on planetary and/or lunar surface characteristics. The major concept groupings introduced on this scale are floater, flyer, jumper, walker, rover, crawler, cable car, crane and stationary shelter concepts. Main concept characteristics of each group have been established and their relative merits have been evaluated qualitatively.

New Mobility Concepts

A few new mobility concepts are proposed. A new Venusian floater concept is based on mechanical configuration changes for flotation. A Mars hybrid mobility concept is based on roving and hopping capability. Another Mars hybrid concept has hopping capability and flying capability via an autorotor which also serves for energy regeneration purposes. For lunar exploration, a dual-mode mobility concept is proposed utilizing, in addition to a manned mode consisting of a stationary surface laboratory or a roving laboratory with relatively limited radius of operation, an unmanned mode, consisting of several small vehicles of which each one has a limited special purpose exploratory objective. After this objective has been fulfilled and the data has been telemetered to the manned laboratory, the respective rover is abandoned. Details of the major characteristics of these concepts are being developed.

Evaluation Criteria

An effort has been initiated to develop consistent evaluation criteria so that the various mobility concepts can be compared with respect to a common yardstick, and as free as possible from subjective judgment. Factors which influence the selection of a particular concept are those that are given or assumed a priori such as science objectives, planetary or lunar environments, and, to some degree, delivery constraints. All of these factors should be known within some realistic certainties before a concept is definitely selected and a design can be considered. One portion of the present effort is directed to the assessment of the extraterrestrial environments, the delivery constraints, and the science objectives as far as they influence mobility concepts and requirements. The present state of knowledge of the environments and the state of technology of delivery system constraints has been evaluated. The evaluation of current science objectives is in progress. Another portion of the present effort is directed to the determination of characteristic mobility design variables of the various mobility concepts, and towards establishing rational criteria for concept evaluation and comparison. The main part of this portion of the effort will be done during the second half of FY 69.

Advanced Research

Plans defining advanced research areas with particular emphasis on important technology gaps are in preparation and will be continuously updated. Areas presently of prime concern and requiring innovations are (1) mathematical formulation of evaluation criteria for mobility concepts, (2) mathematical formulation of related synthesis and optimization techniques, (3) inflatable and other structures and mechanical systems under elevated (Venusian) temperature conditions and under extremely varying thermal environments, (4) propulsion systems, in particular those utilizing local power sources for regeneration, (5) three-dimensional terrain image reproduction and transmission for unmanned systems using, for instance, holographic techniques, (6) vehicle-control-terrain interaction for unmanned vehicles, and (7) soil mechanics for extraterrestrial surfaces, in particular, wheel soil interactions for rover concepts.

PUBLICATIONS

None

PLANETARY ENTRY HEAT SHIELDS

NASA Work Unit 124-08-03-02-55

JPL 324-80401-2-3510

T. F. Moran
R. G. Nagler

OBJECTIVE

The long range objective of this task is to conduct exploratory research into extraterrestrial planetary heat shield problems developing from JPL/NASA mission studies. In order to carry out this activity, a small planetary entry simulation facility has been designed and constructed at JPL which is highly adaptable to a number of environments and inexpensive to operate. The facility capabilities are to include convective heating, radiative heating, and pressure pulsing. Information generated by this facility will be used to delineate and guide extraterrestrial planetary entry heat shield research and development at the NASA research centers, and in industry. Tasks directed at advancing the state-of-the-art in heat shield testing technology, through the definition and solution of problems which larger, less adaptable facilities are unable to handle because of scheduling considerations and priorities, will be undertaken.

The prime objective for the remainder of FY 69 is establishing a facility operating envelope through an intense and thorough program of calibration and diagnostics. Following definition of repeatable facility capabilities, a program of studies to determine the effectiveness of using special concentric calorimeter configurations to evaluate the magnitude of convective blocking phenomena will be undertaken.

PROGRESS

During the last reporting period, the vacuum test chamber, model-probe actuation system, heat exchanger, mechanical blowers and pumps, vacuum valving, and recirculating water system have been delivered and, for the most part, have been installed at JPL. All parts and materials for the vacuum system are on hand and installation is in progress. Initial startup and operation of both the plasma arc jet and the plasma arc radiation sources have taken place during this reporting period. Initial diagnostics with a direction towards optimization of system operation parameters is underway.

An enthalpy probe and a series of steady state calorimeters have been constructed for diagnostic purposes. The preliminary design of a concentric calorimeter probe to evaluate blocking effects has been accomplished. Figure 1 shows a schematic of the instrument. Data from this probe, when referenced against a standard calorimeter, will give information about the effect of heat shield pyrolysis gases on convective heat transfer to a model.

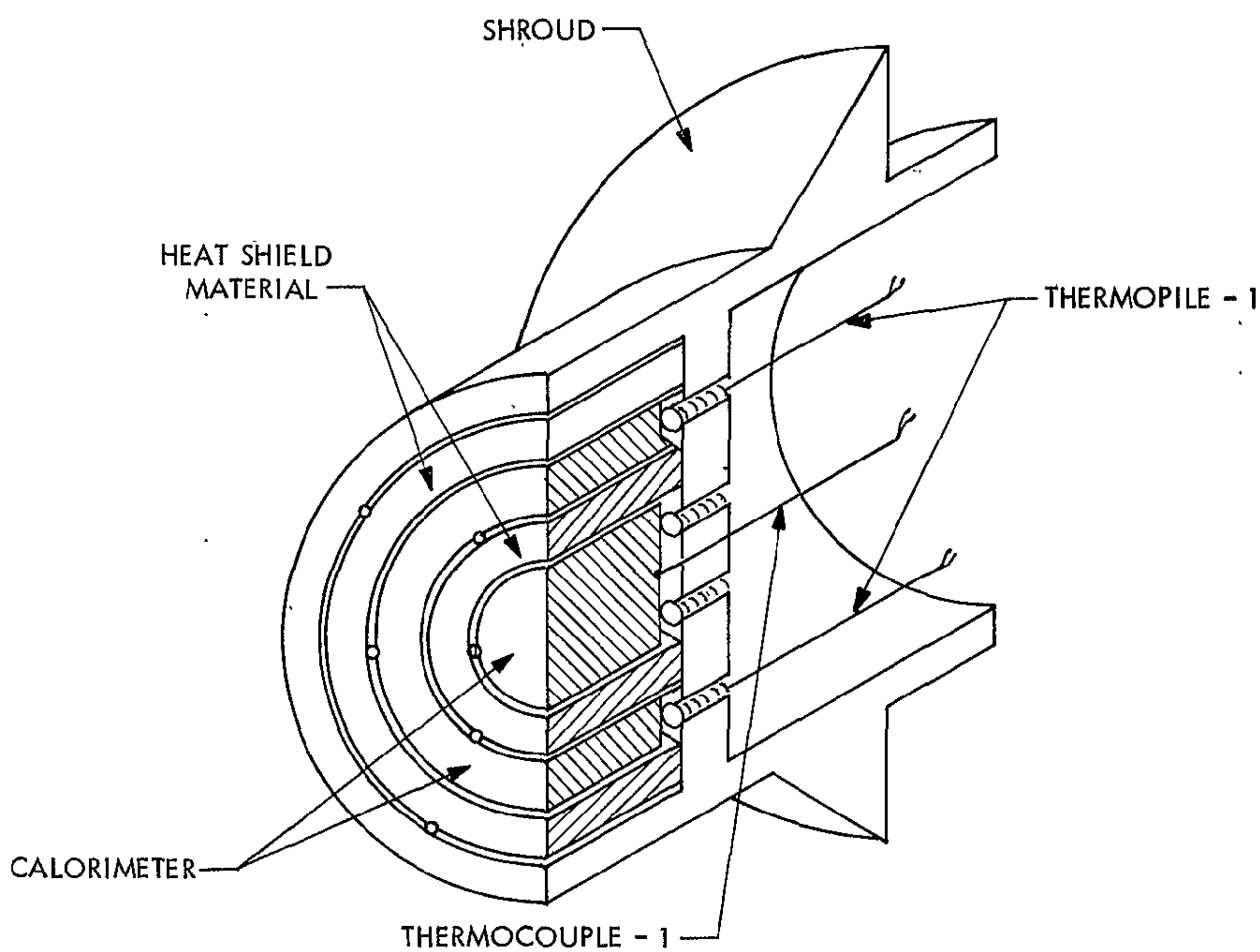
FUTURE PLANS

Installation and checkout of all remaining equipment including the vacuum system will be completed during the next reporting period. Calibration of the arc jet and radiant sources will be undertaken in order to provide a map of repeatable test conditions, and a definition and optimization of the parameters affecting them. Figure 2 gives a test plan for this calibration. Concentric calorimeters for convective blocking analysis will be constructed and initial tests run. Practice testing of material systems such as phenolic nylons will be accomplished to establish necessary techniques for reliable test programs.

Long range plans include the acquisition of the necessary equipment to permit greater Venus entry simulation. This will require new arc jet configurations and increased ac transformer capacity. Other long range needs include equipment to allow fine pressure and power control to permit pulsing operation, and an integrated data collection-reduction system to allow more rapid, more efficient, and more meaningful data analysis and test results.

PUBLICATIONS

None



NOTE: Size, number of rings, relative placement of heat shield and calorimeter sections, and materials are dependent on application

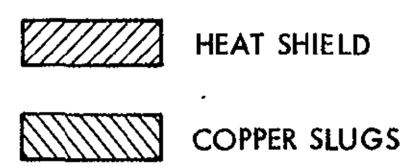
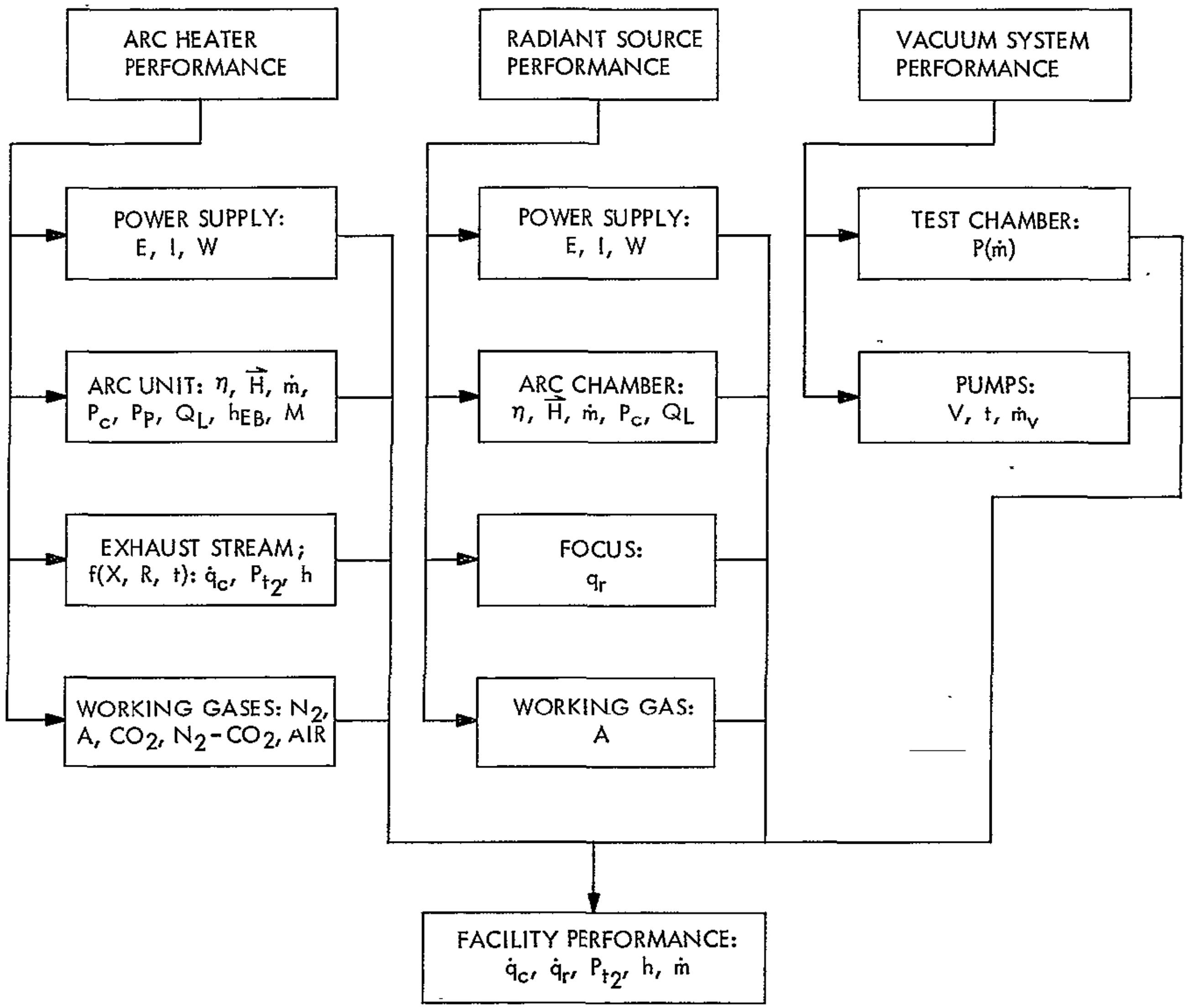


Figure 1. Concentric Calorimeter Conceptual Design



NOMENCLATURE:

E - VOLTAGE
I - CURRENT
W - POWER
η - ARC EFFICIENCY
X - AXIAL POSITION
R - RADIAL POSITION
t - TIME

$\dot{q}_c$ - CONVECTIVE HEATING
$\dot{q}_r$ - RADIATIVE HEATING
Q_L - HEAT LOSSES
P - LOCAL PRESSURE
P_c - ARC CHAMBER PRESSURE
P_P - PLENUM PRESSURE
P_{t_2} - IMPACT PRESSURE

$\dot{m}$ - MASS FLOW
$\dot{m}_V$ - PUMP THROUGH FLOW
M - EXIT MACH NUMBER
V - PUMPING SPEED
h - LOCAL ENTHALPY
h_{EB} - HEAT BALANCE ENTHALPY
$\vec{H}$ - MAGNETIC FIELD STRENGTH

Figure 2. Facility Calibration Plan

INTERCENTER ABLATION ANALYSIS AND SCREENING

NASA Work Unit 124-08-03-03-55

JPL 324-80601-2-3510

R. G. Nagler

OBJECTIVE

In order to maximize the effectiveness of heat shield research and development activities for extraterrestrial atmospheric entry, the complementary capabilities at JPL and the various NASA centers must be organized and coordinated with the anticipated mission requirements. Through an informal organization, such as the Intercenter Planetary Entry Heat Shield Coordination Group, JPL can distribute mission information, organize joint NASA Center test programs to delineate specific areas, and initiate experimental facility and analytical technique development to provide design tools on a timely basis.

PROGRESS

The major effort in the past reporting period has been the development of the planning document organizing the technology in heat shields for planetary entry. A flow chart of the planning concept used and its parallel planning system is shown in Figure 1. The main idea is a pyramid effect wherein the total technology can be compressed by steps into a manageable group of balanced programs. An extensive outline of technology has been completed with the basic contents of the outline shown in Table 1. Fourteen government and industrial organizations were contacted for help both in making the outline comprehensive, and in rating the individual parameters for their importance to particular missions and for the probability of getting a return on any investment made in a particular area. A five point rating system was used and the resulting summary sheets were found to be particularly informative in delineating organization bias and competence. From the first three rating levels, a list of approximately four hundred tasks was constructed. Five to ten percent were considered of critical importance. Another 25% were considered to have a significantly large effect on reliability, weight, and cost thus making accomplishment particularly desirable. The remainder of the tasks were long range technology where the benefits are not necessarily obvious. Funding in this latter area is also desirable, but

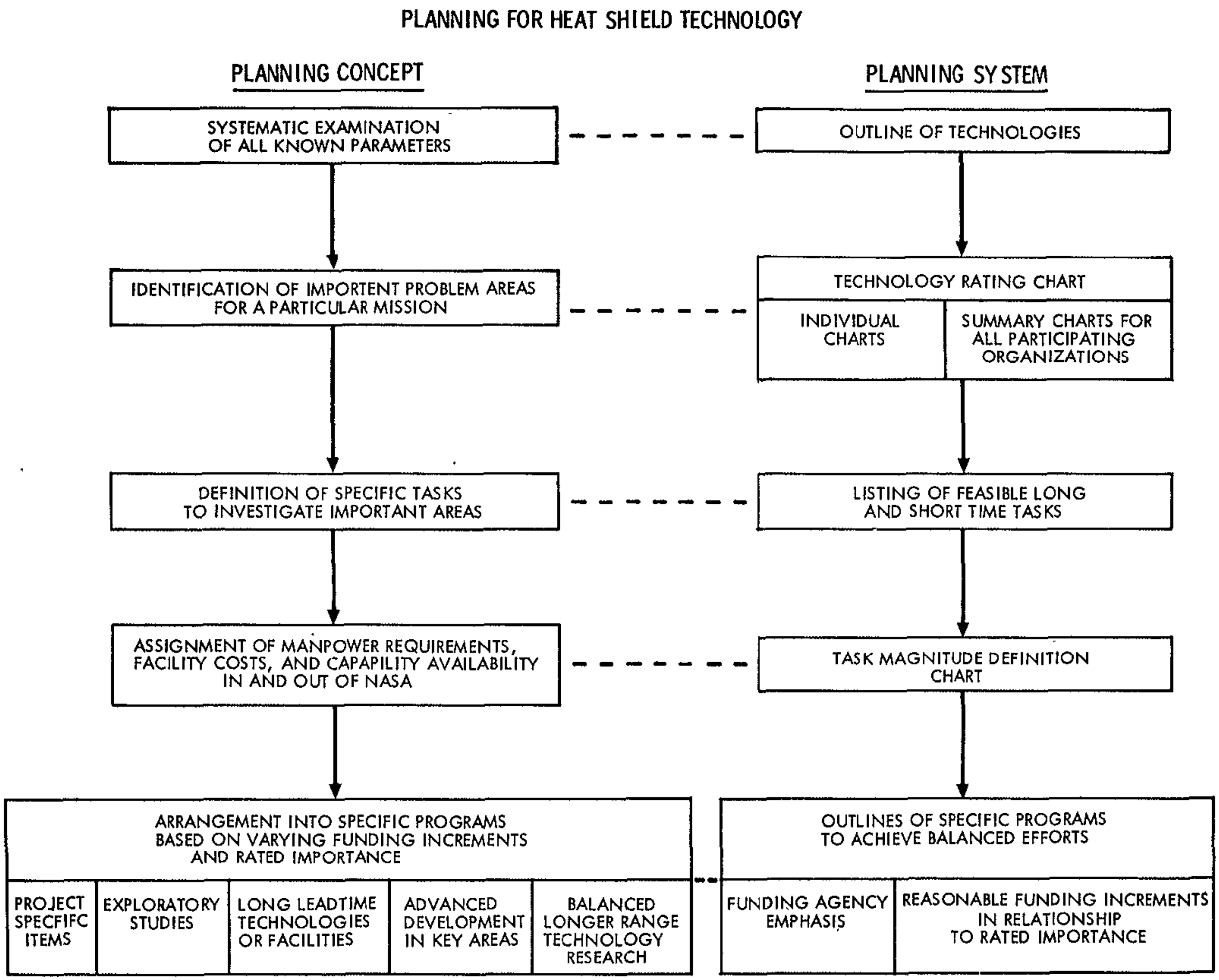


Figure 1. Planning for Heat Shield Technology

TABLE 1

Outline of Contents

I. Ablation Theory
II. Computer Program Development
III. Characterization and Physical Properties
VI. Thermal and Optical Properties
V. Mechanical Properties
VI. Electrical Properties
VII. Degradation Kinetics Investigations
VIII. Pre-entry Environmental Compatibility Tests
IX. Entry Simulator Development
X. Entry Simulation Testing
XI. Rocket Nozzle Testing
XII. Diagnostic Instrumentation Development
XIII. Flight Tests
XIV. Resin Development
XV. Filler Development
XVI. Composite Development and Fabricability Investigations
XVII. Nondestructive Testing
XVIII. Design Criteria and Parametric Studies for Design

choices of one area over another are not based on the relative merit of one task over another, but instead on the availability of competent, interested personnel. The effort remains at this stage with a preliminary list of tasks available and a number of the rating sheets still not completed.

No meetings of the Intercenter Planetary Entry Heat Shield Coordination Group were held in this reporting period since the Intercenter Review of Ablation Heat Shield Technology at Langley Research Center on October 15-17, 1968 adequately covered that function. Venus entry remains a major heat shield problem and a joint test program plan is in process.

FUTURE PLANS

As the remaining rating sheets are completed, the final task listing will take form. At that point, assignment of manpower and funding requirements for each task can begin. Combining the importance, ratings, and funding assessments, separate programs can be put together for each NASA funding office with the technical emphasis keyed to particular interests of that office. Program recommendations will be organized into alternate levels of funding so that the individual gains and losses of each level can be balanced against funding availability and NASA interests. All program recommendations will be sent to key Ames and Langley personnel for their review before submission to Headquarters.

A document entitled "Planning for Planetary Entry Heat Shield Technology" by Robert G. Nagler has been submitted for publication in the JPL SPS.

PUBLICATIONS

None

SPACECRAFT STRUCTURAL DYNAMICS

NASA Work Unit 124-08-05-02-55

JPL 324-80701-0-3530

E. Heer
M. Trubert
R. Simpson
J. Yang

OBJECTIVE

The objective of this work unit is to initiate and conduct a research program to discriminately examine the diverse techniques in spacecraft structural dynamics in the light of meaningful experimental data, and to synthesize a test and analysis approach which realistically simulates actual loading conditions. It is also the objective to define those areas requiring innovation and further study, to implement investigations in the most vital areas, and to incorporate the results into an integrated test and analysis approach for space vehicle structures.

MULTIPLE EXCITER AND EQUALIZATION TECHNIQUE

The analog equalizer has been debugged and is now operational. A check run at two points on a sample structure consisting of a simple beam has been made with good results. The actual running of a three-dimensional check test on a three-dimensional structure has been postponed until the spring of 1969. A paper describing this technique has been published in the Journal of Spacecraft and Rockets.

TRANSFER FUNCTION CONCEPT

RECEP Program

The computer program was written during the previous reporting periods. It is designed to compute the transfer functions of subsystems, combine these functions to compute the transfer functions of the entire coupled system, and then to compute the response due to determinate or random inputs. The main efforts are presently concerned with debugging. The input options currently allow experimental and analytical tape data inputs. A subroutine which accepts digital conversion from analog tape of experimentally determined transfer functions has been included and, for the most part, checked out. A subroutine to accept analytical modal data from the eigen-value computer program (SAMIS) has also been written and checked out. Further debugging of the program is currently under way using a time-shared computer.

Flight Data Analysis

A preliminary three-dimensional analysis based on the transfer function concept has been initiated to extract the induced loads at the booster gimbal blocks for utilization in subsequent flights. This approach will use flight data obtained from Mariner 69 and other previous space vehicles which have utilized the Atlas booster. The RECEP program will be used in this work.

Flexible Structure Control Interaction

An analysis of the effect of flexible appendages on the attitude control of a spacecraft has been carried out assuming small displacements to assure linearity. The frequency transfer function type of solution is proposed. The extension of the RECEP program to implement the analysis is under investigation.

FAILURE ANALYSIS AND RELIABILITY DESIGN

Stability Analysis of Linear Structures

A systematic unified approach to an extended theory of stability analysis, including the effects of initial shear forces and bending moments in structures before buckling, has been investigated. Network concept and transfer matrix techniques have been employed so that the geometric configuration of linear structure can be taken into account in a general fashion. This permits the convenient use of a high-speed digital computer for the numerical computation involved. A few numerical examples have been treated and the final report is presently in preparation.

Fatigue Failure of Structures

When a structure is subjected to a nonstationary random excitation, the distribution of peaks of the response process is no longer the Rayleigh distribution even if the response process is a narrow-band Gaussian. Since the peak distribution is essential in estimating the fatigue life, efforts have been made to establish the distribution of peaks of a nonstationary narrow-band Gaussian response process. It is found that the Rayleigh distribution can be used for approximation in some cases. The final report is now in the final draft form.

Catastrophic Failure of Structures

The bounding technique for the first passage problem was presented in two reports (refer to Publications). Further improvement on the upper bound of the first excursion probability is found to be possible and the results will be given in a report in preparation.

Optimum Design of Structures Based on Reliability and Proof Load Test

The mathematical formulation of the optimum structural design, taking into account the specified reliability of mission and the parameters of testing levels for components of the structure, has been formulated for the first time. The variational principle is used for the optimization of a statically determinated structure while the gradient move technique is used for a statically indeterminated structure. Specific application has been made to the optimum design of an aeroshell. Numerical examples show that considerable weight saving over the conventional optimum design is obtained. The optimum testing levels for components of the system can also be determined numerically from the formulation. A report of this work is in preparation.

PUBLICATIONS

Meetings and Symposia Papers

1. Heer, E. and Trubert, M. R., "Analysis of Space Vehicle Structures Using the Transfer Function Concept," presented at the 19th Congress of the International Astronautical Federation, New York, October 14-18, 1968 (to be published in the Congress' Proceedings).

Open Literature

1. Trubert, M. R., "An Analog Technique for the Equalization of the Multiple Electromagnetic Shakers for Environmental Vibration Testing," Journal of Spacecraft and Rockets, December 1968.

JPL Technical Reports

1. Yang, J. N. and Shinozuka, M., "On the Bound of First Excursion Probability," Jet Propulsion Laboratory, TR 32-1304, August 15, 1968.

2. Yang, J. N. and Shinozuka, M., "A Note on the First Passage Time Problem, "Jet Propulsion Laboratory, TR 32-1334, October 15, 1968.

3. Lutes, L. D. and Heer, E., "Receptance Coupling of Structural Components Near a Component Resonance Frequency," Jet Propulsion Laboratory, TM 33-411, October 15, 1968.

STUDY OF SOME TECHNIQUES AND LIMITATIONS OF ACOUSTIC NOISE SPECTRUM SHAPING

NASA Work Unit 124-08-05-04-55

JPL 324-81001-7-3740

C. D. Hayes
R. C. Woodbury
R. Slusser

OBJECTIVE

The objective of this work unit is to develop techniques to control high intensity sound in a reverberant chamber to ensure accurate simulation of the sound fields generated by spacecraft vehicles during launch and transonic flight.

The program consists of three broad areas of investigation:

(1) Spectrum shaping using sound absorber materials.

(2) Nonlinear parameters effecting the propagation of high intensity sound.

(3) Investigation of sound generator requirements to produce low and high frequency acoustic fields.

ACCOMPLISHMENTS

Sound Absorber Studies

A mathematical model of an acoustic chamber has been developed to predict the acoustic absorption coefficients of absorber materials required to shape specified high frequency spectra.

A 7 cu ft chamber has been fabricated to permit verification of the math model and to establish scaling errors when applied to the JPL 1000 cu ft chamber. Absorption coefficients have been measured for various absorber materials using standing wave techniques. Also, sound absorption as a function of humidity, temperature, and frequency has been measured. These data will be used with the math model to investigate the limits of high frequency spectrum control.

A one-third octave digital computer program using the Fast Fourier Transform has been developed to provide high-confidence spectral analysis of the sound field applied to acoustic absorber materials. Details of this computer program were presented as a paper to the Acoustical Society of America in November 1968.

Nonlinear Parameters Affecting High Intensity Sound

Four 4000 acoustic watt air modulators were procured for installation in the JPL 1000 cu ft reverberant chamber to permit study of the apparent variation in the acoustic absorption coefficient with sound intensity. Cancellation of funds has prevented the installation of these transducers, and no further work has been done in this area.

Sound Generator Studies

A model of a high-frequency sound generator, using piezoceramic material, was fabricated and preliminary data obtained. The data tend to support the feasibility of using this technique to increase the high-frequency response of a reverberant chamber. Lack of funds has terminated this effort.

STATUS

Absorber Materials

Studies completed demonstrate the feasibility of using absorber materials to control the shape of the high-frequency sound field where attenuation rates within 6 to 12 db/octave above 800 Hz are required. The feasibility of determining absorption coefficients and type of absorber material required, using small chambers and scaling to larger chambers, has yet to be demonstrated.

High Intensity Sound

High-intensity air modulators and a high-intensity microphone calibration system has been acquired to perform experiments relating to nonlinear high intensity sound. Lack of funds has terminated this effort.

Sound Generators

Preliminary experiments suggest the feasibility of using piezoceramic transducers to extend the high-frequency sound field in a reverberant chamber. Lack of funds precludes further work in this area.

FUTURE PLANS

No further work is possible because of project cancellation.

PUBLICATIONS

Meetings and Symposia Papers

1. "Digital Technique for Determining One-Third Octave Sound Pressure Levels with More Uniform Confidence Level," Acoustical Society of America, November 1968.

SPACECRAFT SHELL STRUCTURES

NASA Work Unit 124-08-06-03-55

JPL 324-80101-0-3530

J. R. Chisholm

OBJECTIVE

The objectives of this work unit are to complete the consolidation of the structural analysis and matrix interpretive system (SAMIS) for use in structural status and dynamic analyses, and to investigate areas in applied mechanics at JPL which could take advantage of new automatic data processing capability.

PROGRESS

A plot routine was developed to provide graphical presentations of mode shapes generated by the SAMIS program.

PLANNED ACTIVITIES

None

PUBLICATIONS

JPL Technical Memorandum

1. Bamford, R. M., "Application of Structural Analysis and Matrix Interpretive System," JPL TM 33-399, October 15, 1968.

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PLANETARY ENTRY AEROSHELL STRUCTURES

NASA Work Unit 124-08-06-04-55

JPL 324-80201-0-3510

R. A. Boundy

OBJECTIVE

The long range objective of this work unit is to understand and advance the state of the art in fabricating large, lightweight aeroshell structures needed for planetary entry missions. In FY 69, the specific objectives are (1) to complete the development task on contract at Rohr Corporation, (2) to continue data correlation, (3) to investigate several new material combinations that show potential for Venus entry missions, and (4) to examine nondestructive testing (NDT) techniques as applied to the materials and structures of interest in this work unit.

PROGRESS

The contract work at Rohr Corporation (JPL Contract 951612) was completed in December, 1968. A final report is presently being evaluated by JPL prior to being released for publication. A supplement to the final report is being prepared and should be available in the third quarter of FY 69.

The final report covers the following areas:

(1) Reinforced Plastic Honeycomb Sandwich Panels

(2) Aluminum Honeycomb Sandwich Panels

(3) Small Doubly-Curved Aeroshells (Reinforced Plastic)

(4) Small Doubly-Curved Aeroshells (Aluminum)

(5) 6-1/2 ft Diameter Aeroshells (Reinforced Plastic)

The supplement to the final report will cover the results of the S-glass evaluation (E-glass reinforcement was used in all previously reported material combinations), as well as fabrication of several new two-foot diameter doubly-curved aeroshells. These include one aeroshell with a 1/2-in. thick core (compared to the standard 3/4-inch thick core), two all-aluminum aeroshells, one aeroshell with a partial torus at the periphery, and one aeroshell with polimide-fiberglass face sheet. The latter aeroshell was made with the standard phenolic core when attempts by Rohr and the material suppliers to produce double curvature in polyimide core were unsuccessful. Because of funding limitations, the planned high temperature adhesive evaluation was deleted from the scope of effort under the contract with Rohr Corporation.

The two 6-1/2 ft diameter phenolic-fiberglass aeroshells completed during the last report period are described in detail in JPL TR 32-1325. The fabrication of these aeroshells was supported by other funding, but benefited directly from the experience gleaned from this work unit.

To verify the reproducibility of minimum gauge honeycomb sandwich aeroshells, eight identical two-foot diameter aeroshells were purchased on a fixed price basis with funds from another source. The eight aeroshells were delivered during this report period. The first aeroshell has been instrumented with seventeen strain gages and will be ready for testing early in the third quarter of FY 69. The test fixture, shown in Figure 1, has been completed and checked out.

In October 1968, a local seminar sponsored jointly by SPE and SPI on "NDT as Applied to Laminates and Sandwich Structures" was attended. Ultrasonic, microwave, thermal, and holographic interferometric techniques were reviewed in detail. Initial planning was done to evaluate specific NDT approaches to sandwich structures.

During this report period, no new material combinations were evaluated at JPL.

FUTURE WORK

The final report and its supplement on JPL contract 951612 will be thoroughly analyzed to maximize the usefulness of the data. The test program to verify fabricability of two-foot diameter aeroshells will be continued, and should be completed during the last half of FY 69. New material combinations for potential Venus entry missions will be defined. If a facility is available, an

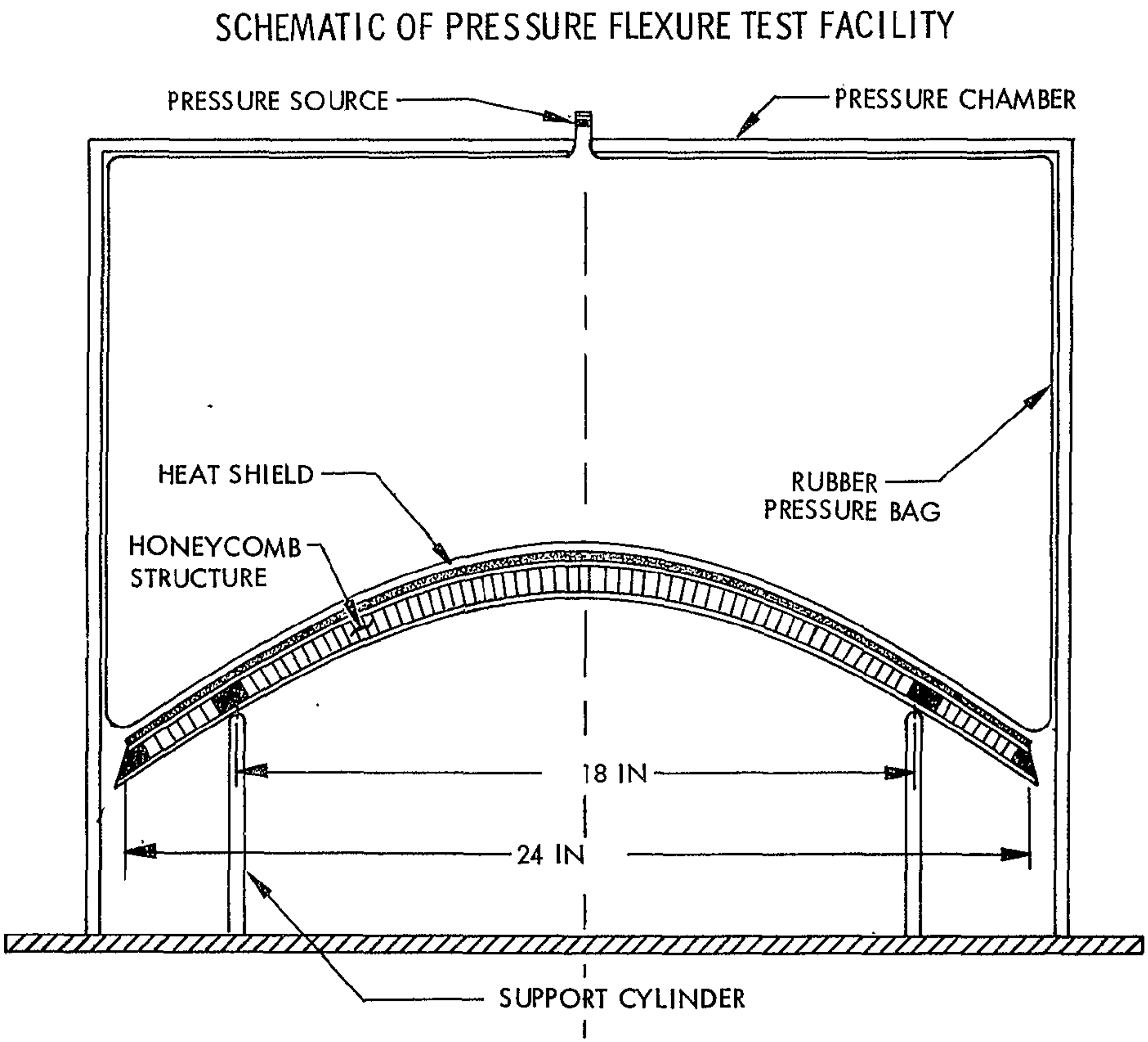

Figure 1. Schematic of Pressure Flexure Test Facility

all-polyimide sandwich panel will be tested as well as panels of phenolic-fiberglass. (There is some indication that sandwich combinations of polyimide face sheets and phenolic core with a high temperature adhesive has potential for Venus entry). The effort to evaluate NDT methods for aeroshell sandwich structures will continue.

PUBLICATIONS

JPL Technical Reports

Nagler, R. G. and Boundy, R. A., (Jet Propulsion Laboratory), and Scholl, J. A. and Dowson, J. E., (Rohr Corporation), "A Lightweight 6-1/2 ft Aeroshell for an early Mars Probe Mission" TR 32-1325, September 15, 1968.

SPACE ENVIRONMENTAL FACTORS (124-09)

EFFECT OF ENVIRONMENT ON SPACECRAFT THERMAL CONTROL MATERIALS

NASA Work Unit 124-09-18-01-55

JPL 324-90401-2-3510

W. F. Carroll

OBJECTIVE

The objective of this work unit is to plan and perform analytical and experimental tasks which will improve the utilization and assure high reliability of materials used for spacecraft temperature control. This will include the effects of various environments on the optical properties of thermal control materials as well as a study of the materials problems associated with active temperature control devices.

PROGRESS

Photolysis of Thermal Control Coating Materials

Work continued during the first quarter of FY 69 at Stanford Research Institute (JPL Contract No. 951522) on photolysis of pigments and methods to prevent degradation. The aim of this program is to provide active surface sites to prevent photo produced changes. Delays in contract negotiation have prevented significant progress during the second quarter.

The effective protection provided by the FeII/FeIII Couple, which was indicated by resistivity measurements reported during the previous period, has been verified by optical tests. Samples of treated powder were prepared and supplied to Dr. John Shutt of NASA Goddard Space Flight Center for test. Samples were irradiated for 70 hours at 5X solar ultraviolet intensity. One of the treated samples showed barely detectable degradation, less than 1/5 that of the control (untreated) sample. The other sample, treated at a lower concentration showed anomalous, as yet unexplained, behavior. No attempt has been, or will be, made under this program to optimize the treatment.

The significance of this result is apparent verification of the theory and selection of surface additive stabilizer materials based on basic chemical behavior characteristics, rather than trial and error radiation damage studies.

Photo-conductance measurements of treated single crystals have continued with candidate additive materials.

Electron spin resonance (ESR) studies were resumed during the period as a sensitive means to evaluate application of additives to powders and the resulting radiation stability. Based on the limited work to date, it appears that the behavior of the resonance at $g = 1.96$ will provide an index of the effectiveness of additives.

As a first step in applying the concept to other pigment materials, experiments were begun to study electron injection into ZrO_2. Insufficient information has been obtained at this time to postulate applicability to ZrO_2.

FUTURE PLANS

Investigations under this contract will continue during the second half of FY 69, but due to contract delays, completion of the work will probably extend into FY 70. Additional applied development will ultimately be required to reduce the fundamental technology to practical engineering use.

Electron injection studies on ZrO_2 and other candidate materials (selected on the basis of criteria described in the previous semiannual report) will be continued to identify candidate surface additive systems.

Resistance measurements will continue for other additive systems for ZnO and, subsequently, for additive systems for other pigment materials.

Similarly, electron spin resonance will continue on ZnO additives and then extended, if applicable, to other pigments.

SPECIAL ACTIVITIES

During the second quarter of FY 69, personnel from SRI and JPL participated in an information review and discussion of photolysis of coating materials. This was the third meeting, held at approximately one year intervals.

PROGRESS

Development of S-13G (JPL Contract 951737)

Work planned for the first quarter of FY 69 was delayed by lack of manpower, and by environmental test equipment problems at IITRI. The work was not completed until late in the second quarter.

FUTURE PLANS

A comprehensive report, including test results and required processing procedures and controls, will be completed and prepared for distribution during the third quarter of FY 69.

PROGRESS

Materials for Active Temperature Control Devices

Due to limitations in available manpower, it was not possible to accomplish the preliminary evaluations which had been planned for this period.

FUTURE PLANS

During the second half of FY 69, the problems of material utilization, compatibility and stability for typical active devices will be reviewed. Major problem areas will be defined and requisite experimental investigation initiated.

PUBLICATIONS

None

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TEMPERATURE CONTROL OF SPACECRAFT

NASA Work Unit 124-09-18-02-55

JPL 324-90501-0-3530

W. A. Hagemeyer
J. Schwartz

OBJECTIVE

The long range objectives of this work unit are to develop advanced test techniques and active thermal control devices for future spacecraft. For the current fiscal year, the objectives were (1) to continue to monitor a contract for research on transient thermal scale modeling at the University of Illinois, and (2) to continue research leading to an understanding of heat and mass transfer in heat pipes.

THERMAL SCALE MODELING

This work is being performed under JPL Contract 951660 at the University of Illinois and is intended to develop techniques of transient thermal scale modeling.

Efforts during this reporting period concentrated on the checkout and calibration of the facility with the Genarco carbon arc solar simulator. Difficulties in distribution and intensity were encountered in attempting to obtain a stable solar beam. To resolve these difficulties required considerable experimentation with the arc power controls and the optics.

In September the beam was considered acceptable for test although the beam size was smaller than desired.

The small solar beam size precluded a test of the full scale model since it was larger than the beam. Both transient and steady state temperature data have been obtained on the one-half and one-quarter scale models.

Preliminary data indicates agreement between these models, at least as good an agreement as that obtained with electric heaters, although a final analysis has not been performed. This program will be completed during the next reporting period.

In July and August of 1968, the heat pipe performance was observed and analyzed during space simulator tests of the M'69 proof test model and Flight 1 spacecraft. The radio was operated in low as well as high power modes for various phases of the mission, including the encounter and playback modes. These tests indicated that (a) the radio temperatures were lower than previously predicted (due apparently to less internal power dissipation than quoted earlier), and (b) the TWT temperatures did not change whether the heat pipes were on or off the spacecraft.

Heat pipe comparison tests using a localized heat source were performed in a parallel effort with the simulator tests. The data agreed with that obtained from the simulator tests thus confirming the fact that the temperature profiles of the test plate did not differ significantly with or without the heat pipes.

In the latter part of September, it was decided that no heat pipes were to be flown on M'69. This decision was based primarily on the analysis of the space simulator data.

The data placed strong emphasis on the need to understand how to incorporate a heat pipe in any system, particularly a system which is similar to that on M'69. Preliminary analysis suggested that the largest portion of the heat was conducted through various paths without reaching the heat pipe, and only a small part was actually transferred by it. This phenomenon occurred in the simulator tests as well as in the comparison tests.

A comparison test is now underway which utilizes the flat plate and heaters of the previous tests. In this test, however, both heat pipes are attached directly to the heaters with the remaining sections bolted to the plate. Unlike the previous test runs, only one heater is attached to the plate while the other does not come in contact with it.

The purpose of this test is to demonstrate whether the heater will reach a lower equilibrium temperature than that obtained during the previous comparison tests, and whether the temperature profile of the test plate is relatively flat compared to the earlier tests.

In September, work was contracted to Professor K. T. Feldman of the University of New Mexico. In this study, computer techniques are utilized to construct a mathematical model of the comparison test set-up. Parameters such as plate and heat pipe physical dimensions will be considered constants. Parametric studies of variables such as plate thermal loads, gap size between the heat pipe and the plate, and various thermal boundary conditions will be presented in the output data.

The purpose of this study is to gain a better understanding of the heat pipe-radiator coupling.

As a result of substituting ammonia for water in the heat pipe, the pinch and electron beam weld sealing technique was unsuccessful. Although the heat pipe was immersed in liquid nitrogen prior to the welding of the pinched fill tube, excessive internal pressure in the weld area was generated by the beam which literally blew the weld apart before effective sealing was achieved.

A new sealing technique was therefore devised which utilized a tapered set screw and a stainless steel plug welded to the heat pipe. The plug, with an internal machined sharp edge seat, effects a good seal with the tapered head of the set screw. The ends of the plug and screw are later electron-beam welded as a precaution against turning the set screw and breaking the seal.

During this period, a new filling technique was also devised utilizing a fill mechanism which was designed specifically for the plug-set screw combination. This filling technique is interchangeable with the technique used previously if some fill mechanism modifications are made.

In August, six heat pipes were placed on life test. Three were filled with water, two with ammonia (NH_3) and one heat pipe filled with water and a trace (0.5%) of ammonia. Each heat pipe had a resistance heater at one end and a calorimeter condenser at the other end. Eight evenly spaced thermocouples were spotwelded to each heat pipe. The purpose of this test is:

(1) To determine whether the performance of any or all heat pipes deteriorates with time.

(2) To determine whether noncondensible gases are generated in any or all heat pipes, and to predict the rate of generation. If the temperature curves along the heat pipes indicate that there are non-condensible gases being generated, a spectrographic analysis will be made to determine the specific composition of the gas.

The temperature data to date indicated that both the water and the ammonia-water heat pipes deteriorated with time over a three month period. The ammonia heat pipes indicated no performance change over the same period. Plans are to submit one water and one ammonia heat pipe to spectrographic analysis, and keeping the remainder in the life test.

Future heat pipe activities involve:

(1) Development of a performance map of an ammonia heat pipe. This includes temperature versus heat load tests, variable condenser length investigations, elevation tests, and multi-component fill fluid investigations.

(2) Wick studies, including the design and assembly of an apparatus which will measure wick parameters such as permeability and effective pore size.

(3) Determining the influence of various physical parameters on the heat load. This includes studies of physical dimension variations, such as heat pipe diameter and length, wick mesh size, and the number of layers employed. In addition, the type of fill fluid and the amount will be investigated.

PUBLICATIONS

SPS Contributions

Schwartz, J.; "Heat Pipes," SPS 37-54, Vol. 1, January 1969.

CONDUCTION AND RADIATION IN SPACECRAFT TEMPERATURE CONTROL

NASA Work Unit 124-09-18-03-55

JPL 324-90601-0-3530

W. A. Hagemeyer
J. A. Hultberg

OBJECTIVE

The long-range objective of this work unit is to develop advanced analytical data, design, and test techniques for the prediction of conduction and radiation heat transfer in spacecraft. The current fiscal year objectives are (1) to improve computer analysis of temperature control, (2) to continue studies of real-surface radiation and computation techniques to obtain a practical solution, and (3) to experimentally verify that laboratory determined values of joint conductances versus pressure and analytically determined pressure loadings in plates can be combined to derive the heat transfer across a given geometry.

REAL SURFACE EFFECTS

In continuation of NASA Research Grant NGR 14-005-036, JPL awarded NASA/JPL Contract 951661 in the amount of $51, 821 to the University of Illinois for one year beginning September 1966. The contract was extended an additional year in December 1967 at a cost of $29, 891.

Work has progressed in the three major areas of research:

(1) evaluation of radiant heat transfer analysis techniques

(2) development of analytical surface radiative models for use in the heat transfer analyses

(3) construction of a facility for measuring surface radiative properties

In the radiant heat transfer analysis area, a computer program has been developed for evaluating heat transfer and temperature profiles in a specified geometry using various surface property models. Provision has been made for more complex geometries as the need arises. This program utilizes an iterative solution to the integro-differential equations of heat transfer. Many cases have been run to compare the accuracy of this program with results obtained by other investigators.

Comparing results, using direction independent surface properties, resulted in local heat transfer rates within two percent of published results.

Results using the surface properties based on electromagnetic theory (Beckman Model) were within three percent of published results.

Because of this good agreement with the work of other investigators, the program is considered ready to use. It will form the basis for comparison with the results of more simplified analytical techniques.

A Monte-Carlo technique has been investigated as an alternative to the iterative technique. Although the results were encouraging, the accuracy of the program used was not as good as the iterative technique. No further effort will be expended on this approach unless the iterative solution becomes intractable.

At the present time, two bi-directional surface property models have been evaluated; the Beckman model for optically smooth surfaces, and the one-dimensional vee-groove model for optically rough surfaces. These two models appear to adequately describe radiant heat transfer effects in the plane of incidence for all ranges of optical roughness. The Beckman model also describes out-of-plane radiant heat transfer, but the vee-groove model must be expanded for out-of-plane characteristics.

The vee-groove model has been utilized in the computer program described previously, but there are no other results for comparison. Comparisons have been made with the direction independent property models which indicate errors in heat flux as high as 20 percent.

The bi-directional reflectance measurement facility has been operated. This facility is capable of measurements only in the plane of incidence. Calibration runs have been made and selected samples have been measured.

Several minor problems have been uncovered, but preliminary data indicates qualitatively good agreement with expected results. As the problems are resolved, more comprehensive measurements will be made.

COMPUTER PROGRAMS

The three major computer programs used in thermal analysis at JPL, (CINDA, CONFAC, and TAS), have been performing without any system or program software difficulties on the JPL 7094/7040 direct-couple system. Early in the calendar year 1969, JPL will convert its computer operations from the present 7094/7044 system to a Univac 1108, operating with EXEC 8 software. JPL has funded the cost at converting operating programs on the 7094 to the EXEC 8 Univac 1108 system. The conversion team has been supplied with the source programs, and sample problems for the programs which are used for thermal analysis. These programs are CINDA, CONFAC, TAS, Radiation Tolerance Program, the Lockheed Orbital Heat Flux Program, and the GSFC thermal analyzer. All of these programs, with the exception of CINDA, are predominately coded in Fortran IV and should offer no particular conversion problems.

The current status of the conversion is as follows:

(1) CONFAC; operational on JPL Univac 1108, EXEC 8.

(2) TAS; operational on Univac 1108, EXEC 2, not at JPL, conversion in progress.

(3) CINDA; operational on Univac 1108, EXEC 8, NASA Michoud, program will be obtained from Chrysler, New Orleans (program developed at government expense)

(4) Radiation Tolerance Program; conversion in progress

(5) Lockheed Orbital Heat Flux Program; conversion in progress, some Fortran IV subroutines must be substituted for machine language subroutines.

(6) GSFC thermal analyzer; in progress.

JOINT CONDUCTANCE

A second series of tests are currently being performed in the joint conductance facility on flat plates, where one plate is subjected to bolt type pressure distributions where the heat flow is from the periphery while the circumference of the other plate is being cooled by a fluid circulating in a tube cemented to the edge of the plate. The fluid is cooled by a liquid chiller. The bolt type pressure distribution is simulated by a dead weight loading apparatus. The entire test is being conducted in a vacuum at better than 5×10^{-5} mm Hg.

Contrary to expectations, the first series of tests did not indicate a significant dependence of the temperature distribution on the loading pressure. The first test samples consisted of as-machined plates with a considerable amount of waviness. It can be postulated from the test data that waviness effects dominated the pressure effects which caused the plates to separate at a distance of about two loading diameters from the center of the load.

In the second series of tests currently in progress, the plates have been lapped to give the highest degree of flatness available without using exotic machining methods. This should minimize waviness effects and the heat flow should reflect a more direct function of load.

Once the joint conductance tests are completed, sterilization tests will be performed in the apparatus. Previous sterilization work, using the joint conductance apparatus, produced significant results and the sterilization group is anxious to resume these tests.

PUBLICATIONS

Contractor Reports, Interim and Final

1. "Radiant Heat Exchange in the Space Environment," Scientific Technical Report No. 4, Contract No. 951661, September 30, 1968.

TEMPERATURE CONTROL MATERIALS APPLICATION DEVELOPMENT

NASA Work Unit 124-09-18-05-55

JPL 324-91601-x-3510

J. C. Lewis

OBJECTIVE

The objective of this work unit is to develop materials technology and processing information which can be used for application of temperature control materials to spacecraft or capsule surfaces where conventional methods are inadequate.

During FY 69, the objective is to develop a system of coating in forms like tape which can be applied by means of pressure-sensitive adhesives, or in-situ cured adhesives. In addition to the obvious advantages of repairability, quality control, schedule, etc., such a system will permit use of materials for temperature control that would otherwise be prohibited by requirements for surface preparation, cure cycle, or reproducibility.

PROGRESS

Effort on this program has been centered on general purpose methods for applying temperature control materials to a variety of spacecraft surfaces rather than on the temperature control materials themselves. Within this approach, tapes and thin films are predominant. Potential failure modes have been defined as:

(1) Blistering; It is necessary to determine the maximum size and limiting size of blisters.

(2) Outgassing contamination

(3) Entrapped gas; crinkling, formation of bubbles

(4) Thermal expanion; curling

(5) Debonding; loss of tack

(6) Dimensional stability

(7) Temperature Effects; thermal shock

(8) Sterilization Effects

A 12-inch square heated plate for thermal-vacuum cycle of temperature control tape materials has been designed and purchased. The heater is sandwiched between two 0.063-inch thick aluminum plates to give a total plate thickness of approximately 0.150 inch. The maximum temperature capability of the plate is 450°F. Ten thermocouples internally monitor the plate temperature at five points on each surface.

A commercial aluminum, FEP Teflon laminate with pressure sensitive silicone adhesive, has been purchased in 1-inch, 2-inch, and 25-inch widths for use as the first step toward evaluation of tape temperature control materials.

Contacts have been made with other investigators working with temperature control tapes. Facilities contacted were NASA Langley Research Center; NASA Lewis Research Center; G. T. Schjeldahl Company, Northfield, Minn.; McDonnell-Douglas Corporation, St. Louis, Mo.; General Electric, Valley Forge, Pa.; North American, Rockwell Corporation, Downey, Calif.; and TRW Systems, Redondo Beach, Calif.

FUTURE PLANS

The thermal-vacuum test apparatus described previously will be used to test selected temperature control tapes. The plate will be covered with tape and then heated in a vacuum chamber with a liquid nitrogen shroud. Attempts will be made to simulate spacecraft temperatures and thermal shock for severe but real conditions such as sun occultation at Mercury. Actual problems will be defined. Degradation will be monitored by energy balance methods.

Further detailed contact will be made with the various investigators working in this field to define actual problems and exchange information on past, current, and planned activities in order to achieve maximum effectiveness for the program.

PUBLICATIONS

None

TEMPERATURE CONTROL ON A PLANETARY SURFACE

NASA Work Unit 124-09-18-06-55

JPL 324-91701-0-3530

W. A. Hagemeyer

D. Ting

OBJECTIVE

The objective of this work unit is to maintain cognizance of the state of the art of temperature-controlling a payload on a planetary surface, and to develop means of deducing significant environmental parameters by use of commonly used engineering telemetry sensors. For this fiscal year, the immediate objectives were to: (1) contractually investigate and experimentally measure values of free and forced convection coefficients for assumed Mars atmospheres, and (2) develop a thermal model of the Mars environment and investigate the effects of the controlling parameters.

HEAT TRANSFER IN A MARS ATMOSPHERE

Contract 952374 was awarded to Purdue University in November 1968 to perform an analytical and experimental investigation of heat transfer in a simulated Mars atmosphere. The contract amount is $25, 000.

A purchase request was issued by the University to several vendors for a fixed price quotation for constructing a test section of the low density wind tunnel. A detail design report of the low density wind tunnel will be issued no later than February 1969.

Analytical computations have not been initiated and probably will not start until the end of January 1969. A literature search has been started.

By the end of FY 69, experimental results shall be obtained for a flat plate as follows:

(1) Hydrodynamic boundary layer of the fluid flow.

(2) Thermal boundary layer and the film coefficient.

THERMAL MODEL

Because of insufficient manpower, this task will be undertaken in the second half of this fiscal year.

PUBLICATIONS

None

SOLAR SPECTRUM SIMULATION RESEARCH

NASA Work Unit 124-09-19-01-55

JPL 324-90701-2-3750

R. E. Bartera

OBJECTIVE

The purpose of this work unit is to improve laboratory predictions of spacecraft thermal performance in flight. In order to predict thermal performance of craft with non gray surfaces, it is necessary to determine the actual extraterrestrial solar spectrum and to duplicate it with sufficient accuracy in space simulation facilities. The unit objective has been to determine the actual solar spectrum, and the unit is now phasing into finding efficient ways to duplicate it.

STATUS

X-15 Flight Data

Since future efforts in this work unit will be critically dependent on the results of this unique extraterrestrial solar spectrum measurement, care has been taken in reduction of data obtained from the X-15 flight. Several complete recalibrations of the radiometers were made aboard the NASA CV-990 aircraft and at the JPL Table Mountain and Edwards Test Station facilities. Sufficient data are available to give adequate confidence in the measurements. Results will be available for review in the very near future.

Meteorological Observations

During measurements at Table Mountain and Edwards, two apparently unrelated phenomena which might be of interest to meteorologists were noted. Variations in the total solar irradiance of about 1% (presumably due to water vapor and/or aerosols) are preceded (approximately 1/2 hour) by variations in the 350-400 nm region of about 10%. During simultaneous measurements at both sites on very clear days, the solar spectrum at one site underwent changes in the space of less than one hour, indicating increased water vapor in the atmosphere. No attempt was made to interpret these observations, but is may be that filter radiometry of this type may be of use in micro-climatology.

Spectrum Modification - Filters

A large portion of our effort during the reporting period was an in-depth study of the practicality of several methods of modifying the spectrum in solar simulators. This is the subject of a report now in preparation.

The largest amount of information is available on filtering techniques which have been used by others with reasonable success. Reflective type filters are used to reduce the intensity of the 800-920 nm xenon line structure to an acceptable level, but there is also an undesirable reduction in intensity one octave away at 400-450 nm and transmission drops rapidly below 270 nm. The reduction in total irradiance in the test plane amounts to about 30%. Considering thermal degradation of the filters, they can certainly be used in the JPL space simulators for tests requiring one solar constant. They would be marginal at two solar constants (Venus) and inadequate at higher levels (e.g., Mercury). It is believed that the currently available filtering techniques are not an acceptable long-term solution.

Spectrum Modification - Additives

Several years ago at JPL, a study was made of the effect of various additives to the primary gas. These included both gas mixtures and metallic elements. No useful results were obtained although a means was established to control the partial pressure of mercury in an operating lamp. Mr. Neuder, of NASA Goddard, has done more recent work in gas mixtures with apparently good results, but details are not yet available.

Spectrum Modification - Magnetics

Because of limited resources, effort in magnetic arc construction has remained qualitative. It is known that a longitudinal magnetic field of about 55 gauss causes both an increase in arc brightness and a shift of the spectrum toward the UV. Plans are to concentrate most of the unit's efforts in this area during the coming months.

PUBLICATIONS

Meetings and Symposia Papers

1. Laue and Drummond, "Instrumental Problems in Precision Measurements of Solar Radiative Fluxes Above the Earth's Surface," IAF Paper AS176, 19th Congress of IAF, New York, October 1967.
2. Laue, "Measurement of Solar Spectral Irradiance as Measured at Different Terrestrial Elevations," 4th Annual Meeting of the Solar Energy Society, Palo Alto, Calif., October 1968.

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TEMPERATURE CONTROL FLUX MONITOR

NASA Work Unit 124-09-19-02-55

JPL 324-90101-0-3530

W. A. Hagemeyer
J. A. Plamondon

OBJECTIVE

The objective of this unit is to convert the Absolute Cavity Radiometer (ACRAD) from a laboratory instrument to a flight instrument for implementation as an engineering experiment on the Mariner Mars 1969 spacecraft. The purposes of this experiment are to support temperature control engineering Research and Advanced Development goals, and to provide flight instrumentation for the spacecraft's temperature control subsystem. The flight version of ACRAD has been renamed the "Temperature Control Flux Monitor," or TCFM.

DEVELOPMENT OF THE TCFM

The TCFM is being built under NASA/JPL Contract 951792 with TRW Systems Group for a contract cost of $736,934. Deliverable major items under Modification 8 of the contract are breadboard electronics and a transducer (radiometer), a flight prototype transducer, five flight electronics packages and seven flight transducers, and one laboratory test set and three system test sets.

At this time, all flight units have been delivered with the exception of one spare transducer. This spare transducer is being reworked to correct a manufacturing flaw and should be delivered in the next three to four weeks. All flight units have completed flight acceptance testing and the PTM unit has completed type approval testing. Throughout the type approval and flight acceptance test programs, no failures occurred that could be classified as fundamentally serious. Most failures during the test programs were of the piece-part type. These failures resulted from reworkable manufacturing flaws or component mortality. No unit has experienced a failure after completion of flight acceptance testing. Most units have accumulated more than 1000 hours of operating time each.

Performance testing of each unit has progressed on a periodic basis. From these periodic performance tests, it has become apparent that all transducers have experienced long-term drift in the temperature set point of the transducer. This long-term drift is not random, but occurs in one direction, and is roughly of the same magnitude for all transducers; approximately -1.5% error. The error can be removed by recalibration of the temperature set point of the transducers which is currently underway. Initial evidence from these recalibrations suggests that little or no further drift will occur.

With the exception of the delivery of the last spare transducer, original vellums and a final engineering report, Contract 951792 is complete. A follow-on contract for $5000 has been awarded to TRW to provide technical consulting as needed to the end of the Mariner 69 Mission.

PUBLICATIONS

None

MEASUREMENT TECHNOLOGY FOR TEMPERATURE CONTROL MATERIALS

NASA Work Unit 124-09-19-03-55

JPL 324-90901-2-3510

W. F. Carroll

OBJECTIVE

The long range objective of this task is to provide spacecraft thermal designers and analysts with necessary data on surface properties of temperature control materials. To accomplish this, the following tasks must be undertaken:

(1) Requirements must be anticipated with the uncertainties and limitations associated with measurements understood and improved, and in some cases new methods developed.

(2) The uncertainties associated with processing reproducibility of the materials must be identified and reduced as required.

(3) Data must be available to designers and analysts in a concise usable form and must include uncertainty limits.

PROGRESS

Measurement Error Study

An experimental program was conducted by TRW to investigate selected parameters which affect the accuracy of integrating sphere reflectance measurements. This program was briefly described in the previous semiannual report. A report on the experimental results and the effect thereof on measurement errors will be available for distribution early in the third quarter of FY 69.

The functional principle of the integrating sphere is based on high, uniform reflectance, and the magnitude of many errors is strongly dependent on the level of reflectance and deviation from uniformity. Therefore, a major portion of the effort has been on the effect of application surface finish, aging, etc., on the reflective characteristics of magnesium oxide.

The detailed experimental results will be in the forthcoming contractor report. The impact on accuracy of current measurements remains to be assessed. Highly accurate reflectance determination may require analytical correction to measured data and/or modification of measurement methods.

The following results seem to be the most significant:

(1) The off-center location and directional sensitivity of the photomultiplier tube in the commonly used integrating sphere produces significant and systematic errors in measured reflectance.

(2) Measured reflectance of magnesium oxide samples is not independent of angle of incidence or polarization of the incident beam.

FUTURE PLANS

During the third quarter and part of the fourth quarter of FY 69, the results of the recent study will be carefully reviewed and analyzed. A subsequent program will be developed based on this analysis. If warranted, as the preliminary review indicates, a contract will be awarded late in FY 69 to further evaluate and reduce errors in measurements.

PROGRESS

Thermal Radiation Properties Summary

During the first half of FY 69, participation in activities of Headquarters Contract with TPRC, Purdue University (NSR-15-005-037), has aided in a constructive modification of planned data presentation. Analyzed Data Graphs (ADG) are being prepared for selected materials and properties. These are simplified graphical presentation of selected data which will greatly enhance the utility of the volumes. Some delay in publication will be necessary to accomplish this change.

A simple handbook of radiative properties is being compiled at JPL from the large amount of data generated for spacecraft and research projects over the past several years. In addition, data from selected other sources will be included to provide a general utility summary. This activity is intended to complement the TPRC work in that it will contain only selected data, it will be available much sooner, and it will be in a simple, readily accessible format. The data accumulation is approximately 60% complete.

FUTURE PLANS

Support to the TPRC contract will continue during the balance of FY 69 and beyond. Future activity will include aid in evaluation of published data quality and organization, categorization, and presentation of radiative properties of nonmetallics and coatings.

Data accumulation for the handbook will be completed during the third quarter of FY 69. The data will be reviewed, organized, assigned an order of merit or reliability, and issued for review in preliminary format by the end of FY 69.

PUBLICATIONS

None

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ADVANCED SOLAR SIMULATION RESEARCH

NASA Work Unit 124-09-19-04-55

JPL 324-91001-2-3750

R. E. Bartera

OBJECTIVE

The purpose of this work unit is to develop systems and technology that will enable us to adequately simulate the effects of solar radiation on spacecraft. Although presently available lamps are close to the brightness of the sun, there is a need for sources of considerably higher brightness for near future accurate solar simulation testing. The additional higher brightness is necessary due to the requirements of true solar field angle in the test beam and the need for optical control with its attendant low efficiency. Furthermore, as the lamp brightness is increased, color filtration becomes practical so that the spectral distribution, the intensity, and the field angle of the sun can be simultaneously matched.

STATUS

20 KW Arc Lamps

A considerable effort has been made to improve the safety of handling the 20 kw lamps, which are prone to explode at unexpected moments. This was especially important because a severe storm last year caused the lamps installed in the 25-ft space simulator to be contaminated with mud and a reasonably safe and efficient method of cleaning the lamps had to be devised. The unit developed a means of depressurizing the lamps in such a way that the xenon gas is saved and can easily be returned to the lamp. A small, compact, and inexpensive depressurization system is permanently attached to each lamp, and the lamp can be made safe to handle in a few minutes. The process is sufficiently straight-forward and fast so that it is planned to depressurize all such lamps, when they are not operating, as a standard procedure.

Several lamps have been modified in the course of this development and tested for several hundred hours. No discernible difference in operating parameters was noted.

Riise Anode Thickness

In the Riise type anode, there should be an optimum thickness which maximizes the total heat that can be transferred to the water. A very thin cap would keep the metal temperature down to acceptable levels, but would require an excessive heat transfer per unit area in the cooling fluid. A very thick cap would reduce the local heat transfer requirement, but would allow the metal temperature to become excessive.

A computer program, which included the effects of lateral heat transfer, was set up to analyze the situation and performed a series of experiments to determine boundary conditions. For reasonable water flow conditions (on the order of 100 feet per minute at 50 psi), the thickness of the anode cap should be about 0.03 inches. Anode caps with thicknesses around this value to check the results are now being fabricated.

Riise Anode Creep

Long-time operation of Riise anodes shows a continuing increase in the resistance to water flow. This can be due in part to deposits in the narrow water channel, but the primary reason (if properly treated water is used) is high-temperature creep of the anode cap. The pressure differential across the hot anode cap is about 100 psi. The creep can be avoided in part by using Cu-Ag or Cu-Te alloys, but a better solution would be to eliminate the pressure differential. Accordingly, the unit has put pressure taps on a Riise Anode and determined the water pressure at the tip for various flow rates. Since the gas pressure can be measured while the lamp is operating (the depressurization system includes a pressure gage), it is possible to balance the pressure differential across the anode cap.

Multi-Anode Lamps

By having several anodes in a lamp and making the arc strike each sequentially, the total arc current can be significantly increased. A lamp with three anodes in a suitable geometry should be able to carry more than three times the current of a single anode lamp because the cathode jet, which carries much of the heat, could strike a different portion of the anode structure from the electrical arc.

Preliminary studies have been made of arc behavior with three- and six-anodes using carbon electrodes in air and 60 Hz, three-phase current. High-speed motion pictures of the arc showed good transfer between anodes and relative stability of the cathode spot. This latter was encouraging because the highest brightness and, therefore, the most useful portion of the arc is just off the tip of the cathode, A six-anode configuration (in tungsten) has been fabricated and very shortly will be evaluated in high pressure inert gas. Incidentally, the xenon from burned-out 5 kw lamps (from the 10-ft space simulator) is being salvaged for this kind of work.

PUBLICATIONS

None

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COLDWELDING TEST REQUIREMENTS

NASA Work Unit 124-09-19-05-55

JPL 324-91401-0-2940

T. E. Gindorf
J. T. Wang

OBJECTIVE

The objective of this work unit is to develop a set of coldwelding test criteria for qualification of spacecraft hardware.

INTRODUCTION

The phenomenon of coldwelding which causes spacecraft mechanisms to fail has been demonstrated in the laboratories. Recent examples include the infrared spectrometer (IRS) geartrain and the television (TV) shutter of Mariner Mars 1969 which failed during test in the JPL MOLSINK facility. In recognizing the seriousness of the problem for current as well as future spacecraft systems, an effort is being made to develop a set of test criteria for qualifying spacecraft hardware.

APPROACH

A research plan was formulated to achieve the following:

(1) Identify and evaluate the environmental parameters to determine the degree of influence they have on the coldwelding of materials.

(2) Calibrate the MOLSINK chamber against the space vacuum.

(3) Perform experiments to determine the thresholds at which these parameters are to be maintained to produce an adequate coldwelding environment.

(4) Formulate coldwelding test criteria.

STATUS

Work began July 1, 1968. A review of publications pertaining to the space vacuum effect on mechanisms provided a fundamental understanding about coldwelding phenomenon. In consultation with the various NASA Centers, private industries and the armed services, it was learned that Goddard Space Flight Center (GSFC) and the Air Force Rocket Propulsion Laboratory (AFRPL) have independently developed test articles for coldwelding experiments in high vacuum chamber as well as in space via satellites. One of the objectives which coincided closely with that of JPL's, was to determine the effectiveness of the vacuum chamber as compared with space. Consequently, current activities have been directed at establishing a joint effort which would result in time and cost savings while achieving the common objectives. Meetings were held with both GSFC and AFRPL to explore all the possibilities. It was concluded that, based on an evaluation of cost, schedule, logistics and the availability of test modules involved in this effort, it would be more realistic and economical to pursue a joint JPL-AFRPL program.

A recent discussion was held between JPL and AFRPL. It was suggested that JPL would provide the MOLSINK as a high quality space simulation facility and AFRPL would provide the friction experiment test modules which were used in previous flight programs. TRW, which had done previous coldwelding studies, would be contracted by AFRPL to participate in the performance of a series of experiments in the JPL MOLSINK facility. Facility operating cost could be shared by JPL and AFRPL. Since then, a TRW proposal had been submitted to AFRPL for review. JPL was asked to comment on the proposal so that AFRPL could initiate a purchase request. This program, described in the TRW proposal ($12, 664. 00), only accomplishes a portion of the total task. Achieving all of the objectives of the total program would require additional work.

The total program is to be implemented in two phases. The Phase I objective is to determine whether MOLSINK can provide an environment which simulates space to a sufficient degree to perform adequate coldwelding tests. If the MOLSINK should prove to require excessively longer time duration to achieve coldwelding than space, then it would be necessary to develop valid methods of decreasing the time difference. However, if MOLSINK were proven to be an adequate simulation of space, then Phase II would answer the following questions: (1) Would a degraded MOLSINK environment be adequate? (2) Can a conventional chamber provide an adequate test environment? (3) In either case (1 or 2), what are the thresholds at which the environmental parameters should be maintained to produce an adequate test condition? (4) How can a test be validly accelerated? The sequence of experiments is presented in Figure 1.

FUTURE ACTIVITIES

Tasks involved in the two phases of the program are as follows:

Phase I

(1) Establish the detailed requirements for the operation of two experiment modules (A and B) in the MOLSINK facility.

(2) Perform experiments to acquire comparison friction data corresponding to the test materials flown on the Environmental Research Satellite (ERS-20). The experiment run profiles used will conform to the mechanical sliding history incurred during Environmental Research Satellite (ERS-20) in-space tests.

(3) Perform data reduction of the coefficient of friction values.

(4) Perform analysis and comparison of the results obtained in space and MOLSINK.

(5) Prepare an interim report for Phase I.

Phase II

(1) Determine adequacy of a degraded MOLSINK environment by performing experiments similar to those in Phase I.

(2) Determine adequacy of the environment in a conventional chamber.

(3) Determine parameter thresholds in a conventional chamber if adequate.

(4) If the conventional chamber is inadequate, determine parameter thresholds in the MOLSINK.

(5) Develop valid methods of accelerating tests.

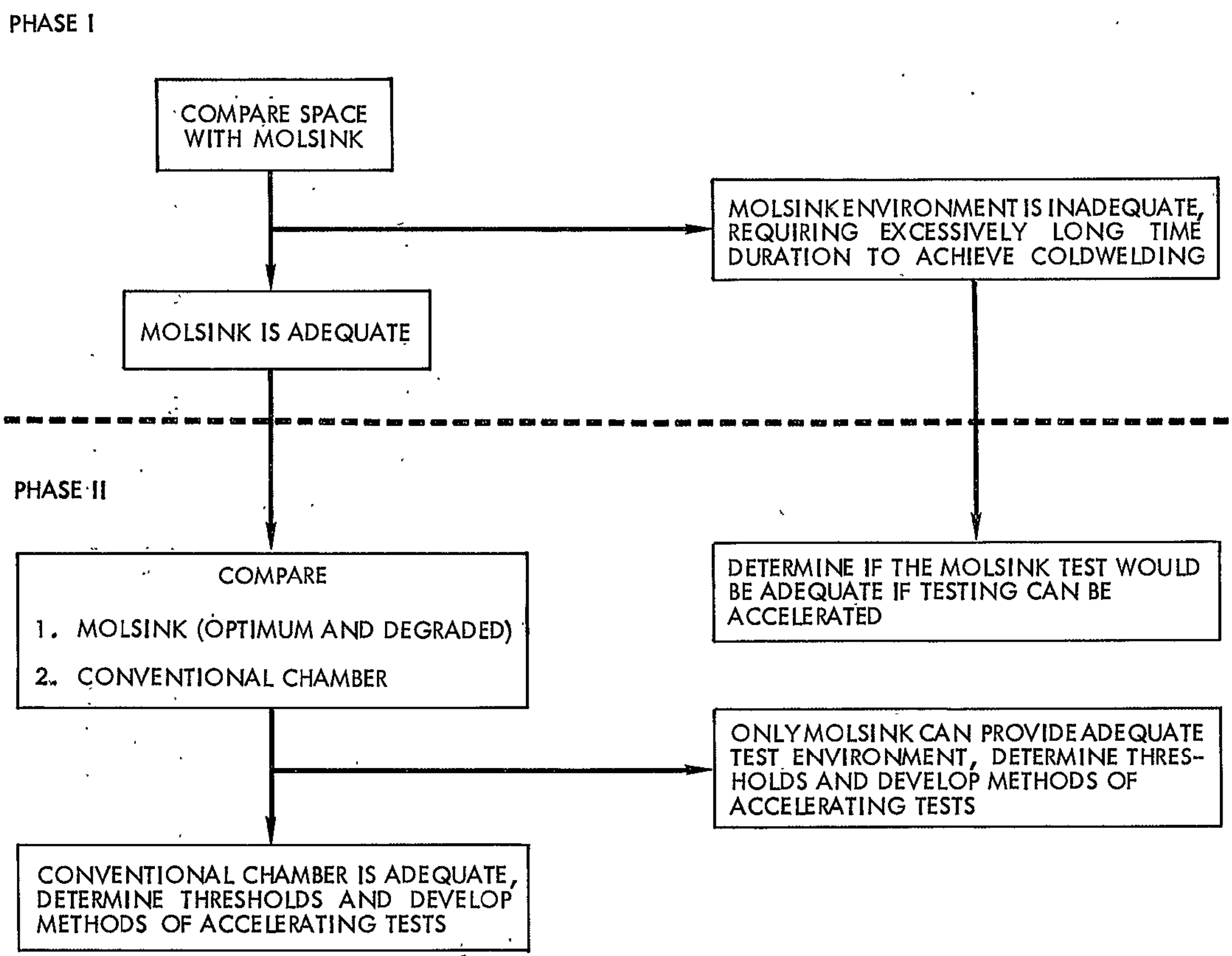

Figure 1. Phase I and II Flow Diagram

(6) Establish coldwelding test criteria.

(7) Prepare final report.

PUBLICATIONS

None.

MOLSINK RECONTAMINATION RATIO EXPERIMENTS

NASA Work Unit 124-09-19-07-55

JPL 324-91801-2-3750

R. E. Bartera

OBJECTIVE

The objective of this work unit is to provide an understanding of the unique environment produced in the JPL 10-ft MOLSINK facility. This facility was designed and built as a medium for developing the technology necessary for simulating the molecular sink of space. It has been operational since June 1968.

It is estimated that, even with a very "dirty" (high outgassing rate) object, the molecular flux impinging on that object will be a reasonable approximation to what would occur in space. If so, it is possible to do a wide range of surface effect experiments not now possible, because conventional extreme high vacuum chambers cannot accept dirty hardware, without seriously compromising results. Included in this class are coldwelding of certain kinds of spacecraft bearings, viability of biological specimens and degradation of thermal control surfaces.

STATUS

This work unit was planned as a second quarter effort but, due to the press of unexpected Mariner 69 tests requiring the MOLSINK the experimental work has been delayed. A metered gas inlet system has been devised and checked out, and a workable molecular flux detector, the cryogenic quartz crystal microbalance has been demonstrated.

Because of funding limitations, this effort will be primarily JPL and not contracted as was originally intended.

PUBLICATIONS

None

SPACE VEHICLE DESIGN CRITERIA (124-12)

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SPACE VEHICLES DESIGN CRITERIA PROGRAM SUPPORT

NASA Work Unit 124-12-01-02-55

JPL 324-20601-0-3500

H. Bank

OBJECTIVE

The objective of this work unit is to support the design criteria program of NASA Langley, Lewis, Goddard, and Electronic Research Centers which are developing design criteria documents for all of NASA's space programs. The JPL role in this activity is to provide (1) technical information concerning NASA projects assigned to JPL for the development of appropriate design criteria, (2) technical support for establishing the scope and content of design criteria documents, and (3) technical review and comment on acceptability of completed document drafts.

PROGRESS

Activities during this period included participation in the formulation of document content as well as review for official criteria approval. Reports involved include:

Structures (Under LRC cognizance)

(1) Staging Loads

(2) Modal Survey

(3) Fracture Control of Metallic Pressure Vessels

(4) Entry Thermal Protection (Final)

(5) Buckling of Thin Walled Circular Cylinders (Final)

Environment (Under GSFC cognizance)

(1) Mars Atmosphere (Final)

(2) Venus Atmosphere (Final)

(3) Planetary and Interplanetary Magnetic Field

(4) Interplanetary Meteoroid Criteria

Propulsion - no activity

Guidance and Control (under ERC cognizance)

(1) Gravity Disturbance Torque

(2) Atmospheric Entry and Guidance

(3) Magnetic Disturbance Torque

(4) Mass Expulsion Torque

(5) Effects of Structural Flexibility on Spacecraft Control Systems

PUBLICATIONS

None

VENUS ATMOSPHERE ENVIRONMENTAL DESIGN CRITERIA

NASA Work Unit 124-12-03-01-55

JPL 324-20201-X-2940

R. A. Schiffer

OBJECTIVE

The objective of this work unit is to synthesize existing state-of-the-art knowledge pertinent to the Venus atmosphere as required to prepare a Venus atmosphere environmental requirements engineering monograph for use in space vehicle design. This monograph is intended to be a guide to Venus atmosphere environmental criteria and not as a NASA requirement, except as may be specified in formal project specifications.

INTRODUCTION

As a part of the NASA Space Vehicle Design Criteria Program, sponsored by the NASA Headquarters Office of Advanced Research and Technology, JPL was assigned the responsibility for the preparation of a Venus atmosphere environmental criteria monograph. Additional scientific measurements and theoretical studies are required before a clear understanding of the structure of the Venus atmosphere can be evolved. In the meantime, Venus atmosphere engineering models reflecting the best current knowledge are still needed for space vehicle design and mission planning. Accordingly, this monograph is intended to provide an interim set of standard models based on the latest scientific data. They should not be considered as new scientific models of the Venus atmosphere, however.

This progress report covers the activities in this task through the second quarter of FY 69.

APPROACH

The approach taken in accomplishing this task was: (1) to determine what information should be included in an atmospheric model for use in space vehicle design, (2) collect and review the principal scientific Venus data, (3) examine the compatibility of the various theoretical atmospheric models appearing in the literature with the measured data, and (4) specify a set of consistent atmospheric models suitable for engineering purposes. The current task status is discussed in the following.

STATUS

A final JPL draft of the monograph was prepared and extensively reviewed by the JPL technical divisions prior to transmittal to NASA August 28, 1968. In developing these models, particular attention was given to assessing the atmospheric environmental interactions which influence the integrity and performance of a planetary vehicle and its major subsystems. These atmospheric interactions are both aerodynamic and thermal, and are directly related to the structure, composition, and dynamics of the atmosphere. Briefly, the vertical distribution of mass density is regarded as the most critical parameter for design functions which involve aerodynamic interactions. However, adequate definition of other such quantities as chemical composition and temperature structure are of importance in that they are implicit in the calculation of density and appear as parameters in thermal calculations. In addition, the viscosity, specific heats and speed of sound influence the vehicle aerothermodynamic analyses, while atmospheric winds primarily affect terminal descent entry dynamics. Finally, the atmospheric aerosol content and opacity constrain the design of landed solar power systems and influence communications equipment performance. Each of these parameters is discussed in the monograph.

The monograph describes six atmospheric models which include high and low density models for each of three levels of solar activity (minimum, mean, and maximum). These models are described briefly in the previous semiannual progress report and the JPL SPS article listed under PUBLICATIONS. A somewhat more detailed description of the atmospheric models will appear in the forthcoming AIAA paper, also listed under PUBLICATIONS.

Upon receipt of the final JPL monograph draft, a NASA version of the monograph was prepared reflecting the style appropriate to the over-all design criteria program. This version, which appears as NASA SP-8011, "Models of the Venus Atmosphere (1968)," has been distributed to the various NASA Centers for final review; and after any resulting revisions will appear as NASA SP 8011.

FUTURE ACTIVITIES PLANNED

As of this reporting, all planned JPL activities relating to the monograph have been completed with the exception of a possible response to any comments submitted by the NASA Centers during final review. Publication of the monograph is anticipated during the third quarter of FY 69.

PUBLICATIONS

<u>Meetings and Symposia Papers</u>

1. Schiffer, R. A.: "Engineering Models of The Venus Atmosphere Based on an Interpretation of Recent Space Vehicle Observations of Venus," presented at the AIAA 7th Aerospace Sciences Meeting, New York, January 1969.

<u>SPS Contributions</u>

1. Schiffer, R. A.: "Engineering Models of The Venus Atmosphere," SPS 37-53, Vol. III, Oct. 31, 1968.

MARS SURFACE ENVIRONMENTAL DESIGN CRITERIA

NASA Work Unit 124-12-03-02-55

JPL 324-20301-2-2940

E. C. de Wys

OBJECTIVE

The objective of this task is to develop, based on existing state-of-the-art knowledge pertinent to the Mars surface, a Mars surface environmental monograph.

INTRODUCTION

As a part of the NASA Space Vehicle Design Criteria Program sponsored by the NASA Headquarters Office of Advanced Research and Technology, JPL was assigned the responsibility for the preparation of a monograph covering the Mars surface. This progress report covers the activities in this task through the second quarter of FY 69.

APPROACH

The approach to the development of the monograph includes: the identification of the environmental parameters required for design criteria; the review of observational data and theoretical models on the surface of Mars; and the subsequent selection of an internally consistent set of values for the environmental parameters required for the monograph.

STATUS

During the first half of FY 69, a first JPL draft of the Mars surface monograph has been completed, extensively reviewed by the JPL technical divisions and forwarded to NASA. This draft, in turn, has been sent by NASA to technical experts both outside and within NASA for review. As a result of this review, several comments have been received and incorporated in the second JPL draft which is currently being prepared.

The monograph draft contains an interim set of engineering models reflecting current state-of-the-art knowledge of the Mars surface. The models provide the Mars surface environmental criteria which space vehicle design should accommodate for missions involving Mars landing and surface operations. However, they should not be considered as new scientific models of Mars. Selected values for the mechanical, electrical, and thermal properties of the Mars surface are shown respectively in Tables 1, 2, and 3.

FUTURE EFFORT

The final JPL draft will be forwarded to NASA during the third quarter of FY 69. A NASA version of the draft will be prepared in the published monograph style and sent to the Centers for final review. Consideration will be given to incorporating any final comments prior to publication.

PUBLICATIONS

None

Table 1. Mechanical Properties of the Mars Surface

Properties	Values		Units
	Bright Areas	Dark Areas	
Density	0.6 - 1.9	0.9 - 2.9	gm cm^{-3}
Porosity of Combined Top Few cm	15 - 55	15 - 55	%
Cohesion	0 - 100	0 - 100	dyne cm^{-2}
Soil Stability Factors: (For Level Ground)			
N_γ	10 - 40	10 - 40	
N_Q	15 - 40	15 - 40	
N_c	25 - 55	25 - 55	
Bearing Capacity Minimum (For 10 cm Radius Circular Plate)	3×10^5	1.3×10^6	dyne cm^{-2}
Modulus of Deformation:			
K_ϕ	0.5 - 3.5	0.45 - 6	
K_c	0	0	
Sinkage Exponent η	0.5 - 1.5	1.1 - 1.25	
Angle of Internal Friction	25 - 35	25 - 35	deg
Slope Stability (For Cohensionless Soil)	25 - 35	25 - 35	deg
Median Slopes	5 - 7	9 - 11	deg
Average Elevations	-1 - +1		km
Elevations Parallel to Equator		2 - 6	km
Circular Hellas Type Region Elevation		1 - 2	km
Average Crater Diameter	3 - 175	3 - 175	km
Permafrost Micro Elevations	0 - 0.5	0 - 0.5	m
Dust Storm Speeds	40 - 100	40 - 100	km hr^{-1}
Average Duration of Dust Storms	2 - 4	2 - 4	day

Table 2. Thermal Properties of the Mars Surface

Properties	Values		Units
	Bright Areas	Dark Areas	
Thermal Conductivity	$4 \times 10^{-4} - 6 \times 10^{-3}$	$4 \times 10^{-4} - 6 \times 10^{-3}$	gm cal cm^{-1} sec^{-1} $°K^{-1}$
Specific Heat	0.17 - 0.19	0.17 - 0.19	gm cal gm^{-1} $°K^{-1}$ at 0°C
Emissivity	0 - 8	0 - 6	
Average Albedo	0.18 - 0.20	0.18 - 0.20	
Speed of Wave of Darkening	20 - 45	20 - 45	km/day

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Mean Planetary Temperature at Noon	200 - 260°K
Disc Center Temperature at Noon	290 - 300°K
South Polar Temperature at Noon	260 - 290°K
North Polar Temperature at Noon	230 - 250°K
Minimum Polar Temperature at Noon	<145°K
Southern Temperate Region (-24° to 66° latitude) Temperatures at Noon	290 - 300°K
Northern Temperate Region (24° to 66° latitude) Temperatures at Noon	270 - 290°K
Equatorial Region at Noon	260 - 320°K
Average Temperature of Yellow Dust Cloud at Noon	245 - 250°K

Table 3. Electrical Properties of the Mars Surface

Properties	Values		Units
	Bright Areas	Dark Areas	
Dielectric Constant	1.9 - 8.3	2.4 - 6.4	
Dielectric Constant Uppermost Layer	1.5 - 2	1.5 - 2	
Tangent Dielectric Loss Angle	0.01 - 0.15	0.01 - 0.15	

MERCURY ENVIRONMENTAL DESIGN CRITERIA

NASA Work Unit 124-12-03-03-55

JPL 324-20401-0-2940

A. J. Beck

OBJECTIVE

The objective of this work unit is to prepare a Mercury environmental criteria monograph which contains a synthesis of pertinent state-of-the-art knowledge relative to the planet Mercury.

INTRODUCTION

As part of the Space Vehicle Design Criteria Document program sponsored by the NASA Headquarters Office of Advanced Research and Technology, JPL has been assigned responsibility for the preparation of a monograph on the environment of Mercury. This progress report covers the activities carried out in support of this task in the first half of FY 69, from its initiation in the first quarter through the second quarter.

APPROACH

The approach followed to accomplish this work unit consists of collecting and reviewing all pertinent state-of-the-art knowledge, examining the compatibility of observational data, and preparing a set of environmental engineering models which reflect the latest scientific knowledge of the planet Mercury.

The environmental criteria generated from these engineering models will be published in a Mercury Environmental Criteria Monograph.

STATUS

Due to limitations of funding during FY 69, and a redirection of manpower for FY 70 to support the Thermoelectric Outer Planets Spacecraft (TOPS) study, the level of effort for this task has been reduced to 25% of that initially anticipated. A low level of effort will continue through FY 70. However, a higher level of effort is anticipated during FY 71.

A literature survey has been initiated to collect pertinent state-of-the-art knowledge of Mercury. This knowledge is being reviewed and assimilated in anticipation of formulating a set of engineering models for Mercury. Concurrently a preliminary outline for the monograph has been prepared, and a format for the presentation of atmospheric data has been adopted. This format is similar to that adopted for the Venus Atmosphere Monograph.

FUTURE ACTIVITY

A schedule of future activity to completion of the monograph has been developed. This schedule assumes that the funding level during FY 71 will be at a sufficient level required to complete the remaining effort by June 1971.

The literature survey will continue. The major part of this effort is expected to be completed by the end of FY 69. However, current literature will be examined up to June 1970 for recently published pertinent information relative to Mercury. During the first and second quarters of FY 70, the observational data and theoretical models which have been collected from the literature search will be reviewed and assimilated, leading to the final selection of values for environmental parameters during the third and fourth quarters of FY 70. Environmental models will be selected and numerical data for environmental criteria computed using selected environmental parameters. During the first and second quarters of FY 71, the preliminary internal drafts will be prepared and reviewed at JPL. The JPL drafts are scheduled for delivery and review in the NASA cycle during the third quarter of FY 71, with publication of the Mercury Environmental Criteria Monograph about June 1971.

PUBLICATIONS

None

JUPITER ENVIRONMENTAL DESIGN CRITERIA

NASA Work Unit 124-12-03-04-55

JPL 324-20501-0-2940

N. Divine

OBJECTIVE

The objective of this work unit is to prepare a Jupiter environmental criteria monograph which contains a synthesis of pertinent state-of-the-art knowledge relative to the planet Jupiter.

INTRODUCTION

As part of the Space Vehicle Design Criteria Document program sponsored by the NASA Headquarters Office of Advanced Research and Technology, JPL has been assigned responsibility for the preparation of a monograph on the environment of Jupiter. This progress report covers the activities carried out in support of this task in the first half of FY 69, from its initiation in the first quarter through the second quarter.

APPROACH

The approach adopted for this task anticipates the compilation of a comprehensive bibliography of recent published work relating to Jupiter, the assimilation of pertinent material, and the synthesis of current qualitative and quantitative information into a consistent description of the Jupiter environment. Space vehicle environmental design criteria will be generated from this description and published by NASA in a Jupiter environmental criteria monograph.

STATUS

A detailed schedule which calls for the completion of the task in December 1969 has been prepared as Table 1.

A preliminary bibliography has been compiled from a literature survey which was initiated to obtain current state-of-the-art knowledge of Jupiter. Some of the material which has been collected as a result of this survey has

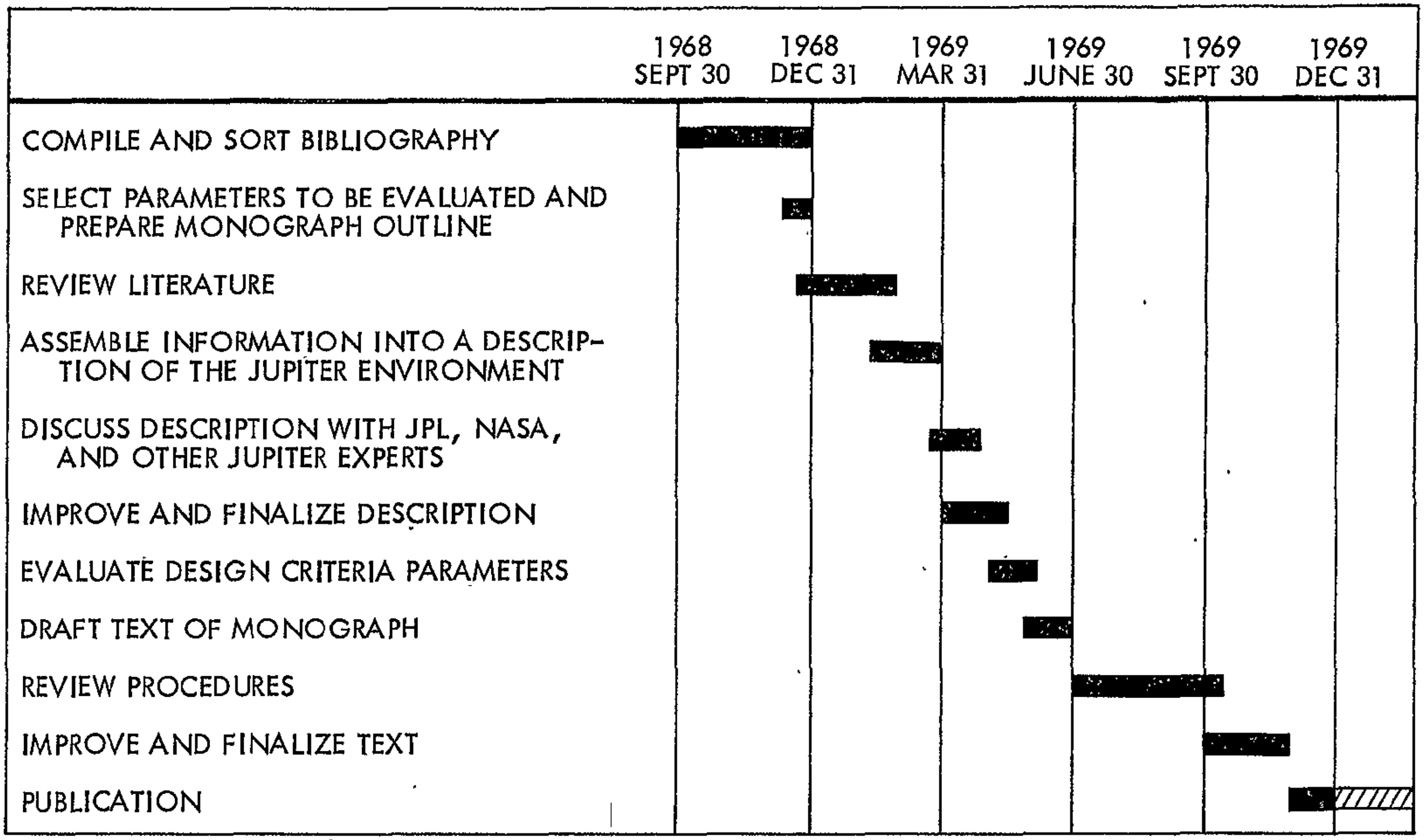

Table 1. Schedule of Activities for Jupiter Environmental Design Criteria Monograph

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been reviewed in preparation for the selection of those environmental parameters required for spacecraft design. As a guide to selecting required environmental parameters, a matrix has been formulated which shows the interaction of environment and the design of spacecraft subsystems. Based on these results, a preliminary outline for the monograph has been prepared.

FUTURE ACTIVITY

The remainder of the steps outlined in the schedule will be completed at the anticipated level of effort in the remainder of FY 69 and the first two quarters of FY 70.

A thorough review of pertinent literature selected from the bibliography will be undertaken. From this material a "best" description of the Jupiter environment will be formulated, and then modified by the results of discussions with Jupiter experts at JPL, the several NASA Centers, and elsewhere. On the basis of this description, the pertinent design criteria parameters will be evaluated. A draft for the text of the monograph will be written and submitted for JPL and NASA review in June 1969. A final draft will be prepared after the completion of the review procedures, and publication of the monograph is anticipated during the third or fourth quarter of FY 70.

PUBLICATIONS

None

6

ELECTRONICS SYSTEMS SRT (125)

ADVANCED CONCEPTS (125-06)

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EXTREME TEMPERATURE REQUIREMENTS FOR ELECTRONIC PIECE PARTS

NASA Work Unit 125-06-02-01-55

JPL 325-60101-0-2940

T. E. Gindorf
T. Hutchinson

OBJECTIVE

The objective of this work unit is to determine temperature and life requirements for survival and operation of electronic components to be used as criteria for development of electronics piece parts for future space missions.

BACKGROUND

The study is being performed in two phases. Phase I had as its objective the determination of how to obtain the extremes of temperature requirements and was completed in FY 68. The second phase is concerned with using the results of Phase I to obtain temperature information and piece part requirements.

During Phase I, existing studies of future missions were reviewed to identify those missions likely to produce extreme temperatures in electronics. Some 45 studies were examined in detail. Most were concerned with near-earth interplanetary missions (mainly to Mars and Venus). In all studies reviewed, a nominal room-temperature environment for spacecraft electronics was used as a study constraint. This nominal environment was achieved in all cases without need of excess weight or power for thermal control. This implies a bias toward systems optimized for near-earth planetary missions and consequently, none of these cases could be extrapolated toward more extreme missions, as was planned earlier in the study.

Since no mission studies existed which considered the more severe mission thermal constraints, another means was needed (aside from performing new mission studies) for examining possible temperature/time extremes. Studies have shown (and JPL Mariner experience has verified) that flyby spacecraft can be thermally decoupled from direct solar radiation by shielding and controlling heat transfer between the bus and the rest of the spacecraft. This is a reasonable assumption for planetary orbiters also, but the degree to which planetary landers can be decoupled from the surface environment has to be determined. Once the possibility of effective thermal decoupling is established for a particular type spacecraft, thermal control methods can be devised to provide a suitable thermal environment for the majority of spacecraft electronics (those inside the bus). With the bus effectively isolated from the sun or planet surface, the extreme temperature effects are then most likely to occur on those electronic parts not inside the bus, such as science experiments and sensors.

STATUS

This decoupling approach will be used initially on a flyby mission to the outer planets, the JPL thermoelectric outer planet spacecraft (TOPS), which will serve to determine what extreme low temperature problems exist for electronics at distances as far as 30 AU from the sun.

The first task for this (Phase II) effort, electronics parts type identification, is being completed at this time. Based on the TOPS preliminary equipment list, the JPL technical divisions are preparing lists of electronic parts types likely to be used on assemblies under their cognizance. Other items being determined are the current temperature limits of each parts type, estimated performance degradation from exceeding these limits, and the estimated and experienced operational lifetime of the equipment.

FUTURE PLANS

FY 69 will be spent determining the probable temperature extremes for the assemblies in which these piece parts will be used.

The results of this ETR study of TOPS will be useful in completing the remainder of the tasks and should demonstrate the capability of solar decoupling arrangements to be used for studies of inner planet flybys. FY 70 work activity will include examination of inner planet flyby missions, orbiters, and landers, as shown in Figure 1.

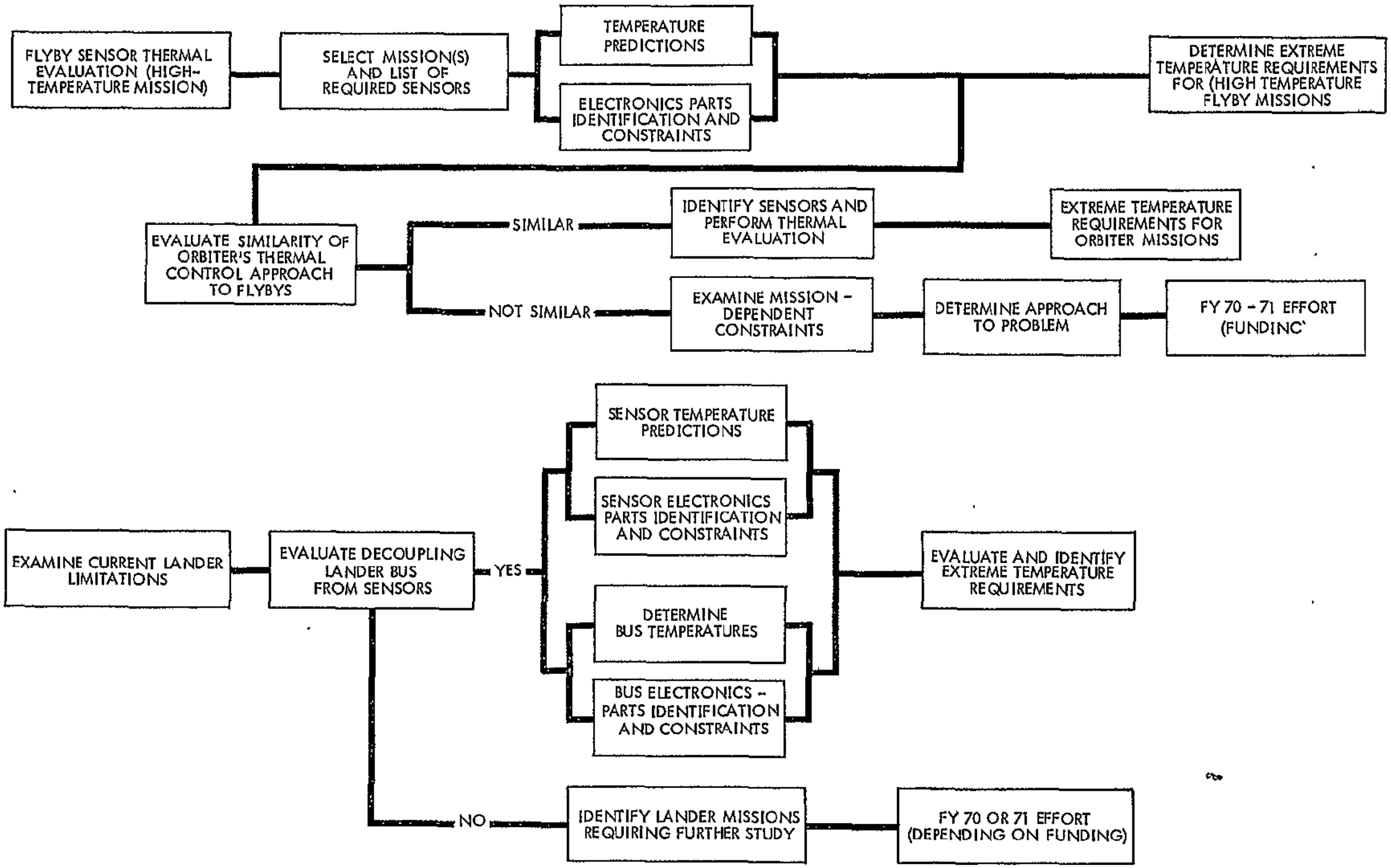

Figure 1. Phase II, FY 70

PUBLICATIONS

1. "Extreme Temperature Requirements for Spacecraft Electronics Parts: Final Report -- Phase I," JPL Document 900-212, Nov. 10, 1968.

INERTIAL SENSORS, ELECTRICALLY SUSPENDED GYROSCOPE

NASA Work Unit 125-17-01-02-55

JPL 325-70501-2-3440

T. J. Donlin

OBJECTIVE

The objective under this work unit is to develop a strapdown, electrically suspended gyroscope (ESG) to be an inertial, two-axis, angular-reference sensor for spacecraft and capsule attitude control. The objectives for this report period have been ESG testing and the evaluation of the ESG test data.

STATUS

JPL Contract 951148

The work under this contract was successfully completed and the contract was closed out.

JPL Contract 951149

As previously reported, the ESG built under this contract could not be sealed against an airleak into the vacuum. A new housing is required to make this ESG operable. There are no funds available to renovate this ESG, so no further work is contemplated until such time as funds are allocated. The test program described in this contract is being performed upon the ESG built under Contract 951148.

ESG Drift Testing and Data Analysis

In each ESG, a drift compensation calibration was obtained from the acceptance-test data. This compensation calibration was acceptable for the data used in obtaining the calibration, but it gave an unacceptable compensation for any other test data. The calibration was obtained by setting up a least-squares matrix with the test data. The inverse of the matrix was obtained, and a solution for the torque coefficients was calculated which was the ESG drift compensation calibration. The calibration would not acceptably compensate all drift errors which indicated that the matrix used in the solution did not have enough ESG performance information.

It was necessary to decide what ESG test conditions were necessary to obtain a good matrix with sufficient information. To do this, drift compensation calibration was selected based upon ESG torque theory. Then a series of test conditions were chosen to give sufficient variation to the effects of the torques. From these choices, computer calculation of simulated test data was obtained. The simulated test data were used to set up matrices from which drift compensation calibrations were calculated. The matrices added together in various combinations to obtain the calibration most accurately agreeing with the originally selected calibration. These simulations of ESG tests assist in eliminating those tests that yield awkward matrices and inaccurate solutions.

Six laboratory ESG drift tests of two days duration were selected and conducted based upon the simulation study. In all the tests, the Z case axis was vertical. The X and Y axes were horizontal and each was 45 deg from north in the first test. These axes were shifted 90 deg around the compass for each of the next three tests. The ESG spin axis was 60 deg to the earth polar axis. The first test was repeated except with the ESG spin axis parallel to the earth polar axis. The sixth test repeated the first test except the spin axis was 120 deg from the earth polar axis. Of all the various combinations possible, it was found that combining the matrices from tests 1 and 6 gave a very good drift compensation calibration for any of the test data gathered. For the remainder of the test program it was decided that the effects of different rotor speeds or rotor suspension force, and the effects of different gravity orientation would be investigated.

Courses Attended

A two week short course in matrix error analysis was taken at UCLA. This course dealt with computational problems in obtaining accurate solutions to problems requiring matrix manipulation.

Plans for the Next Reporting Period

The analysis of the remainder of the test program will be completed and the final report submitted.

PUBLICATIONS

None

GUIDANCE SYSTEMS (125-17)

SEAN SYSTEM DEVELOPMENT

NASA Work Unit 125-17-01-04-55
JPL 325-70901-2-3410
JPL 325-70902-2-3430
JPL 325-70903-2-3440
JPL 325-70904-2-3440

B. Dobrotin
G. Paine
E. Imlay
G. Starks
R. Williamson

OBJECTIVE

The Strapdown Electrostatic Aerospace Navigation (SEAN) system program is a joint NASA/JPL/USAF cooperative effort to develop a feasibility strapdown navigator incorporating electrostatically suspended gyros (ESG).

JPL is responsible for the system design and development, system analysis, integration, and test. The Air Force Avionics Laboratory is providing the gyros, the inertial measurement unit (IMU) and support electronics (IMU console). The JPL effort is divided into 4 major task areas within the Guidance and Control Division. The objectives of each task area precede the following summaries of each activity. Implicit in the SEAN program (though not included as a separate activity) is the task of system integration and test. As an aid in understanding the interrelation of the tasks, the SEAN functional diagram (Fig. 1) is provided.

SYSTEM INTEGRATION AND TESTING

During this report period, two system level tests took place. These were preliminary tests to prove mechanical and electrical compatibility between the IMU and the computer adapter (CAD)/computer. Since only one ESG was available, all tests used a single ESG. The tests were successful and proved that the CAD/computer could handle the ESG outputs without rework.

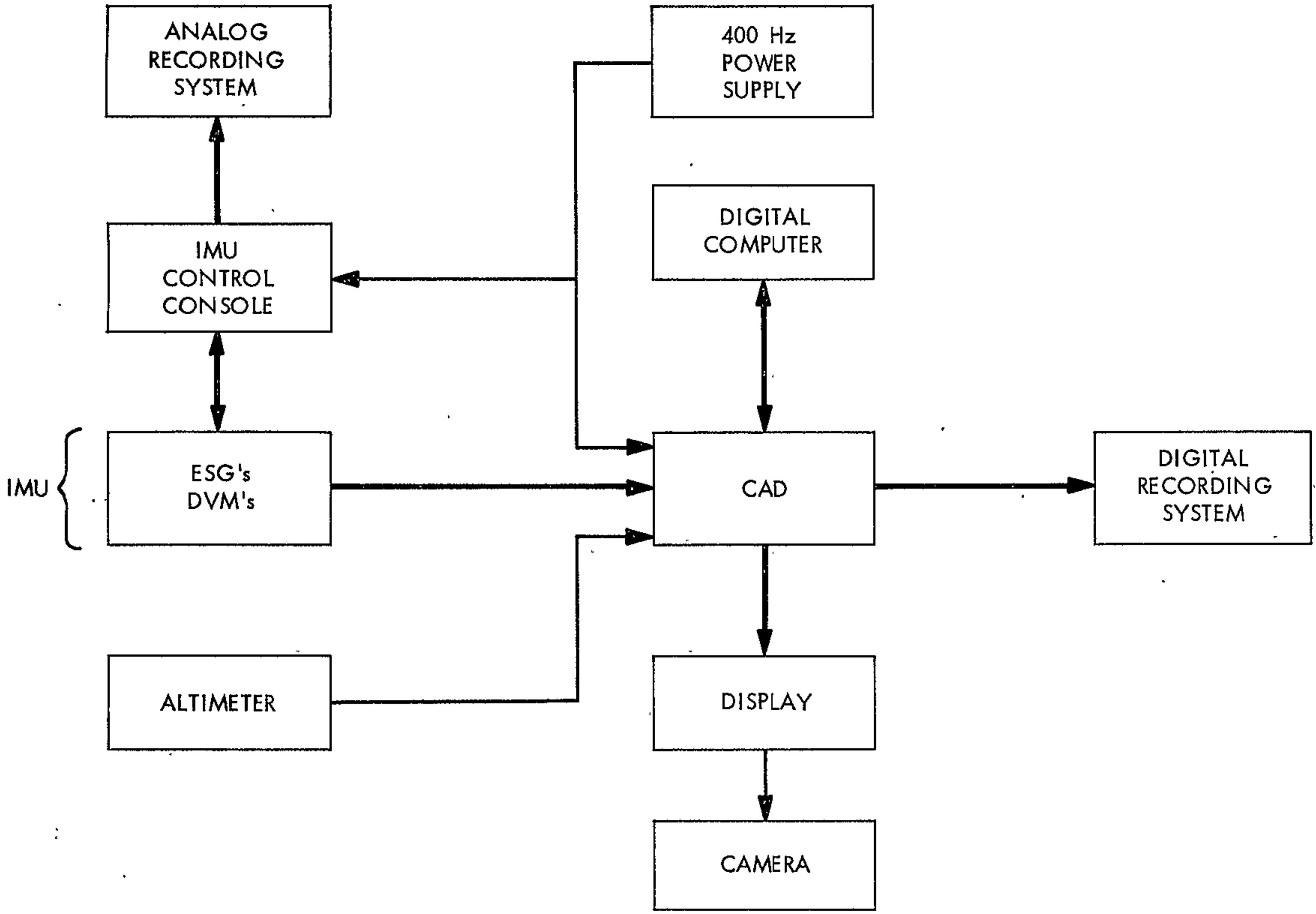

Figure 1. Sean Functional Diagram

The second system-level task was actual navigation using the LAB 1 program. This program navigates using actual digital velicometers (DVM) inputs and a simulated gyro transformation matrix. This test was completed three months ahead of schedule. The purpose of this test was to verify the system analysis by obtaining as much actual data as possible.

PROGRAM TASKS

Computer System

The objective of this task is to develop the computing subsystem (including the CAD equipment) required to convert the measurements provided by the IMU to position information in geodetic coordinates and to provide a visual display (Fig. 1) of the information.

During this report period, fabrication of the CAD display and buffer units was completed and the CAD/computer subsystem has been assembled and checked and is completed.

During the first half of FY 69, a program was carried out to maintain and upgrade the Honeywell, Inc. ALERT computer. Early in the report period, the computer was returned from Honeywell, Aerospace Division, Florida, where it had been sent for rework due to numerous problems. After the return to JPL, the computer experienced several logic failures, a power supply failure, and a complete memory failure. Since the computer is an integral component of the CAD/ computer system, this has severely restricted the system integration schedule. The necessary repairs were made and the computer was subjected to environmental tests. This consisted of thermal and vibration testing. No anomalies were noted during the vibration testing, but the thermal testing revealed several trouble areas, which were traced to loss of synchronization in the processor clock. Investigation indicated that all components were operating satisfactorily. Consultation with Honeywell engineering uncovered the fact that, while undergoing rework, the computer was updated. During rework a transformer was changed on the timing board, but the corresponding variable capacitor was not changed at that time. This component was changed and the computer is operating satisfactorily.

Subsystem integration accomplished during this reporting period with the CAD/computer consists of integration with the IMU, including both ESGs and DVMs, and integration with the Avtel power supply, the camera, and the altimeter. Preliminary integration with the digital recording system is scheduled at the start of the second half of FY 69.

SEAN OSE

The objectives of this task are to provide a road test van, the prime power system, digital and analog data-recording equipment, and system integration engineering support.

Van System

During this report period the test van was procured and road-tested with a mockup system installation comprising consoles and lumped masses equivalent to a normal installation. In addition, the vibration isolators for each of the cabinets were procured and the design of the mounting cradles and baseplates was completed.

Power Subsystem

The uninterruptable power conversion unit was finished during this report period and was operated with dummy loads while being powered from the various optional power sources. The unit was integrated with the IMU and control console, and with the ALERT computer and associated equipment.

Data Recording Subsystem

The data-recording system has been designed to provide the capabilities required for evaluating and troubleshooting the SEAN system. The system consists of a digital magnetic tape recorder, oscillograph recorders, and a recording camera.

Digital Recording System

A magnetic-tape digital recording system is provided to record computer system outputs, total IMU data, and other parameters as required. The procurement of a complete recording system is complete. Two flight-qualified-magnetic-tape digital recorders were procured during this report period. The design and fabrication of the recording system control unit was completed. The integration of the control unit with the ALERT computer and tape transports will be performed by the system manufacturer. Delivery of the complete system was accomplished during the second quarter of FY 69

Oscillographic Recording System

An oscillographic recording system consisting of two recorders is provided to monitor analog functions such as gyro suspension g loading, IMU temperatures, gyro status, and power supply voltages. The Brush Mark 848, 8-channel thermal-writing recorder has been reworked and integrated with the IMU console and a Mid-Western Model 603, 36-channel optical-writing recorder has been obtained from the JPL loan pool during the last report period. A 50-channel recorder, previously considered, was not required.

Photo Recorder

An instrumentation camera will be used to photographically record the CAD display output information (latitude, longitude, speed, azimuth, time). The camera is a 35-mm remotely controlled photorecorder designed for use in aircraft. It will be controlled by the SEAN ALERT computer to take a photograph of the display panel every 2 to 10 seconds to provide a continuous flight test record of at least 4 hours. The camera system was finished during this report period. A preliminary camera/CAD integration test was made. Some camera rework is necessary and will be done by the middle of the next report period.

Altimeter

A CPU-46/A altitude computer, Bendix Type 31101, was obtained to provide digitized altitude information. The altimeter was delivered during this report period and was integrated with the CAD.

Cabling

System cables required for integration of the SEAN (IMU, CAD, etc.) equipment into the van and flight test configuration has been procured and delivered. Other cabling is being built in-house. The SEAN system block and cabling diagrams have been updated and released. Detail interface schematics and signal descriptions have been prepared for those equipments which have not yet been integrated.

INERTIAL MEASUREMENT UNIT (IMU)

The objective of this task is to assist in the design of the IMU; perform the necessary component testing of the ESG and DVM; calibrate, maintain, and align the IMU; and support the system testing. The component-level testing of the ESGs and DVMs is necessary to both check out component performance and provide data for system calibration and error analysis.

IMU Test and Calibration Status

During this report period, advantage was taken of the ESG rework to correct numerous deficiencies previously noted in the IMU control console. Problems included bare wires, bent connector pins, and marginal power supplies. After complete rework the console was successfully subjected to a vibration test, which not only environmentally tested the console but proved the effectiveness of the shock mounts to be used in the van.

During the first of this report period the IMU was integrated with the CAD/computer as mentioned under system integration. During the IMU-CAD integration, the IMU heater circuits caused noise to appear on the ESG optical sensor outputs. By reworking the heater circuitry and adjusting the timing gates in the CAD, this problem was eliminated. The alignment of the IMU with the DVMs was rechecked. Alignment was maintained with the exception of a null shift in one accelerometer. This null shift is being monitored to determine the stability of the new null.

ESG STATUS

At the beginning of this report period, a decision was made to rework the ESG rotor assemblies to eliminate arc marks and widen the rotor lines used in the readout system. At the same time an attempt would be made to improve rotor balance.

The ESGs were returned from the Honeywell Aero Division, Minneapolis, during the last part of this report period.

At the start of the drift testing on ESG 2 several problems were noted. At first the rotor would not levitate. Checking of the electronics disclosed that a transistor in the rotor position sensing loop had a degraded gain. This particular transistor was then replaced in all three position feedback loops. Next, a problem which was noted in ESG 2 for the last two years was found to still exist. This was the problem of the rotor not levitating with the Y2 axis down. Returning and rebalancing the suspension circuits has alleviated this problem. Last, Honeywell had sandblasted the logic line in the rotor pattern once and the cosine lines twice which created problems in the reflected light level for the optical pickoffs. Careful tuning overcame the problem, but the gyro is marginal in the latitude that can be covered by one pickoff.

ESG 1 was received three weeks later and has experienced no functional problems. However, when JPL measured the angle between the pickoff mirrors, which are used to establish the gyro case axis, a 1 arc-min difference between the angle supplied by Honeywell, Inc., and the JPL measurement was found. An error of this magnitude would seriously affect system performance. The difference was traced to two probable causes. First, the mirrors are not optically flat. Honeywell compensates for this by assuring that the normal to the mirror center and the collimated light source are parallel, which is a very critical procedure. JPL uses an autocollimator focused at infinity, which is not so critical. Second, the gyro must be at operating temperature. Honeywell uses the heater circuits in the ESGs and JPL checks the gyro in the IMU. It was decided to accept the JPL measurement. In addition, the difference between the two angles means the pickoff calibration must be rechecked. This will be done during the next report period after the ESGs are aligned in the IMU.

During this report period, it was found that the vibration capability of the SEAN ESGs is only 0.75 g at the suspension resonant frequency instead of the design goal of 15 g. One remedial action was to increase the gain and preload on the gyros and accept the anticipated higher drift. With the increased performance of the ESG mathematical model this should not degrade system performance. As a second remedial measure, specifications for an IMU cradle were prepared and a purchase order issued. This cradle, which should be delivered during the third quarter of FY 69, will replace the existing IMU shock mounts with those of a much lower spring rate and damping characteristic.

SEAN SYSTEM ANALYSIS

The objectives of this task are to provide:

(1) System analysis, including navigation equation development and error analysis and system functional definition.

(2) Inertial measurement unit mathematical model development and verification for component calibration and compensation.

(3) Development and support of the flight programs including test specification and reduction of the system test data.

System Analysis

The following tasks were completed during the first half of FY 69. The development and error analyses of the basic navigation equations was completed. A set of equations which compensate for the fact that all the inertial sensors are not located at one point within the IMU (and which would otherwise make the system oscillation-sensitive) has been prepared and will be included in the navigation program for the van test where appreciable oscillations of the IMU are expected. A report on the final navigation equation simulator (SIM 3) was published. This completes the system simulation program development. This program is now being used to generate test cases for the flight computer program checkout.

The investigation of filtering has been concluded. The current best approach to filtering is to simply edit the data to remove incorrect points. This editing will be based on a comparison between the real data and estimates made from past data.

The equations for the reduction of flight data were developed. As presently formulated, these will be useful only if an accurate time history of true position and velocity is available. Whether or not these equations will be programmed to automatic data reduction will be decided after a better estimate of their usefulness has been prepared.

The system analysis work planned for the last half of FY 69 will concentrate on the reduction of the data generated by the system tests and performing the associated error analysis. This includes developing the required computer programs to perform these tasks.

IMU Analysis and ESG Mathematical Model Status

The following work was completed during the first half of FY 69. The development of an ESG math model was completed. One set of computer programs that can be used to obtain values for the coefficients in the math model was completed. This was revised to permit more efficient processing of the gyro drift data and to improve our confidence in the statistical validity of the coefficients obtained from a particular set of drift tests.

Tests have been specified for the drift runs to be made on the refurbished gyros. This set is believed to be the minimum that will produce adequate coefficients for drift compensation in both the laboratory and the van tests.

A JPL technical report on the ESG mathematical modeling system was initiated during this report period. The report will cover the development of the mathematical basis, the computer programs available, the techniques for their best use, and the results obtained on the refurbished gyros.

The principal activities planned for the last half of FY 69 are the reduction of the gyro test data, the analysis of laboratory system tests, completion of the mathematical modeling system, and completion of the report.

Flight Program Development and Support

During this report period, the preliminary ALERT navigation program (LAB 1) was checked out with the entire SEAN system (less gyros). A report was published following successful test conclusion. LAB 1 comprises about 20% of the final program.

All of the remaining subroutines needed for the basic navigation program to be used in the tests of the complete SEAN system have been programmed and checked out individually during this report period. The subroutines will be merged into a unified navigation program during the first part of the next report period. A subroutine to edit the data received from the gyros will be included to enhance system performance. To enable rapid checkout on the flight computer standing alone, a driver to provide simulated gyro and DVM data was incorporated.

The work in this area planned for the last half of FY 69 will concentrate on the completion of the flight computer program and definition and support for the SEAN lab and van test.

PUBLICATIONS

SPS Contributions

1. Karpenko, V. A., and Lipscomb, D. H., "Strapdown Electrically Suspended Gyro Drift Math Model Development," SPS 37-52, Vol. III.

2. Markiewicz, B. R., "Strapdown Inertial System Alignment Technique," SPS 37-52, Vol. III.

3. Paine, G., "Strapdown Inertial Systems Analysis," SPS 37-52, Vol. III.

4. Paine, G., "Partial Inertial System Integration Test," SPS 37-54, Vol. III.

5. Starks, G., "Vibration and Shock Analysis," SEAN, SPS 37-53, Vol. III.

6. Williamson, R., "OSE for SEAN, SPS 37-55," Vol. III.

Contractor Reports, Interim and Final

1. Haigler, Karen B., "SEAN Navigation Program 3," Informatics, TR-68-700-51-4.

2. IBM, "Gyro Drift Coefficient Analysis Program, Main Processor Extended, Phase II," IBM-FSD/WEST, Eagle Rock Projects TM-W26-68-200

3. IBM, "Statistical Simulation Program Extended Phase II," IBM-FSD/WEST, Eagle Rock Projects TM-W26-68-201

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OPTICAL APPROACH GUIDANCE ANALYSIS AND DESIGN

NASA Work Unit 125-17-02-01-55

JPL 325-70802-2-3430

T. C. Duxbury

OBJECTIVE

The objectives of this task are to demonstrate planetary near-encounter orbit determination using spacecraft-based optical measurements, and to show that these measurement data can be processed by earth-based computing equipment to provide a trajectory estimate within the time constraints of near-encounter operations.

MARINER MARS 1969 OPTICAL ORBIT DETERMINATION

The feasibility of using spacecraft-based measurements in near-real-time for estimating the spacecraft trajectory is to be demonstrated during the near-encounter phase of the Mariner Mars 1969 mission. The on-board measurements, obtained from the far-encounter planet sensor (FEPS), attitude-control sensors, scan platform , and television, will be combined to give Mars' direction as the observable direction for the orbit-determination process. The measurements will be ground-processed and used to estimate the spacecraft trajectory prior to encounter.

A computer program was written to extract the FEPS, scan platform, and attitude-control measurements from the engineering telemetry data stream and place these data in a time-ordered optical data file. Calibration data have been obtained for each of these instruments which relate the telemetered digital measurements to their proper engineering units. Equations were derived relating these on-board data to the spacecraft trajectory and to instrument measurement errors. A computer simulation of the orbit-determination process using on-board data has been developed to evaluate the trajectory estimate resulting from these data.

To evaluate the televised data, calibration test targets were developed which simulate Mars, various magnitude stars, and moons. A computer program was written to determine the television field-of-view location of Mars' center. Equations were derived relating the planet-spacecraft-star angle to the spacecraft trajectory and relating the planet-spacecraft-moon angle to the spacecraft trajectory and moon orbit. A two-body trajectory computer program was developed to simulate the celestial geometry of the spacecraft, target planet, target planet moons, and stars. The program is applicable to both orbiter and flyby missions.

The two remaining major computer programs to be completed perform the following tasks:

(1) They combine the spacecraft optical data to give the proper on-board observables for use in the trajectory estimation process.

(2) They combine the on-board observables with the earth-based trajectory data to estimate the spacecraft trajectory and on-board instrument measurement errors.

These computer programs are 30% complete.

MARINER MARS 71 ORBIT DETERMINATION

An initial contact was established with the Mariner Mars 71 project concerning the extention of the 1969 effort to the 1971 mission. Emphasis has been placed on obtaining television images of Mars and its moons.

Studies are to be completed in the last half of FY 69 defining the trajectory estimation data content of these televised pictures.

THERMOELECTRIC OUTER-PLANET SPACECRAFT (TOPS) PROJECT

The MM 69 and MM 71 efforts directly support the TOPS-related approach guidance activities being performed under NASA Work Unit 125-17-05-55 (Guidance Studies for Future Missions) and NASA Work Unit 186-68-02-21-55 (Guidance and Control Subsystem Integration for Future Missions). The knowledge and experience gained from processing on-board optical flight data will form a basis from which the definition and requirements of an outer planet on-board guidance instrument will de derived.

PUBLICATIONS

JPL Technical Reports

1. Duxbury, T. C., "Near Encounter Geometry Generation," Technical Report No. 32-1338, Jet Propulsion Laboratory, Pasadena, California, November 15, 1968.

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DEVELOPMENT OF ADVANCED ELECTRO-OPTICAL SENSORS

NASA Work Unit 125-17-02-02-55

JPL 325-71101-2-3440

W. C. Goss

OBJECTIVE

This work unit provides for studies of requirements and for mechanization of new concepts resulting in increased performance capabilities of advanced electro-optical sensors. These sensors are directed toward advanced mission applications. The tasks to be performed are (1) star tracker improvement studies, based on the M 69 Canopus tracker, devoted to signal processing optimization for high performance and reliability, and (2) obstacle avoidance sensor studies based on an active laser radar mapping concept.

This work unit had proposed an additional objective to develop optical sensors for a high gain radio antenna. However, the overall effort relative to antenna pointing was discontinued and the optical sensor development was not pursued.

STATUS

The principal activity to date on this work unit has been on star tracker signal processing studies.

The effects of high voltage power supply ripple on the angle-sensing and star-intensity sensing circuits have been studied and measured. Ripple is integrated to a negligible effect by the JPL Canopus Tracker signal processing circuits as long as the ripple signal does not exceed the linear response of any of the circuit elements.

Typical noise-in-signal and noise-in-the-absence-of-signal effects have been calculated and measured. At a light flux input level characteristic of the star Canopus illumination which is gathered by the JPL Canopus tracker objective lens, shot noise is the major contributor. Image dissector dynode noise is the other contributor; other circuit elements only contribute a negligible amount. Angle noise under these conditions is 0.03 milliradians, and the illumination measurement noise is negligible. Under dark conditions, the image dissector dynode noise is the major contributor at acceleration voltages typically used. This anomalous noise, under worst conditions, sporadically saturates the pre-amplifier, causing angle error and illumination measurement disturbances.

Results of this study have been provided to the Mariner 71 project and will result in improved image dissector noise specifications, and in a pre-amplifier design modified to be less susceptible to noise saturation. In addition, this information is being used with a NASA Work Unit 384-64601-2-3440 task for design and development of an improved image dissector to be utilized in future flight programs.

PLANNED ACTIVITIES

Star Tracker Signal Processing Studies

The remaining study tasks are as follows:

(1) The definition of circuit elements response to large input signals which may occur during exposure of the tracker to illumination from a nearby planet. Identification of thresholds for failure, saturation, and non-linear response will be made.

(2) The comparison of the relative advantages and disadvantages of a fixed electron multiplier voltage versus an automatic gain control of the multiplier voltage which will maintain constant signal output.

(3) The evaluation of signal processing circuit immunity to electrical or optical transients.

(4) The evaluation of angle and illumination measurement stability with temperature, time, and power supply frequency.

(5) The evaluation of angle and illumination circuit response in the presence of illumination gradient backgrounds and multiple stars which are simultaneously in the field of view.

(6) To survey the radiation environment which may be encountered on a Grand Tour mission that uses a radioisotope thermoelectric generator spacecraft power supply, and estimate the effects on circuit performance.

(7) The summarization of study results and recommendations for improved design of flight units.

Obstacle Avoidance Sensor Studies

The tasks which are to be accomplished are:

(1) To evaluate the possible laser source/optical modulator/optical detector combinations available, and to compile a tabulation in suitable tradeoff form. Finally, to select an optimum combination.

(2) To fabricate a breadboard of a mode-locked helium-neon laser for the evaluation of pulse-code-modulation techniques that will generate optical radar words.

(3) To fabricate a breadboard of an optical modulator suitable for use with pulse code modulation circuits.

(4) To evaluate beam-steering techniques, and to compile a tabulation in suitable tradeoff form. Finally, to select an optimum technique.

(5) To fabricate the breadboard of a demonstration beam-steering device.

(6) To evaluate possible field-scanning patterns, and compile a tabulation in suitable tradeoff form.

PUBLICATIONS

None

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SPACECRAFT RADARS

NASA Work Unit 125-17-03-03-55

JPL 325-71401-1-3396

R. L. Horttor

OBJECTIVE

The objective of this work unit is to determine the feasibility of utilizing the present spacecraft transponders as a coherent source for radar measurements.

ACTIVITY

The work during the current reporting period was devoted entirely to the Lunar Orbiter V Side-Looking Radar Experiment. The basis of the idea was the realization that the known orbital motion, the S-band high-gain antenna, and the spacecraft transponder-ranging system constitute the key elements of a side-looking radar. All that was necessary was to orient the spacecraft so that the high-gain antenna beam would radiate at right angles to the ground track and intersect the surface at a reasonably shallow angle. The ranging signal is a pseudo noise (PN) code biphase modulated on the RF carrier. The signal reflected off the lunar surface is correlated with a locally generated version of the code. The portion in time-synchronization with the code corresponds to the signal from a fixed distance from the spacecraft. Range resolution is thereby achieved. Resolution in the "along track" dimension is attained by a matched filter whose phase characteristics complements the phase of a point scatterer as it moves through the antenna beam.

Analysis continued on the Lunar Orbiter V Side-Looking Radar Experiment to determine the system response to signal from a point reflector. Signal phase variation and time delay are related to the surface coordinate of the point reflector. The main effort during this reporting period was concentrated in determining the matched filter required for the phase variation of the returned signal.

This work unit was terminated early in the second quarter and modest effort has been expended in documenting the most recent analysis.

FUTURE PLANS

Since this work unit has been terminated, it will not be reported further. Internal summary reports of the activities to the date of termination will be completed and the Surveyor RADVS hardware obtained for S/C Guidance radar systems evaluation will be disposed of.

PUBLICATIONS

None.

GUIDANCE COMPUTER ORGANIZATION

NASA Work Unit 125-17-04-02-55

JPL 325-70401-2-3410

D. A. Rennels

OBJECTIVE

The objective of this work unit is the development of designs and design techniques for ultra-reliable spacecraft guidance computers for unmanned space vehicles with missions of one year or longer. The major effort continues to be the design and construction of an experimental self-testing and repairing (STAR) guidance computer.

PROGRESS

Construction of the memory interface unit, control processor, and test and repair processor is continuing, and all three processors should be completed in January 1969. These units have been designed for convenience of error analysis and testing. All internal registers are displayed with lights on the front panel, and special switches are provided to allow off-line testing. Internal logic in these processors has been designed in such a manner as to localize the effects of faults, and simplify error analysis. In the design of these units, large subsections were standardized so that these circuits can be used in future designs.

The STAR bus system has been designed, and the bus drivers and isolators have been constructed. These devices have been tested and found satisfactory.

A bootstrap I/O system to enable a card reader and typewriter to interface with the base system has been designed, and is being constructed. This I/O system will allow reading of absolute binary program cards from the STAR Computer Assembly Language (SCAL) assembler, and will also allow entering and outputting of data from the computer via the typewriter. A special mode has been incorportated in this I/O system to simulate groundlink control of the computer.

A study of medium scale integrated circuits applicable for use in a STAR prototype system has been undertaken. A number of low power bipolar moderate size integration (MSI) devices have been found which will be incorporated to a limited extent in future STAR construction to gain experience in the use of these units.

A reliability study of the STAR system has been undertaken. Curves of probability of mission success versus time have been plotted for an idealized STAR model with varying numbers of spares. The objective of this study is to generate reliability figures for the STAR computer in various configurations using a highly detailed model of the STAR system, and to critically compare the STAR organization with the various redundancy techniques available. The study will also develop a design tool in the form of a computer program that will, for a given mission and its related constraints, allocate the resources (e.g., number of spare functional units and processors to be carried) to the STAR computer. This permits the optimization of the reliability, availability, mean time to failure, or any other desired function.

The detailed operation of the logic processor and the new arithmetic processor has been defined in terms of the algorithms associated with each op-code. Detailed logic design of these units is under way.

During this reporting period, the Laboratory has established a new research program for showing the feasibility of a Thermoelectric Outer Planetary Spacecraft (TOPS). It appears that a highly reliable computer will be required in this spacecraft, both because of a long mission time, and because reconfiguration of certain spacecraft functions is being considered. Reconfiguration would take place in case of failure and would substitute redundant units. The STAR program work unit is being coordinated with the TOPS program so that a second generation STAR can be used. A study has been undertaken to estimate the weight, volume, power, and operating characteristics of a prototype STAR computer using low poser bipolar MSI. Preliminary results indicate that a STAR type computer can operate with a 30 μsec add time, and 200 μsec multiply time with a power consumption of 40 watts.

FUTURE WORK

Construction of a subset of the STAR computer, which will allow computation with a restricted op-code set, is nearing completion. This base system consists of one 4096 word memory module (RWM), the control processor (COP), the arithmetic processor (ARP), and a part of the test and repair processor (TARP). Following completion of the base system, two new processors will be built concurrently which will allow the STAR to do full general purpose computation. These two processors will be the logic processor (LOP, and a new, more flexible arithmetic processor (ARP). The new arithmetic processor will operate exclusively upon residue coded numbers, and will contain special instructions to allow the programmer to conveniently program in floating point and multiple precision. These units should be complete and operating with the STAR base system in the summer of 1969.

A series of tests will be conducted on the STAR computer. The objectives of these tests are the validation of fault detection, and recovery procedures and their further refinement. Further reliability improvement of critical STAR computer components (e.g., the data bus and the power switch) will be studied. The reliability study of the STAR computer will be continued, and in conjunction with new component studies, estimates will be made of weight.volume, power, and operational characteristics of a second generation proto-STAR flight computer in coordination with the TOPS program.

PUBLICATIONS

Meetings and Symposia Papers

1. Avizienis, A., "An Experimental Self-Repairing Computer", presented at the 1968 Congress of the International Federation for Information Processing, Edinburgh, Scotland.

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SYSTEM PROGRAMMING FOR STAR COMPUTER

NASA Work Unit 125-17-04-03-55

JPL 325-71001-0-3410

J. J. Wedel

OBJECTIVE

The objective of this work unit is the development of system programs for the STAR computer. This computer is being developed under the Guidance Computer Organization Work Unit 125-17-04-02-55 to which reference should be made for overall objectives, etc.

The basic nature of the STAR computer as a redundant machine, using automatic replacement of faulty units for self-repair, necessitates special facilities for the resident executive program. This program will, in combination with hardware-implemented facilities, control reassignment of units and control restart after error detection. The error detection itself is primarily implemented by hardware. Other functions provided by the executive program are interrupt processing, control and monitor of input-output, and scheduling of time-shared programs required in an onboard guidance computer. An assembler, loader, and simulator will also be provided under this work unit for preparing STAR programs on the JPL scientific omputing facility.

WORK STATUS

During the present reporting period, the simulator and a system executive program (SYS) have been essentially completed.

The STAR computer simulator is a functional simulator which simulates the information busses, the registers, and the memory contents which would be in the STAR machine if the program were run on the STAR. The actual processes used to simulate the STAR computer instructions may not be the exact STAR algorithms, but the effects on busses, registers and memory are the same as the STAR itself. The smallest time increment in the simulator is a STAR major cycle. The simulator is implemented on a parallel machine (IBM 7094); the byte-serial information flow of the STAR itself is not preserved.

Trace functions are provided by the simulator as an aid in debugging programs. Trace control statements in the data section of the input deck permit initiation or termination of the trace by program location, simulated time, or instruction type. Three basic printouts are available; (1) a standard trace line giving contents of important simulated registers and effective address and operand of current instruction, (2) an extra trace line giving contents of all remaining simulated registers, and (3) a dump of any selected portion of the memory.

A separate sub-program is used in the simulator for each functional unit of the STAR. This portion of the simulator contains the simulated registers and the subroutines for simulating the instructions processed by the given unit. The modular nature of the program facilitates addition, deletion, or changes in functional units. The information busses are simulated as a functional unit to permit easy simulation of bus errors. In the actual machine, all functional units receive all instructions, and examine them to decide if action is required by a particular unit. In the simulator, an extra step has been introduced to avoid activating all the functional unit subroutines, and only the unit which processes the instruction is activated. After execution of the STAR instruction, the trace routine is called. Finally, the Test and Repair Processor and the Interrupt Processor are checked for possible interrupts before going to the next instruction to be simulated.

At the conclusion of a simulation, a register dump is automatically provided and selected memory contents may also be printed. Various summary data is also provided.

The executive program (SYS) controls coordinated use of the assembler, the loader, and the simulator. Control statements in the jobstream are used by SYS for this purpose. All system programs are currently stored in absolute form on magnetic tape. A small binary card deck is used to load SYS which, in turn, loads and runs the other programs as needed.

Seven control statements are used by SYS for processing the jobstream and exercising various options. They specify the number of jobs and separate jobs; determine whether to assemble only, assemble and load, or assemble, load, and run; and specify options associated with the loader and simulator. The SYS program is complete and no further modifications are planned.

The STAR system programs are currently implemented on the IBM 7094, but will be changed to the UNIVAC 1108 when that machine is installed in the scientific computing facility to replace the 7094. Due to delays in the scheduling of the replacement, work on conversion has not been started. The programming personnel on this work unit have, however, gained familiarity with the UNIVAC machine during the present reporting period.

FUTURE WORK

The STAR computer concept will be used for implementing the Central Computer and Sequencer (CC&S) subsystem of the Thermoelectric Outer Planetary Spacecraft (TOPS) program. The STAR system programming work unit will be used to develop software for this subsystem. During the next reporting period, work will be initiated on the determination of software requirements, and the interaction between software and hardware for proposed CC&S machine.

The design of the resident executive program for the STAR will also be initiated, and updating of programs already written will be carried out as required. The conversion of routines to the UNIVAC 1108 machine will not be started until schedules are available for the phasing-in of the 1108, and the removal of the IBM 7094.

PUBLICATIONS

SPS Contributions

1. Rohr, J. A., STAR Computer Assembler and Loader, SPS No. 52, Vol. III, pp. 27-30, August 31, 1968.

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PROGRAM MEMORY FOR STAR COMPUTER

NASA Work Unit 125-17-04-04-55

JPL 325-71201-0-3410

J. J. Wedel

OBJECTIVE

The objective of this work unit is to develop a read-only program memory (ROM) for the JPL self-testing and repairing (STAR) computer. The overall objectives of the STAR computer are considered in the report for the Guidance Computer Organization Work Unit 125-17-04-02-55.

PROGRESS AND FUTURE WORK

The final report for Phase I, which includes a detailed description of the memory logic, has been received. Reference should be made to this report for a description of the read-only memory.

The memory electronics has been completed and tested by the contractor using a simulator to replace the wire rope. Final testing will be accomplished using a wire rope containing information supplied by JPL. The construction of such a rope has not been started due to delays in furnishing this information by JPL. The information is now scheduled to be supplied during February 1969.

Study of the format of the punched paper tape used in controlling the loom which weaves the wire rope has indicated that considerable time and effort will be required to convert the information in the JPL format to the necessary form. It is deemed advisable to have this conversion performed by the contractor who is throughly familiar with the format involved.

A contract modification will be negotiated which will provide that only a single wire rope be supplied by the contractor. The information will be supplied by JPL in standard computer word format and converted by the contractor. Additional cost to the contract will be incurred by this modification requiring programming effort by the contractor.

An additional fixed price purchase can be used to obtain a second rope later. The procurement of a single wire rope in this contract will permit delay in determining contents of a second rope. This second wire rope should have a program which can be used to demonstrate the performance of the STAR machine working as a guidance computer. By delaying the procurement of the rope, it is expected that this application program can be concerned with the Central Computing and Sequencing subsystem of the Thermoelectric Outer Planetary Spacecraft which is currently being developed at the Laboratory.

PUBLICATIONS

None

AUTOMATIC ROVING VEHICLE COMPUTER DEVELOPMENT

NASA Work Unit 125-17-04-06-55

JPL 325-71501-0-3410

L. Y. Lim

OBJECTIVE

The objective of this work unit is the development of computer techniques for the operation of an automatic roving vehicle. The presently available information on advanced planetary and advanced lunar missions indicates that a roving vehicle for exploration purposes is highly desirable. Particularly in the case of planetary missions, it is not practical to control such a vehicle by direct commands from the earth. This situation arises from the excessive time delays due to the great distance, from the fact that continuous movement may be desirable and the vehicle will not be in view at all times, and from the formidable logistics problem involved in continuous control. However, the completely self-contained control of such a vehicle is beyond the present state-of-the-art. There are various known efforts to attack the problem, but they generally involve the utilization of a data processing computer which seems much too large to be considered for this application. The problems in the roving vehicle computer and its application are severe from several standpoints. The computer itself must be sufficiently small in order that its weight and power consumption are not excessive, and it must be sufficiently reliable in order to operate without maintenance for the life of the mission. This work unit will be performed in three phases:

(1) Development of computational algorithms for the computer

(2) Preliminary design of the computer

(3). Construction and testing of the computer

COMPUTATIONAL ALGORITHMS

The development of algorithms for the navigation of the vehicle, and for the processing of environmental information from the sensor inputs is very essential to the design of the computer.

PROGRESS

During the last report period, a pathfinding algorithm was developed. The algorithm uses only local information which is available from the vehicle's sensor to find a path from the starting point to the target point. The algorithm assumes that there exists at least one path between the starting point, Po, and the target point, Pn. A more comprehensive computer program for the navigation of an autonomous roving vehicle has also been developed. It consists of a global and a local mode. The global mode utilizes gross terrain information (available from a previous orbiter mission) to determine the nominal optimal path between any two points on a preselected grid. The local mode uses only information available from the vehicle sensors. The local mode is an extension of the pathfinding algorithm described previously. The global and local modes are combined to route the vehicle along a quasi-optimal path between any two points on a terrain surface. Upon initiating an exploration, the global mode supplies to the vehicle computer the sequence of coordinates of the grid points on the nominal optimal path. The roving vehicle then follows the nominal path as long as no obstacles are encountered. If an obstacle is detected, control is switched to the local mode which routes the vehicle around the obstacle to a selected point on the nominal path. The vehicle then continues on the nominal path. The grid point on a nominal path is called a secondary target. Whenever a secondary target is within sensor range and there is an unobstructed straight-line path from the current location to this secondary target, the vehicle follows this path. This algorithm has been successfully simulated on the IBM 7090/94 computer.

Development of the global mode was performed in conjunction with NASA work unit 125-19-03-02-55, "Land Operations", and represents a joint cooperative effort between the two discipline areas.

FUTURE WORK

During the next report period, effort will be expended to develop computational algorithms for the processing of environmental information from sensor inputs. These data processing techniques will be different for various types of sensors. The final data will be applied to the pathfinding algorithm for navigation of the vehicle.

This work is coordinated with Remote Operations of a Roving Vehicle (186-68-02-25-55), and also with Man-Machine Functions in Control of an Unmanned Roving Vehicle (127-51-01-02-55).

PUBLICATIONS

Meetings and Symposia Papers

1. Kirk, D. E., and Lim, L. Y., "A Pathfinding Algorithm For An Autonomous Roving Vehicle." The Second Hawaii International Conference on System Sciences, January 22, 23, 24, 1969.

JPL Technical Reports

1. Lim, L. Y., "A Pathfinding Algorithm For A Myopic Robot," NASA/JPL Technical Report 32-1288, 1968.

GUIDANCE STUDIES FOR FUTURE MISSIONS

NASA Work Unit 125-17-05-01-55
JPL 325-70301-2-3430

J. M. Moore

OBJECTIVE

The long range objectives of this work unit are to determine and specify the guidance system requirements for future missions, to develop functional descriptions of guidance system configurations, and to analyze and evaluate system performance of the configurations. The near-term objective is to develop and demonstrate the approach guidance capability required to perform the Grand Tour type mission. The effort described by the near-term objective is in direct support of the Thermoelectric Outer Planet Spacecraft (TOPS) project.

PROGRESS

Low Thrust Guidance

The low thrust guidance effort in this work unit was terminated in the first quarter of FY 69. The termination was necessitated by the priority of other research and advanced development tasks, and a reduction in resource allocations. This effort was primarily concerned with the study and development of guidance and control techniques for electrically-propelled spacecraft. Progress achieved included the development and application of tools for the solution of optimal control problems by variational techniques.

Optimal Gliding Re-entry into the Mars Atmosphere

During the first quarter of FY 69, the problem of reentry into the Mars atmosphere was considered. Specifically, an analysis was performed to design the minimum heat generation trajectory for the reentry of a Mars space vehicle using a variable lift force. Consideration was given to capsule reentry from both orbiting and fly-by spacecraft. It was assumed that the capsule trajectory was ballistic, and defined by the height of the detectable atmosphere and a terminal altitude several thousand feet above the surface. The primary output of the analysis was the specification of a reentry trajectory which generated the minimum total convective heat transfer at the stagnation point for an average atmospheric density model. The control law for this trajectory was obtained in closed form by making suitable approximations. The effect of parametric variations in entry conditions, switching criteria, and terminal conditions was studied. Also, the mechanization problems associated with the variable lift force control was studied.

Thermoelectric Outer Planet Spacecraft (TOPS) Project

The FY 69 work objectives were modified at the beginning of the second quarter to satisfy the requirements of the TOPS Project. This Advanced System Technology work has the prime objective of developing the technology required to perform the Grand Tour type mission in the late 1970's. In this work unit, the effort will be concerned with developing the guidance capabilities required for the Grand Tour. Recent guidance studies have shown that fuel requirements for the four planet mission can be reduced significantly with the addition of onboard optical measurements in the orbit determination process.

The initial output in this area was a detailed program plan, developed jointly under this work unit and Work Unit 186-68-02-21-55 (Guidance and Control Subsystem Integration for Future Missions), for support to TOPS through FY 71, the projected end-date for TOPS. The program plan contains task statements, a schedule, and resource estimates. Implementation of the plan has begun, and results from the previous guidance studies are currently being revised to reflect the latest parameter data.

Activities in this work unit are directly related to those in Work Units 186-68-02-21-55 and 125-17-02-01-55, respectively, (Guidance and Control Subsystem Integration for Future Missions and Optical Approach Guidance Analysis and Design). In the former, the objectives have been modified to support TOPS, and the tools and technology developed in the latter directly benefit TOPS.

FUTURE PLANS

Plans for the remainder of FY 69 include (1) completing the guidance analysis for the TOPS Project, (2) developing functional requirements for the approach guidance system, and (3) developing an approach guidance functional design. The first item specifically refers to orbit determination studies using approach guidance measurements and the resulting implications on maneuver policy, requirements, and fuel consumption. The second and third items represent the outputs required to complete the system hardware and software definition phase, and to begin the system implementation phase. The implementation phase begins in the first quarter of FY 70.

Since the program outlined is a joint effort, a work unit prefix is assigned to each activity. The prefix 186 indicates the activity will be supported primarily from Work Unit 186-68-02-21-55, and the prefix 125 indicates support from this work unit.

PUBLICATIONS

None

MANEUVER STRATEGY AND NAVIGATION ANALYSIS

NASA Work Unit 125-17-05-02-55

JPL 325-70701-1-3110

C. B. Solloway

OBJECTIVE

The objective of this work unit is to conduct navigation and maneuver strategy analyses associated with advanced lunar and interplanetary trajectories.

CONTINUOUS ESTIMATION PROGRAM

The continuous estimation program (CEP) continues in service as a tool for applied research in the field of orbit determination.

In Ref. 1, the accuracy of the continuous minimum variance estimate of the state of a distant space probe was observed over a span of time that included several successive 12-hr passes of two-way integrated range-rate data from a single tracking station, located on the earth's equator. The dependency of the estimation accuracies on the number of completed passes and the earth-probe geometry was noted, and, in particular, sensitivities of the results to the lateral velocity of the probe were observed.

In recent months the results of Part I have been generalized to include the behavior of the estimation accuracies when more than one tracking station is available for making observations of the probe. In particular, studies have dealt with the time history of the covariance matrix of errors in the probe state estimates, when the probe is being observed in succession by two stations, located on the earth's equator, whose respective longitudes differ by an angle ϕ. Sensitivities of the state uncertainties to both ϕ and the station tracking switching strategy have been noted.

Studies are being conducted in order to determine the advantage of employing ranging data as well as counted doppler data for orbit determination purposes. Both internal and external reports will be forthcoming within a few weeks, as the study is nearing completion. Application of the results to a simulated interplanetary mission will follow.

OPTIMAL STOCHASTIC TRANSFER PROBLEMS

Completed is the first stage of the continued work on the problem of "Optimal Orbital Transfer Strategy" which seeks for a single and two impulsive correction of a spacecraft orbiting around a target planet via dynamic programming. Two computer programs have been developed to solve this problem and the basic strategy has been established. The outline of the work was presented as a paper at the AIAA Guidance, Control and Flight Dynamics Conference at Caltech in August 1968. The same paper was submitted to the AIAA Journal for possible publication. An SPS article was written to report the concluding part of the subject, as well as experimental results.

In supporting this optimal transfer problem a Technical Memorandum, Ref. 2, was issued in which a cotangential orbital transfer (deterministic case) was studied in detail. When the precision of orbital period is mandatory, this cotangential transfer strategy will play an important role under the circumstance that an impulsive correction is subject to a relatively large pointing error.

The work on the optimal stochastic transfer problem will be continued to its second stage, in order to extend it to insertion maneuvers as well as to midcourse corrections. Feasibility of applying this program to the Mars 71 mission will be studied.

OPTIMAL CONTROL

The second variation approach to the computation of optimal control with discontinuities (Ref. 3) has been extended to include cases with terminal equality constraints and free terminal time. The approach also has been extended to include impulsive controls, and a computer program has been written to study the performance of the algorithm. Several significant numerical techniques have been reported for the optimization of trajectories in this reference. Current work is being done on the optimization of multiple impulsive guidance.

Future work will include the study of impulsive guidance schemes and the application of the estimation algorithms to planetary orbiters, and the application of optimal stochastic control theory.

COMPRESSION OF TRACKING DATA

The feasibility of data compression was shown in Ref. 4. Current work is being done to actually apply data compression to real data and results should be reported soon. A computer program, which should be operational in early CY 69, has been written to compress real data.

Current work is being done on an analytic analysis of the information content of doppler data of a planetary satellite. In the future, programs will be written to explore the effects of specific model errors for planetary orbiters.

ESTIMATION THEORY

Effort on filtering and estimation theory has been continuing. The smoothing problem described in the previous period was solved by applying the filtering (Kalman-Bucy) technique to an augmented state vector containing the accumulated contribution of process noise, and a solution using forward integration in time was derived. These results were submitted to the IEEE Aerospace and Electronics Conference.

Another paper was prepared jointly with Professor Kim (RRA - currently at JPL) which discussed the performance of a suboptimal discrete filter ignoring certain parameters (considered option), and it was accepted by the Second Hawaii International Conference on System Sciences to be held in Honolulu, Hawaii, in January 1969.

A continuous filter consider option has been developed which can analyze the error in state estimates due to ignored nonlinear terms in the dynamical equation. A modification of the standard Kalman formulas to account for such nonlinearities has been developed, and publication of the findings are pending the results of numerical studies.

Further results have been established for the relative accuracies of sequential estimators, and a paper describing these results has been accepted for publication.

Effort is still being made on the analysis of how specific error sources, e.g., pole wander, ionospheric effect, affect orbit determination accuracies. Techniques for improving navigations that involve sequential estimation are being investigated. An effort to obtain a stochastic model for various effects is being made currently.

LOW THRUST GAS LEAKAGE PROBLEM

One of the primary unmodeled forces acting on the Mariner V spacecraft stems from the attitude control system. Precise knowledge of this force is required to properly determine the trajectory for both operational and scientific purposes.

Work on trajectory perturbations due to attitude control system forces was completed in the reporting period. A paper summarizing the results of this study will be presented at the AIAA 7th Aerospace Sciences Meeting in New York, January 20-22, 1969.

REFERENCES

1. Jordan, J. F., "Continuous Estimation of the State of a Distant Spacecraft During Successive Passes of Data. Part I: Single Tracking Station Results," SPS 37-52, Vol. II, pp. 37-44, July 31, 1968.
2. Nishimura, T., "Cotangential Orbital Transfer Strategy and Reachable Region by Single Maneuver," Technical Memorandum 311-57, July 10, 1968.
3. Dyer, P., and McReynolds, S. R., "On Optimal Control Problems with Discontinuities," J. Math. Anal. and Appl., Sept. 1968.
4. Dyer, P., and McReynolds, S. R., "Data Compression and its Application to Orbit Determination," SPS 37-53, Vol. II, Sept. 30, 1968.

ATTENDANCE AT SCIENTIFIC MEETINGS

1. AIAA Guidance, Control and Flight Dynamics Conference, Pasadena, Calif., Aug. 12-14, 1968.

2. Joint Automatic Control Conference of Japan, Tokyo, Japan, Oct. 16-18, 1968.

PUBLICATIONS

Meetings and Symposia Papers

1. Nishimura, T., and Pfeiffer, C. G., "A Dynamic Programming Approach to Optimal Stochastic Orbital Transfer Strategy," AIAA Guidance, Control and Flight Dynamics Conference, Paper No. 68-872, Pasadena, Calif., Aug. 12-14, 1968.

2. Nishimura, T., "A New Approach to Estimation of Initial Conditions and Smoothing Problems," IEEE Aerospace and Electronics Conference, Ohio, May 1969.

3. Bourke, R., McReynolds, S. R., and Thuleen, K. L., "Translational Forces on the Mariner V Spacecraft Stemming from the Attitude Control System," AIAA 7th Aerospace Sciences Meeting, New York, N. Y., Jan. 20-22, 1969.

4. Nishimura, T., and Kim, M., "On Synthesis of Suboptimal Filters," Second Hawaii International Conference on System Sciences, Honolulu, Hawaii, Jan. 22-24, 1969.

Open Literature

1. Dyer, P., and McReynolds, S. R., "On Optimal Control Problems with Discontinuities," J. Math. Anal. and Appl., Sept. 1968.

SPS Contributions

1. Jordan, J. F., "Continuous Estimation of the State of a Distant Spacecraft During Successive Passes of Data. Part I: Single Tracking Station Results," SPS 37-52, Vol. II, pp. 37-44, July 31, 1968.

2. Dyer, P., and McReynolds, S. R., "Data Compression: Its Application to Orbit Determination," SPS 37-53, Vol. II, Sept. 30, 1968.

3. Dyer, P., and McReynolds, S. R., "On the Computational Accuracy of Square-Root Filtering," SPS 37-54, Vol. III, Dec. 31, 1968.

4. Jordan, J. F., "Continuous Estimation of the State of a Distant Spacecraft During Successive Passes of Data. Part II: Twin Tracking Station Results," SPS 37-54, Vol. II, Nov. 30, 1968.

5. Nishimura, T., "A Dynamic Programming Approach to Optimal Stochastic Orbital Transfer Strategy: Part II," SPS 37-54, Vol. II, Nov. 30, 1968.

LANDED OPERATIONS

NASA Work Unit 125-19-03-02-55

JPL 325-90401-2-3440

A. K. Bejczy
D.E. Kirk
Y. E. Sahinkaya

OBJECTIVE

The long-range objective of this work unit is to develop advanced control systems for planetary vehicles and surface exploration vehicles.

MARTIAN SURFACE PROPULSIVE SOFT LANDER FOR AN IMPRECISELY KNOWN ATMOSPHERE

Any type of soft lander proposed for an initial Mars landing must deal with the fact that the physical parameters of the Mars atmosphere are not well known. During the last six months, progress has been made in the area of applying optimal control theory to a propulsive lander problem in an imprecisely known atmosphere. Pontryagin's "Maximum Principle," Bellman's "Dynamic Programming," and Kalman's filter theory were applied to develop a complete or "full" filter to accomplish two tasks:

(1) Derive accurate estimates of the state variables of the vehicle from on-board instrumentation whose outputs have been corrupted by noise.

(2) Utilize these on-board data to determine and execute an optimal retrothrust control program. (Results of this analysis are control laws that are not in the least practical to mechanize.)

Given that modern control theory has produced impractical results, the most important effort that is being undertaken is to evolve ways of simplifying the full filter to something that is realizable, but at the same time, close enough to the full filter so that the gains in optimality are not lost.

Favorable progress has been made in the development of such suboptimal filters. In the case at hand, a suboptimal filter has been developed that is only about 3% as complex as the full filter.

Computer simulations have been run to test the performance of the filter when used to determine the state variables of a soft lander from on-board instrumentation whose outputs are corrupted with noise. This filtering scheme determines the state variables within an accuracy of 98% of the true value, and converges on the value within a little over one second.

The plans for the next six months are to start the application of this filtering scheme to a lifting-body vehicle for entry into the Mars atmosphere.

A PATH FINDING ALGORITHM FOR AN UNMANNED PLANETARY ROVING VEHICLE

The communication distances encountered for a Mars surface-roving vehicle make it quite infeasible to utilize an earth-based operator, viewing television pictures from the vehicle, to obtain terrain information to control the vehicle. Under NASA Work Unit 125-17-04-06-55, "Automatic Roving Vehicle Computer Development," the Flight Computers Section of JPL has developed an algorithm that uses the information from a vehicle sensor, with limited range, to detect and avoid unexpected obstacles (if one exists), but may take a devious and nonoptimal route to the desired target. Therefore, under this work unit, a new algorithm has been developed by the Spacecraft Control Section which can utilize aerial photography from a Mars orbiter, such as Mariner Mars 71, to maintain the vehicle on an optimal path. But this global algorithm is limited by the photographic resolution of the orbiter, and cannot deal with unexpected obstacles.

The local and the global algorithms have been combined and are capable of determining a quasi-optimal path between any two points on the surface. The vehicle initially operates on the global algorithm until an unexpected obstacle is encountered, at which point it transfers to the local algorithm until the obstacle is avoided, and then transfers to the global algorithm to continue on the quasi-optimal path.

A MINIMUM ENERGY CONTROLLER FOR A MARS SURFACE ROVING VEHICLE

Under this work unit, a contract has been given to the Electrical Engineering Department of the California Institute of Technology to develop ways of applying modern control theory to spacecraft control problems. For FY 69, the total funds allocated to this contract are $26,000. During this report period, the most significant accomplishment was in the development of a minimum energy controller for a planetary surface roving vehicle. The objective was to use Pontryagin's "Maximum Principle", Kalman's filter theory, and Bellman's "Dynamic Programming" to develop a complete filtering scheme to provide the optimal control law for an electric drive system for a roving vehicle that may in fact be mechanized.

The application of modern control theory to the problem discussed is not unusual from the standpoint of contemporary work. But what is quite unusual is the attempt to derive a feasible mechanization result from the theory. In the case of the minimum energy controller discussed above, considerable research was conducted to seek ways to arrive at simplifications to the complete filtering scheme that would still provide accurate suboptimal performance. Extensive detail computer simulations were utilized to obtain and demonstrate the results of a meaningful simplification. A suboptimal controller was developed that virtually matches the performance of the optimal controller, and a practical mechanization block diagram was derived. The plan for the next six months is to begin the implementation of that controller.

Aside from the specific application of this device to a roving vehicle, it would seem that there could be significant fallout in commercial applications, wherever electric drive systems are used, such as paper mills, steel mills, etc.

PUBLICATIONS

Meetings and Symposia Papers

1. Bejczy, A. K., Ph.D., "Fuel-Optimal Retro Thrust Control in State Dependent Retarding Force Fields," Second Hawaii International Conference on System Sciences, University of Hawaii, Honolulu, January 22-24, 1969.

2. Bejczy, A. K., Ph.D., "On the Realization and Computational Aspects of the Maximum Principle Least-Squares Nonlinear Filter," Second Hawaii International Conference on System Sciences, University of Hawaii, Honolulu, January 22-24, 1969.

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1. Bejczy, A. K., Ph.D., "Fuel-Optimal Retro Thrust Control Programs for Propulsive Soft Landing Maneuvers in the Presence of Drag," TR 32-1361.

2. Kirk, D. W., Ph.D., "A Path Finding Algorithm for an Unmanned Planetary Roving Vehicle," TR 32-1369.

Contractor Reports

1. California Institute of Technology Annual Report on Contract 69821-69822, December 1968.

CONTROL SYSTEM SYNTHESIS UTILIZING FLEXIBLE BODIES

NASA Work Unit 125-19-04-01-55

JPL 325-90501-2-3440

G. E. Fleischer

OBJECTIVE

The objective of this work unit is to investigate alternate or new control techniques for future JPL missions, and to develop ways to analyze these control systems, especially with respect to flexible structures, rotating devices, and articulated members.

PROGRESS

Most spacecraft of the future will have significantly flexible structures that will interact with the attitude control systems in ways that will require the solution of difficult non-linear differential equations. Under this work unit, two different analytical methods are being developed to adequately describe and allow computer simulations of the dynamic motion of various flexible vehicles under the influence of an attitude control system.

The first method treats a structure (spacecraft) as a collection of interconnected rigid bodies capable of large deformations. A multi-purpose digital computer program has been developed, based upon the published equations of Hooker and Margulies, for the simulation of vehicles modeled as N point-connected rigid bodies. This type of analysis is particularly suited to control systems analysis in that it provides a time history of the discrete parts of the structure. This is quite significant as it directly effects the input to sensors, and the output of reaction control devices. The disadvantage of this approach is that for a vehicle represented by more than three or four rigid bodies, the computational complexity may become prohibitive. However, this technique has been applied quite successfully to a problem involving a scan platform on a dual-spin stabilized vehicle.

When a vehicle undergoes small deformations, it becomes possible to make a transformation to modal coordinates, and very substantial computational advantages then accrue. This technique is quite familiar to structural dynamicists. However, the time history of the structure is no longer available, and if rotors and articulated parts are present, the technique is inapplicable.

A hybrid system, utilizing both discrete and model coordinates, is being developed to obtain the advantages of both. An application and test of this method is being applied to spacecraft configurations possessing large, flexible solar panel arrays and/or large, relatively flexible antenna structures that are being considered for outer planet missions. This hybrid coordinate system is showing great promise for the effective analysis of the interaction of flexible bodies and control systems.

For the coming six months period, the hybrid system will be utilized to solve practical problems to test the system applicability to real problem solutions. In addition, the efficacy of the hybrid method utilization depends on the application to a given problem. It must be applied properly to those parts of a typical spacecraft that may best be represented respectively by discrete and modal coordinates. Therefore, different types of problems will be examined to determine the most appropriate way to combine the advantages of the hybrid system.

PUBLICATIONS

SPS Contributions

1. Fleischer, G. E., "ION Engine Thrust Phase Attitude Control with Flexible Solar Arrays," SPS 37-54, Vol. III, December, 1968.

JPL Technical Reports

1. Likins, Dr. Peter, "Dynamics and Control of Flexible Space Vehicles," TR 32-1329.

COMMUNICATIONS (125-21)

COMBINATORIAL COMMUNICATION

NASA Work Unit 125-21-01-01-55

JPL 325-10701-X-3310

E. R. Rodemich
R. J. McEliece

OBJECTIVE

The objective of this work unit is to provide a fund of combinatorial and algebraic theory and techniques for use in the design of coded spacecraft and ground communication systems. In addition, theoretical yardsticks are developed against which the performance of such systems can be measured.

PROGRESS

It was discovered (Refs. 1, 9) that a well-developed branch of classical mathematical (algebraic geometry) may be used to shed considerable light upon many aspects of algebraic coding theory. In particular, a precise estimate of the correlation between a PN sequence and its reverse was obtained.

It has been possible to obtain substantial results (Refs. 2, 3, 4) on the distribution of the number of feedback functions in an n-bit shift register as a function of the number of cycles of register states and the "weight" of the feedback function.

A systematic treatment of a general class of error metrics that might reasonably correspond to error patterns encountered in actual communication systems was given (Ref. 5).

A powerful mathematical tool for the study of the weight structure of cyclic codes was given (Ref. 8). This has already lead to the solution of some outstanding conjectures in coding theory.

A new approach to the determination the maximum possible error-correcting capabilities of block codes, which unified all previously known such results, was developed (Ref. 10 and 11).

An investigation into the feasibility of allowing a decoder for a bi-orthogonal code (such as in the Mariner 69 high data-rate system) to make erasures was made (Ref. 14).

Work continued on the preparation of a definitive report on the state of knowledge of difference sets.

PLANS

Further investigation into the applications of algebraic geometry to coding theory will be made, with special emphasis on the development of efficient decoding algorithms for the codes already discovered.

It is planned to make a study of the use of block codes other than the bi- and trans-orthogonal codes in future telemetry systems, using the well developed techniques of algebraic coding theory, in order to conserve bandwidth.

Further research into the properties of difference sets is planned, using the tools of algebraic number theory.

A close study of the proposed DSN teletype code will be made, with particular attention paid to the synchronization-recovery strategy to be adopted by the decoder.

REFERENCES

1. Dowling, T. A., and R. J. McEliece, "A Note on Cross-Correlations of Reverse Maximal-Length Shift Register Sequences," SPS 37-53, Vol. III.
2. Fredricksen, H. F., "The Maximum Number of Cycles in the de Bruijn Graph," SPS 37-52, Vol. III, pp 193-196.
3. Fredricksen, H. F., "Cycle Decomposition of the de Bruijn Graph," submitted to IEEE Trans. on Info. Theory for publication.
4. Fredricksen, H. F., "The Lexicographically Least de Bruijn Cycle," J. Combinatorial Theory, in press.
5. Golomb, S. W., "A General Formulation of Error Metrics," SPS 37-52, Vol. III, pp 190-192.

6. Golomb, S. W., and L. Welch, "Algebraic Coding and the Lee Metric," Ch. 10 in Error-Correcting Codes, H. B. Mann, editor, Wiley, N. Y., 1968.

7. McEliece, R. J., "Factorization of Polynominals Over Finite Fields," submitted to Mathematics of Computation for publication.

8. McEliece, R. J., "Periodic Sequences From GF(q)," submitted to J. Combinatorial Theory.

9. McEliece, R. J., "Cyclic Codes and Exponential Sums," proceedings of second Hawaii International Conference on Systems Sciences, January 1969, in press.

10. McEliece, R. J., and Rumsey, H. C., "Sphere Packing in the Hamming Metric," SPS 37-52, Vol. III, pp 189-190.

11. McEliece, R. J., and Rumsey, H. C., "Sphere Packing in the Hamming Metric," Bulletin American Math. Soc., in press.

12. Posner, E. C., "Combinatorial Structures in Planetary Reconnaissance," Ch. 2 in Error-Correcting Codes, H. B. Mann, editor, Wiley, N. Y., 1968.

13. Rodemich, E. R., and Rumsey, H. C., "Primitive Trinomials of High Degree," Mathematics of Computation 22 (1968), pp 863-865.

14. Welch, L. R., "Orthogonal Codes and Erasures," SPS 37-52, Vol. III, pp 187-188.

PUBLICATIONS

See foregoing References 1, 2, 5, 6, 10, 12, 13 and 14.

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SEQUENTIAL DECODING

NASA Work Unit 125-21-01-02-55

JPL 325-10201-X-3310

J. A. Heller

OBJECTIVE

The object of this work unit is to develop simple and efficient convolutional coding-decoding systems to improve the performance of deep-space communication links. In particular, methods are sought to generate convolutional codes with the best possible error-correcting capabilities. In addition, methods of decoding convolutional codes, such as sequential decoding and maximum-likelihood decoding, are compared to determine their appropriateness for various missions.

PROGRESS

Work has been done concerning short constraint-length convolutional codes and maximum-likelihood decoding (Ref. 1 and 2). Good convolutional codes of constraint length 8 and less have been generated and tested with a computer simulated channel and the optimum maximum-likelihood decoder. Results indicate that this coding-decoding system yields a savings of about 1 dB, at an error probability of 5×10^{-3}, over a block biorthogonal coder-decoder of corresponding complexity, such as that used on the high data rate telemetry system of Mariner 69. In addition, the convolutional codes use significantly less bandwidth and have excellent synchronization properties.

The convolutional codes used in these experiments have been of the nonsystematic variety, since it has been shown that these have much greater error-correcting capabilities than corresponding systematic codes such as that used with Pioneer VI (Ref. 3).

Work has also been done concerning the degradation in performance with sequential decoding due to imperfect knowledge of carrier phase. The results are applied particularly to the Pioneer-type systems (Ref. 4).

PLANS

Efforts will be made to study algebraic and other properties of convolutional codes with the aim in mind of obtaining codes with the best possible error-correcting capabilities for given constraint lengths and rates.

Also, work will be done on concatenating convolutional codes, i.e., on using more than one level of coding in a system. The aim is to reduce the error probabilities attainable with one level of convolutional coding still further without increasing system complexity prohibitively.

Another area of active research concerns the erasure probability with sequential decoding. Sequential decoders are capable of yielding very low error probabilities at the expense of a moderate erasure probability. Erasure probability had been thought to drop inversely with a small power of the decoder memory size. There is evidence now, however, that the true behavior may be somewhat poorer than this at very low erasure rates. This is being studies both analytically and by simulation. The programs for the simulations have already been written.

REFERENCE

1. Heller, J. A., "Short Constraint Length Convolutional Codes," SPS 37-54, Vol. III, December 1968.

2. Heller, J. A., "Short Constraint Length Convolutional Codes," Submitted for presentation at the Polytechnic Institute of Brooklyn International Symposium on Computer Processing in Communications, April 1969.

3. Heller, J. A., "Error Probability Bounds for a Class of Convolutional Codes," to be published in the IEEE Transactions on Information Theory (co-authored with E. Bucher).

4. Heller, J. A., "Performance of Pioneer-Type Sequential Decoding Communication Systems with Noisy Oscillators," SPS 37-53, Vol. III, October 1968.

PUBLICATIONS

See foregoing References 1 and 4.

ADVANCED SOLID STATE RF TECHNOLOGY APPLICATIONS

NASA Work Unit 125-21-01-03-55

JPL 325-10301-2-3360

B. Conroy

OBJECTIVE

The objective of this work unit is to improve spacecraft communication capability through the application of recent developments in advanced solid state technology. If properly applied, the properties of several recently discovered devices can provide a means of achieving significant improvements in spacecraft transmitter reliability, life time, and efficiency. In addition, the inherent small size and weight characteristics offer advantages for planetary landed capsules or other size and weight-limited probes.

Specific areas of new technology being considered include (1) basic devices, such as new high power, high-frequency transistors and bulk effect oscillators like the Gunn and L. S. A. Diodes, (2) circuit configurations and (3) media for microwave circuit construction.

STATUS

Basic Devices

The new device that shows the most promise for use as a spacecraft transmitter element is an IMPATT diode operating in the "Anomalous Avalanche" mode. It was given this name by its discoverers, Prager, Chang, and Wiesbord of RCA, because the efficiency was nearly twice that predicted by the most optimistic model of the IMPATT diode. Efficiencies of up to 60% were observed with 180 watts of pulsed power at 873 mHz. Later work at Bell Labs has produced continuous power at 1 GHz with 40% efficiency.

Plans

Plans for these devices are to investigate methods to produce the frequency stability required for spacecraft use.

Work on high power high frequency transistors is being reported under work unit 160-21-02-01-55, UHF FM Transmitter Investigation.

Circuit Configurations

Investigation of the distributed amplifier has shown that while there are some problems associated with it, it still holds promise as a method of combining several devices to achieve higher power for spacecraft transmitters.

Several amplifiers of this type were built at RCA Laboratories, and the data show that the efficiency is not impaired and power outputs very nearly add. The amplifier gain, however, was lower than that of a single device. One amplifier employed four pairs of TA 2675 transistors spaced at half wavelength intervals along input and output lines and produced 100 watts of power with 75% efficiency and 3.2 dB gain at 400 mHz. The major problem is matching to the low impedances of the transistor bases.

Plans

It is planned to build and test breadboard units operating at frequencies up to 2.3 GHz and to improve amplifier gain characteristics.

Media for Circuit Construction

In-house capability has been built up in breadboarding circuits in both stripline and microstrip. Several hybrid couplers and tuned amplifiers have been built on Rexoline Dieletric with good agreement between experimental and predicted performance. The best hybrid had less than 0.17 dB insertion loss and greater than 30 dB isolation. The design frequency was 575 mHz and the isolation peaks were at 573.3 mHz and 580 mHz for the two different paths. In microstrip, the high Q resonant elements showed higher loss than expected, but this has been attributed to radiation loss.

Plans

Materials are being acquired to work with aluminum oxide as the dielectric. This dielectric will both reduce size and lower the radiation from the circuits.

PUBLICATIONS

None

LARGE SPACECRAFT ANTENNA STUDY

NASA Work Unit 125-21-02-02-55

JPL 325-11001-2-3330

P. W. Cramer

OBJECTIVE

The purpose of this study is to develop the technology of large light-weight erectable antennas for planetary exploration missions. The radio frequency performance is being given the primary emphasis and includes developing analytical techniques for calculating the patterns of these antennas and application of the results to a parametric study to determine the required mechanical properties including cassegrain antenna configurations.

ACCOMPLISHMENTS

Accomplishments have primarily consisted of experimentally verifying the results of the pattern calculating program developed during FY 68 and the development of a method of describing the surface shape of rib-type erectable antennas.

As mentioned in the last semiannual review (Document 701-15, p 367), a surface current integration program was developed to calculate the far field radiation patterns of radial ribbed erectable antennas. The surface between the ribs were represented by parabolic cylinders which included the ribs. To evaluate the accuracy of this program, an antenna was built to simulate a 6-foot diameter erectable antenna with eight ribs. Each of the parabolic cylindrical surfaces is made of aluminized mylar. Based on measurements performed on this antenna, the computed results agreed within ±0.2 dB and the best focus agreed within ±0.15 inches.

The assumption that a parabolic cylinder represents the shape of the surface of an erectable antenna is not accurate, but it was used up to this time, as a more accurate model was not available. The problem results from the fact that when a fabric is stretched between two curved ribs, the fabric does not produce a cylinder with the shape of ribs, but rather causes the fabric to bow in a direction opposite to the direction of the curve of the ribs. Since this movement is in the opposite direction from a cylindrical surface for the direction required to produce a true paraboloidal surface, the shape for highest antenna efficiency, the bowing of the fabric must be taken into consideration when calculating the antenna radiation patterns. Therefore, a program was developed to calculate the actual shape of the reflecting surface of an erectable antenna and is in the process of being evaluated. The present form of the program is expressed in rectangular coordinates. Figure 1 illustrates the output of this program for one antenna shape at one section perpendicular to the center line of one gore of the antenna. The figure also shows the effect of varying the ratio of the orthogonal forces in the surface of the antenna. The equations used were derived from the premise that all the forces normal to the surface must be zero when the surface equilibrium shape is reached, and the equations were solved using the finite difference method. The program can handle any rib shape to account for rib distortions or for some radial geometries.

NEXT PHASE OF STUDY TO BE INVESTIGATED

The surface integration program is to be modified to handle antenna sizes up to 25 feet in diameter by taking advantage of a new integration program developed by A. Ludwig at JPL. Also, changes will be made to accept the output of the program that calculates the shape of the reflecting surface of the antenna.

Additional work will be performed on the reflecting surface shape program to express its results in spherical coordinates so that it will be compatible with the coordinate system used in the surface current integration program.

Test sections of a sample erectable antenna are to be fabricated to evaluate the accuracy of the reflecting surface shape program.

The antenna pattern calculation programs will be expanded to handle cassegrain erectable antenna configurations.

PUBLICATIONS

None

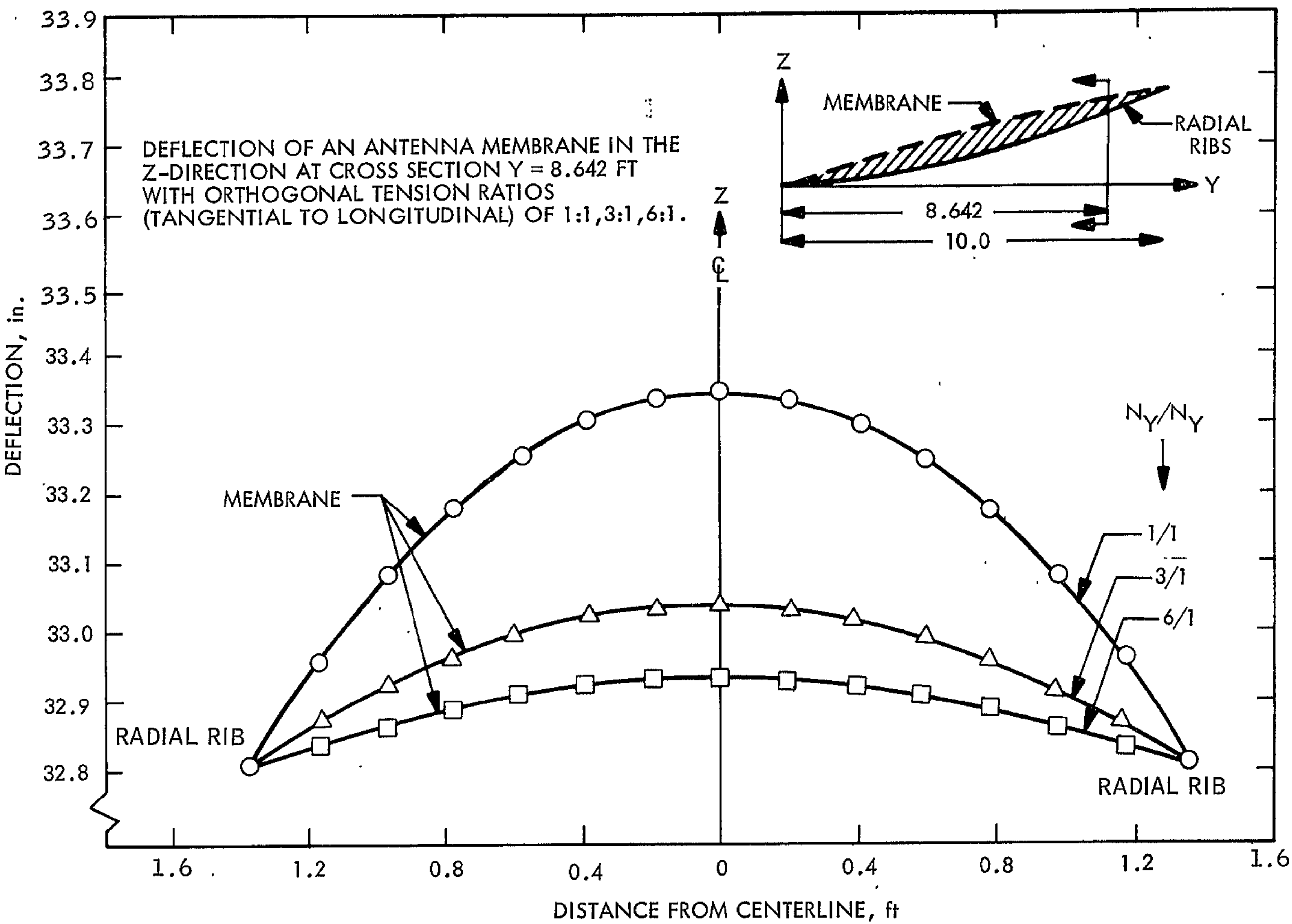

Figure 1. Output of Program

CODING AND SYNCHRONIZATION STUDIES

NASA Work Unit 125-21-02-03-55

JPL 325-10601-X-3310

J. K. Holmes

OBJECTIVE

This work unit finds advanced techniques for carrier and symbol synchronization and tracking in deep space communication systems.

PROGRESS

A general-purpose symbol synchronizer and data detector has been developed, tested, and analyzed; it has been incorporated into a sequential decoder proposed for post-Mariner spacecraft (Ref. 1 and 2). Its performance exceeds any existing symbol synchronizer currently available. Some new results derived from a nonlinear analysis of a phase locked loop, have been obtained (Ref. 3, 4, and 5) for the variance of the phase error in such loops. These results will be of use in predicting performance of the receivers in upcoming missions during times when the loop is operating at threshold. The effects of phase jitter on a proposed convolutional coding - sequential decoding scheme was analyzed (Ref. 6) and it was found that at low rates there is significant degradation compared to high rates. Some new algorithms were obtained for the identification of linear systems (Ref. 7). The effects of quantization on the Mariner 69 digital dump-matched filter was analyzed (Ref. 8). Noncoherent detection of digital signals through randomly time varying channels was analyzed in the general case and should prove useful in capsule entry communication links (Ref. 9).

PLANS

Analysis of the Mariner 69 high-rate telemetry system will be finished. Further studies on phase-lock loops will be made, concentrating on the nonlinear aspects of the loops. Channel modeling will be continued.

REFERENCES

1. Anderson, T. O., Hurd, W. J., "Symbol Synchronizer for Low Signal - Noise Ratio Coded Systems," SPS 37-53, Vol. II, August 1968.

2. Lindsey, W. C., and Anderson, T. O., "Digital - Data Transition Tracking Loops," to be presented at ITC 68 and Published in Conference Proceedings.

3. Holmes, J. K., "On a Solution to the Second Order Phase Lock Loop," SPS 37-54, Vol. III, November 1968.

4. Lindsey, W. C., "Non-Linear Analysis and Synthesis of Generalized Tracking Systems (Part I)," to be published, IEEE Trans. on Comm. Tech.

5. Lindsey, W. C., "Non-Linear Analysis and Synthesis of Generalized Tracking Systems (Part II)," to be published, ibid.

6. Heller, J. A., "Performance of Pioneer-Type Sequential Decoding Communication Systems with Noisy Oscillators," SPS 37-53, Vol. III, December 1968.

7. Holmes, J. K., "Two Stochastic Approximation Procedures for Identifying Linear Systems," SPS 37-53, Vol. III, December 1968.

8. Holmes, J. K., "Effect of Quantization on the Mariner 69 Digital Dump Matched Filter," SPS 37-52, Vol. III, August 1968; pp. 185-187.

9. Holmes, J. K., and Lindsey, W. C., "Noncoherent Detection of Digital Signals Through Randomly Time-Varying Channels," pending publication in IEEE, Trans. on Information Theory.

PUBLICATIONS

- See foregoing References 1, 3, 6, 7, and 8.

PROPAGATION STUDIES
NASA Work Unit 125-21-02-04-55
JPL 325-10801-X-3310
G. A. Morris, Jr.

OBJECTIVE

The purpose of this work unit is to determine the effects of deep space transmission media, planetary atmospheres, and lunar and planetary surfaces on telemetry, command, and radio navigation systems.

PROGRESS

Since early August 1968, observation of pulsars at S-band has been conducted on a regular basis, to determine if they can be used as time synchronization clocks. These observations yield time of arrival and flux information. Preliminary reduction of arrival time data indicates one of the pulsars is slowing down. Periods of all pulsars under observation are now known to approximately one nanosecond. Scintillation studies of the flux data indicates differences in the temporal behavior of the several pulsars. Observations at X-band with the Venus Site 85-foot antenna failed to yield any detectable pulsar signals.

PLANS

Pulsar data collection is planned to continue at S-band. New sources will be investigated as they are reported. Interesting sources will be continued under observation for at least a year and the data analyzed.

Pulsar observations at X-band with the Mars Site 210-foot antenna are planned as soon as time is available. A newly reported source which is quite strong at S-band is a good candidate for detection at X-band. This source was not known during the last X-band observation period.

RF TECHNIQUES RESEARCH

NASA Work Unit 125-21-03-04-55

JPL 325-10901-1-3330

W. Higa

OBJECTIVE

The long-range objective of the millimeter wave program is to develop technology for application to antennas and microwave scale model work and to provide a basis for evaluating the potential of future use of these frequencies for special purpose space communications. Emphasis is placed upon the capability of designing, improving, and operating the RF hardware of experimental equipment.

LOW NOISE RECEIVER INVESTIGATION

Maser materials (ruby, rutile, etc.) are being evaluated for microwave and millimeter wave applications. In order to evolve practical techniques for the millimeter wavelengths, it has been decided to start with a 15.3-GHz maser. This frequency was chosen because of the possibility of using the Applications Technology Satellite for making further measurements on the 210-foot advanced antenna system.

Technology developed at 15-GHz would then be extended to higher frequencies.

JPL CONTRACT (#952210) WITH USC

The modification of the 5-foot diameter 90-GHz radio telescope into a radio sextant has been completed. An optical sun tracker is used to maintain a RF boresight on the sun. The RF attenuation through the atmosphere as a function of weather conditions and time can be obtained.

FUTURE PLANS

A 15-GHz maser will be designed and fabricated for laboratory testing. A final report on the 90-GHz radio telescope and sextant will be prepared.

ANTICIPATED PUBLICATION

The following paper has been accepted for publication in the near future:

Rusch, W. V. T., Slobin, S. D., Stelzried, C. T., Sato, T., "Observations of the Total Lunar Eclipse of October 18, 1967 at a Wavelength of 3.33 MM," in the Astrophysical Journal.

PUBLICATIONS

SPS Contributions

1. Sato, et al. "Switching Frequency Determination for Nodding Subdish System," SPS 37-51, Vol. III, pp 295-299.

2. Oltmans and Sato, "A Precision DC Potentiometer Insertion Loss Test Set and Reflectometer for Use at 90 GHz," SPS 37-52, Vol. III, pp 229-233.

TRACKING AND DATA ACQUISITION (125-22)

MULTIPACT AND IONIZATION STUDY

NASA Work Unit 125-22-01-02-55

JPL 325-20501-2-3330

R. Woo

OBJECTIVE

The objective of this task is to study RF voltage breakdown in order to obtain information helpful in avoiding voltage breakdown in RF components designed for space applications. Another objective is to study the effects of a plasma environment on the performance of spacecraft antennas.

STATUS SUMMARY

In the previous reporting period, breakdown data in air were obtained for 50 Ω coaxial transmission lines. Using similarity parameters, we succeeded in unifying data covering the various breakdown processes into a compact and useful plot. A paper on this work will be published in the IEEE Proceedings Letters, January, 1969. For the Martian atmosphere, the gas composition consists mainly of carbon dioxide. There is also a slight amount of argon present. For comparison, we have therefore repeated the aforementioned breakdown experiments for argon and carbon dioxide gases. As a result, similar plots have been constructed for breakdown in argon and carbon dioxide for 50 Ω coaxial transmission lines. The carbon dioxide breakdown values are approximately 10% lower than those of air while the argon breakdown values are about 50% lower than those of air.

The computer program for the problem of a turnstile antenna located in a plasma shell has been debugged by rewriting it in double precision and performing the matrix operations on the computer. Two electron density profiles have been approximated and evaluated. In the near wake region, electron density increases at first and then decreases in the radial direction, with the maximum occurring near the edge of the wake; while in the far wake region, electron density is maximum on axis and decreases in the radial direction. The radiation patterns for both near and far wake electron density profiles develop a conical null region whose extent is proportional to the peak electron density in the wake. For the near wake electron density profile, sharp peaks, which are attributable to leaky-wave radiation, appear within the null region of the patterns. The effect of the conical null region in the patterns is to prolong blackout time for communication cone angles that lie within the null region. There are no serious depolarization effects in the non-null region, and satisfactory communications can be carried out.

The problem of an antenna located in a plasma shell has been further extended to that of an antenna in N cylindrically stratified plasma layers. The results have been combined with those of the plasma shell and column configurations in a paper submitted for publication in the special issue of IEEE-PGAP on space antennas.

Ray-tracing and geometrical optics techniques have been used to study the effects on antenna radiation of an axisymmetric inhomogeneous plasma whose electron density is a function of radius only. Preliminary results are in agreement with those obtained for the cylindrically stratified plasma configurations.

The voltage breakdown facility has been completed.

PLANNED ACTIVITIES

The following activities are planned for the next 6-mo period:

(1) Obtain breakdown data for coaxial transmission lines with characteristic impedances other than 50 Ω.

(2) Initiate antenna breakdown experiments.

(3) Complete ray-tracing studies of axisymmetric inhomogeneous plasmas and investigate other plasma configurations.

PUBLICATIONS

Meetings and Symposia Papers

1. Woo, R. and Ishimaru, A., "Radiation from a Circularly Polarized Antenna Through the Ionized Wake of a Mars-Entry Capsule," 1968 International IEEE/G-AP Symposium, September 9-12, 1968.

mount is being designed, and appropriate detector elements are being purchased in order to test these designs in a carbon dioxide laser heterodyne receiver.

Plans are now being formulated to incorporate the carbon dioxide laser heterodyne receiver into an optical system which will operate as a narrow-band infrared radiometer. Such a device will serve as a test bed to investigate the remaining receiver noise sources and will have application in the investigations of atmospheric turbulence and thermal emissions.

ISOTOPIC CARBON DIOXIDE LASER

The sealed-off laser system used for the isotope shift measurements is now being used for a carbon dioxide laser life time study. The device has operated for approximately 500 hours without a gas refill.

A paper on the isotope shifts has been published (see Publications).

INFRARED SEEING STUDY (Cal Tech-JPL Contract No. 69818, $14,979 in FY 69, J. Westphal, Cal Tech, principal investigator)

The new infrared photometer was completed during the first quarter of FY 69. The device is a dual wavelength single aperture photometer, capable of operation in any orientation and equipped for double-beam reception in order to balance out background emissions. It was successfully tested on the 200-inch Hale telescope on Oct. 1 to 3, 1968, and significant infrared seeing data was gathered. Preliminary reduction of the data indicates that when the visible seeing is 1 arc sec, the coherence diameter at $\lambda = 10\ \mu m$ exceeds 2 m.

The study will be continued for the remainder of FY 69 and into FY 70 to obtain an adequate amount of seeing data for a variety of atmospheric conditions, elevation angles, and telescope aperture diameters.

ATMOSPHERIC MICROTHERMAL MEASUREMENT

The correlation between astronomic "seeing" and atmospheric microthermal temperature variations has been well established. In cooperation with the Electronic Research Center, we are preparing to supply two sets of microthermal monitoring apparatus to the joint NASA-Smithsonian Astrophysical Observatory site at Mt. Hopkins, Arizona.

Further study of the correlation between microthermal activity and seeing is also being undertaken at Mt. Palomar. A helium-filled balloon is being used to carry microthermal sensors to an elevation of 1000 ft above the local terrain. A complete balloon system has been assembled, and field tests will be undertaken later in the year, when the weather patterns at Mt. Palomar become more predictable.

PUBLICATIONS

Open Literature

1. Siddoway, J. C., " Calculated and Observed Transitions Using $C^{14}O_2^{16}$," Journal Applied Physics, 39, 0. 4854 (September 1968).

ADVANCED SPACECRAFT TRANSMITTERS

NASA Work Unit 125-22-03-01-55

JPL 325-20601-2-3360

L. Derr
H. Detweiler

OBJECTIVE

The objective of this work unit is to improve the efficiency, lifetime and reliability of microwave tubes to meet the requirements of future space missions. The specific activities being pursued are (1) a study of the life and electron production capabilities of hot cathodes, (2) development of an automatic cathode replacement mechanism, and (3) a theoretical investigation of the large-signal performance of traveling-wave amplifiers.

CATHODE LIFE AND EMISSION STUDY (JPL Contract 951810 with Raytheon)

The purpose of the study is to evaluate the performance of oxide, dispenser, and coated particle cathodes (CPC). Up to sixteen samples of each type will be life-tested for two years under various levels of current densities and temperature.

During this period, dispenser cathode test units have completed 10,000 hours of operation exhibiting stable emission but high evaporation of barium. Oxide cathodes have completed 8,000 hours and show a general downward trend at higher current loading and elevated temperatures. Life testing of CPC cathodes has not yet begun due to activator problems. Three nickel materials, with varying amounts of tungsten and zirconium impurities, are being studied to improve CPC emission. Plans for the next 6-month period are to continue present life tests and to evaluate CPC test vehicles with new activator base materials.

AUTOMATIC CATHODE REPLACEMENT MECHANISM (JPL Development)

An electron gun system for numerous automatic replacements of cathode/filament assemblies in linear beam tubes has been originated at JPL. It is described in NASA Invention Reports No. 30-1265 and 30-1290. This device is visualized to be of importance to extremely long-life space missions such as TOPS (Thermoelectric Outer Planet Spacecraft).

A working mechanical model which meets the tolerance requirements of cathode placement in electron tubes has been built and demonstrated (Fig. 1).

During this period, in-line and axial configurations have been fabricated and improvements in thermostatic motors were realized. The original motors were energized by radiating heaters that required 50 watts of electrical power. The new designs have eliminated these heaters by exciting the bi-metal motors directly. This has also lowered the heating power to 15 watts.

During the next 6-month period, materials will be studied to insure that all components are compatible with tube fabrication requirements. The next configuration to be designed will employ "active" cathodes so that live testing of this device can be made in vacuum bell jars. Testing thus far has been done at atmospheric pressure.

THEORETICAL INVESTIGATION OF TWT PERFORMANCE

A general nonlinear interaction theory is being developed which takes into account all effects that significantly influence efficiency and allows for the practical techniques commonly used to achieve high efficiencies in O-type traveling-wave amplifiers. Rowe's (Ref. 1) two-dimensional large-signal theory, as modified by Detweiler (Ref. 2) to allow for spatially varying magnetic focusing fields (e. g., periodic magnetic fields), forms the basis of this theory.

A Lagrangian formulation is used in which the electron beam is modeled in terms of axisymmetric charge rings which are allowed to move both axially and radially in response to the RF circuit field, space-charge field, and applied static magnetic field. Thus, the axial debunching and radial defocusing of the beam which occur under large-signal conditions are considered along with collection of the beam electrons on the circuit. In addition, this theory accounts for the radial variation of the RF fields across the beam and the variation of the coupling between the beam and wave which results from radial motion of the electrons, as well as the effects of distributed loss along the circuit.

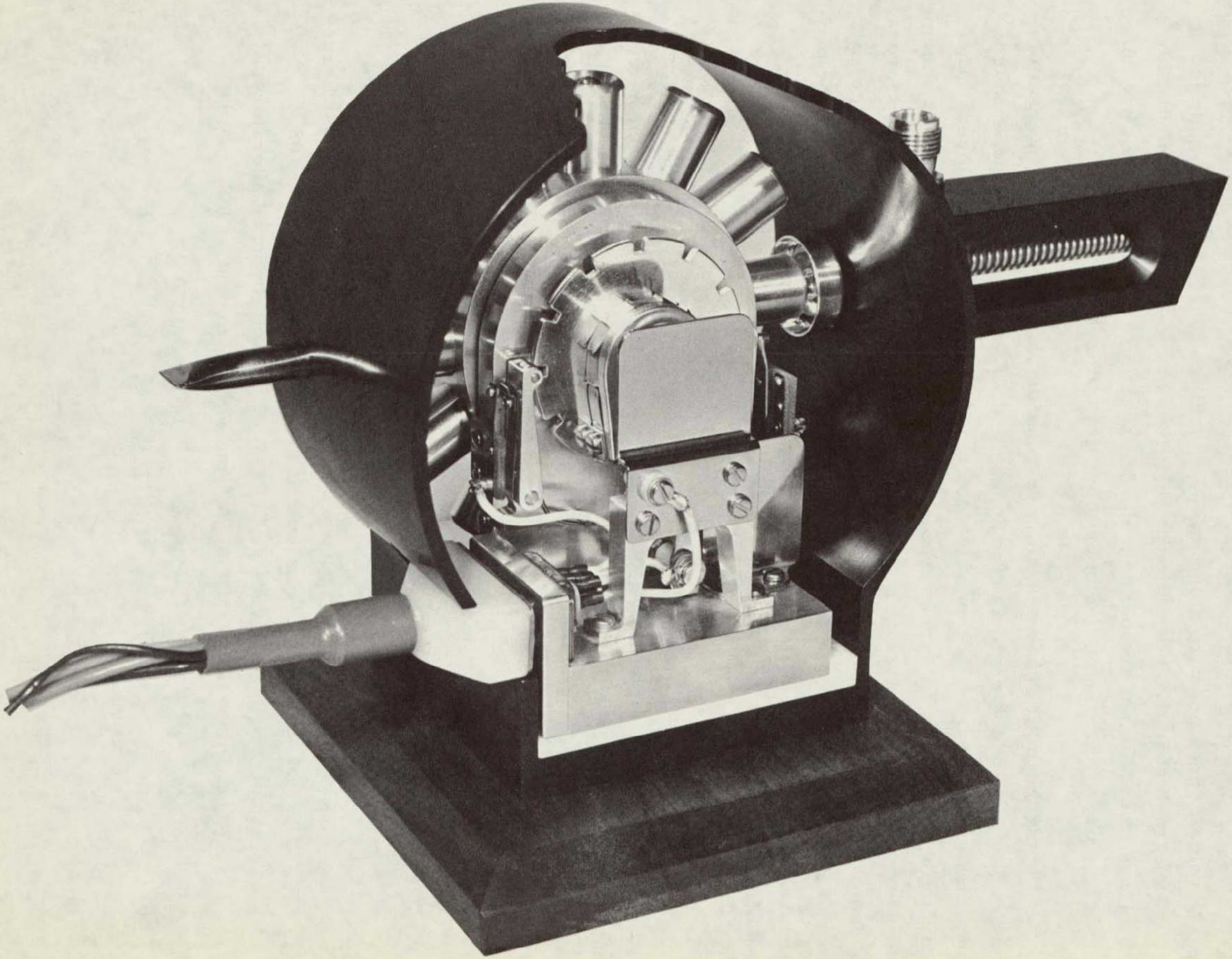

Figure 1. Automatic Cathode Replacement Mechanism

The earlier two-dimensional theories (Ref. 1, 2) assume that the cold-circuit phase velocity does not vary along the RF circuit and that there is no applied dc potential gradient in the interaction region; thus phase-focusing techniques for efficiency improvement are not considered. The interaction equations have been modified during this period to remove this limitation of the theory.

During the initial phase of this investigation, an approximate interaction theory (Ref. 2), which neglects circuit loss and RF space charge and is based on a disk-model representation of the electron beam, is being employed. The effects of circuit loss have been incorporated into this approximate theory during this period, and explicit expressions for the inter-electron space-charge forces, appropriate to the disk model for the beam, have been obtained through the solution of Poisson's equation within the interaction region. A digital computer program is being developed to solve the approximate equations including these modifications.

PLANS

The computer program will be used to verify the methods utilized in treating phase-focusing techniques. Upon successful completion of this part of the study, the general interaction equations will be programmed for solution on the digital computer.

REFERENCES

1. Rowe, J. E., Nonlinear Electron-Wave Interaction Phenomena, Academic Press Inc., New York, 1965.

2. Detweiler, H. K., "Characteristics of Magnetically Focused Large-Signal Traveling-Wave Amplifiers," Tech. Report No. 108, Contract No. F30602-68-C-0043, Electron Physics Laboratory, The University of Michigan, Ann Arbor, August, 1968.

PUBLICATIONS

Contractor Reports

1. Hill, F. T., Thermionic Cathode Evaluation Study, Raytheon Company, First Annual Report, April 12, 1968, JPL Contract No. 951810.

2. Hill, F. T., Thermionic Cathode Evaluation Study, Raytheon Company, Interim Report No. 4, August 5, 1968, JPL Contract No. 951810.

DATA HANDLING AND PROCESSING (125-23)

DIGITAL VIDEO PROCESSING TECHNIQUES

NASA Work Unit 125-23-02-01-55

JPL 325-30101-2-3240

F. C. Billingsley

OBJECTIVE

The long-range objective of this task is to develop methods and techniques for the recording, scanning, interpretation and manipulation of video information. These are to include consideration of digital processing, analog electrical processing, optical processing or suitable combinations thereof. This is a long-range task which is expected to continue as long as digital processing development is required.

This is a continuation of part of the FY 68 effort emphasizing the development of advanced imaging processing techniques, i. e., algorithms and software. Computer and hardware development are being co-supported by the Mariner 69 flight project and by the Digital Video Processing Equipment task (NASA 186-68-03-10). As this job continues to support computer-associated advanced developments, they will be reported.

In addition, JPL is supporting the development of similar capabilities at the Manned Spacecraft Center (MSC), Houston.

The primary objective this fiscal year is the further development of the special purpose operating system (VICAR), which has been developed to facilitate the processing of pictures and the writing of processing programs.

PROGRESS

As part of this task and co-supported by the flight projects, a complete Image Processing System has been defined in a previous report (JPL Technical Memorandum 33-353, Vol. 2, p. 271). A brief discussion of the criteria involved in the design of an operating software system was given in that reference. This task is primarily supporting the continued development of that software system.

IBM Programming System, PS-III

The IBM PS-III has been assembled and installed to replace the previous version of the system.

VICAR (Video Image Communication and Retrieval) System

This is the special purpose supervisor which has been developed to facilitate the processing of pictures and the writing of processing programs. VICAR III is in operation. Development of VICAR to include further functions and to simplify the job of the using programmer is continuing.

The complete set of image processing programs has been submitted to COSMIC.

During this period while VICAR is being used, a modification to VICAR is being designed to incorporate the user-interchange mode of operation. This mode of operation is required to facilitate the interruption of batch processing jobs by connected peripheral gear such as the automated light microscope. This mode will also enhance the efficiency of the system in both processing and program development.

A detailed study is beginning in conjunction with MSC to define the long-range NASA image-processing system requirements. This will result in definition of image processing requirements, reduction of these requirements to an overall system design and to computer requirements, and a study of possible computer systems to satisfy these requirements.

PROBLEMS

Minor technical problems in the debugging of programs have been overcome as encountered. There have been no major problems.

FUTURE PLANS

During the remainder of the year, the user-interchange mode of operation will be installed, including a prototype live-display console for user-interaction with processing. This will eliminate the last remaining major cause of slow turn-around in the image processing and greatly facilitate both algorithm development, parameter selection, and experimental processing.

In addition, software development will be begun to provide interactive display of alpha-numeric and graphical data on the live console and for contiguous graph-plotting with grey shades and color on 35-mm or 70-mm film.

REPORTS PUBLISHED

The complete set of image processing programs has been submitted to COSMIC.

PUBLICATIONS

Paper by Contract Programmer

1. Efron, E., "Image Processing by Digital Systems," Photogrammetric Engineering, 1968, p.1058-1062.

Paper at Symposium

1. Billingsley, F. C., "A Digital Image Processing Rationale," SPSE Symposium on Photo-Electronic Imaging, Washington, D. C., October 31 - November 2, 1968.

ADVANCED SCIENCE DATA SYSTEM TECHNIQUES

NASA Work Unit 125-23-02-02-55
JPL 325-30201-2-3240
M. Perlman

OBJECTIVE

The following are the objectives of this work unit:

(1) Development of formal mathematical characterization of finite automata.

(2) Maximization of scientific information transferral within the available communication bandwidth.

(3) Reliability enhancement through circuit redundancy and/or signal redundancy.

(4) Develop algorithms for selecting state assignments which minimize overall logical complexity.

PROGRESS

Logical Automata

One phase of a research study contract has been completed by IBM Watson Research Center. The results include the following:

(1) An axiomatic development of the theory of cubical complexes independent of set theory.

(2) A multiple output minimization algorithm for combinational logic which does not involve a transformation to an imaginary single output function or tagging.

(3) JPL applications of the MIN-6 program for multiple output minimization.

Sequential Networks

A class of linear feedback (Boolean) functions has been found which decomposes the 2^r states of an r-stage feedback shift register into cycles of equal length.

A feedback shift register has been built with the capability of introducing linear feedback (modulo 2 sum) of the content of 6 or fewer stages. The length of the register can be varied up to 35 stages and the feedback can be modified by means of patchcords and switches. A search has been initiated to find near-maximal length cycles, 2^r-2 and 2^r-4, which can be characterized by tetranomials. Each tetranomial is the product of $(x + 1)$ or $(x + 1)^2$ and $\emptyset(x)$ where $\emptyset(x)$ is a primitive polynomial. Thus primitive polynomials will be determined up to degree 35. Existing tables of irreducible polynomials are not complete beyond degree 19.

Signal Redundancy

Reed-Muller, Hamming, and Bose-Chaudhuri-Hocquenghem codes are under investigation for possible application in spacecraft signal processing. These are three classes of group codes where each code word is of the same fixed length and decoding is based on maximum likelihood detection. This controlled redundancy provides error-detection and error-correction capability for science information transferral.

Reliable Data System

Dr. John F. Meyer, University of Michigan, has been retained as a consultant to advise on long-range supporting research in the area of long-life data system architecture. It is planned to support a proposal in this same area from the University of Michigan at a level of about $30K per year. The contract should be let during the third quarter of FY 69.

FUTURE ACTIVITIES

Convolution coding (sequence transformation) will be investigated in conjunction with data compression.

Logical automata research will be extended into fault diagnosis of sequential networks where memory portions are localized by means of latches.

The non-autonomous feedback shift register will be investigated with application toward sequential network synthesis.

PUBLICATIONS

Open Literature

1. Perlman, M., "The Synthesis of Binary Sequence Detectors," IEEE Transactions on Computers Vol. EC-17 No. 9, September 1968.

SPS Contributions

1. Perlman, M., "Digital Techniques for Generating a Time Dependent Acceleration Voltage for a Mass Spectrometer," SPS 37-51, Vol. III, June 30, 1968.

2. Perlman, M., "The Decomposition of the States of a Linear Feedback Shift Register Into Cycles of Equal Length," SPS 37-52, Vol. III, August 31, 1968.

VIDEO INFORMATION EXTRACTION

NASA Work Unit 125-23-02-09-55

JPL 325-30901-2-3240

T. Rindfleisch

OBJECTIVE

The long-range objective of this work unit is to develop video data compression techniques achieving compression factors in excess of 100. Implicit in this goal are the development and improvement of methods to enhance, extract, and encode various types of image information.

The objectives for this fiscal year are the continued in-house development of two-dimensional digital processing techniques for noise suppression and the enhancement and extraction of various types of video information. An R/AD contract will be let to USC to study Fourier transform approaches to data compression.

PROGRESS

In-House

Since the last report, efforts have concentrated on both the preprocessing of video data to suppress random noises relative to significant information and the automated extraction of quantitative pattern characteristics from enhanced pictures. Sample imagery for testing these techniques has been derived from the fields of biomedicine (radioisotope scanner pictures and trabecular bone x-rays), industrial radiography (weld analysis x-rays) and astronomy (star field pictures).

A problem common to all low-illumination photography is the presence of shot-type noises, which in fact commonly form the limiting factor to image interpretation. A statistical filter which dynamically adjusts its pass band on the basis of the square root of intensity dependence of the noise amplitude is being investigated. In addition filters which pass information based on shape are being pursued with promise. Results include the enhancing of a severely shot noise-degraded radioisotope scanner image of voids in an artificial isotope distribution and of an x-ray of an artificially generated weld defect with encouraging progress.

Techniques for automatically recognizing and evaluating the quantitative characteristics of both network and isolated object patterns are being developed. Algorithms for locating the edges in multi-gray level images of significant objects have been operational for some time, but with the consistent problem of not being able to perform the detection reliably on nonuniform backgrounds. New techniques which search for slope inflections appear more reliable and are being pursued. Given the isolation of objects of interest, the measurement and cataloging characteristics proceeds on the basis of the particular pattern shape. Improvements to the trabecular bone network analysis algorithms have resulted and the first steps to applying the techniques to fluorescent antibody microphotographs are under way.

Contract

A six-month study contract for $9, 000 has been let, dated August 6, 1968, to the University of Southern California (Professor W. Pratt). The goal of the study is to understand the characteristics and compressibility of video data as represented in the Fourier and more general transform domains. Depending on the type of transformation, various kinds of image information (such as periodicity in the case of the Fourier transformation) are isolated in small regions of the transform space. The entire original image is required to portray the same information. By suitably encoding these isolated transformed regions, a potential data compression will result. A study of the Fourier transformation is being performed in which various encoding schemes for transformed test images are being quantitatively evaluated in terms of statistical reconstructed image error as a function of data compression factors. Initial analytic and software work is underway to study various forms of the Hadamard transformation. The results to date are preliminary, and more questions have been opened than have been answered.

FUTURE PLANS

In-House

During the coming half fiscal year, there will be continued development of algorithms for suppressing shot noise. These will emphasize dynamically adaptive filters. Work will continue on algorithms to reliably define pattern edges in multi-gray level photography and to extract quantitative characteristics for several problems of interest.

Contract

The short time remaining in the current contract will be used to assimilate the quantitative error analysis for the Fourier transform study and to pursue as far as possible the investigation of more general transformations. The fact that few natural scenes, e.g., spacecraft imagery, exhibit strong periodicities leads one to consider other than periodic transform functions and perhaps a transform set which dynamically adapts itself to the scene. All of these questions are desirable to pursue under an extension to the contract. A technical report is in the process of being published.

PUBLICATIONS

None

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EFFICIENT TELEMETRY DATA SYSTEMS

NASA Work Unit 125-23-02-13-55

JPL 325-31301-X-3340

A. Couvillon

OBJECTIVE

The purpose of this work unit is to discover, understand, and demonstrate advanced techniques for the digital on-board treatment of spacecraft telemetry and command data. The overall objective is to allow the efficient design of telemetry and command data systems for future missions without the necessity for long lead times and expensive redesign as the profiles of these missions change. The on-board treatments considered include buffering, multiplexing, formatting and measurement selection, data compression, encoding for the noisy channel, command synchronization, ranging code cleanup, etc. Techniques worked on will be aimed at the "post-Mariner" generation of planetary spacecraft. The Thermoelectric Outer Planet Spacecraft (TOPS) outer-planet mission will be given emphasis as a special customer useful as a demonstration vehicle, because its long life and complexity require the telemetry data system to be substantially more powerful and flexible than those of the Mariner class. Multimission ideas and implementations will be stressed so that any deep space mission can use the concepts and techniques developed under this work in procuring its spacecraft telemetry and command data system equipment and software.

APPROACH

The general approach is to make an in-depth comparision of alternative block diagrams for the data system function, using an assumed list of input data and their characteristics (e.g. the TOPS telemetry list). One example block diagram organization is that of a small central programmable GP computer controlling individual digital peripheral subsystems such as data compressors, multiplexers, data stores, and the like. A second block diagram is a single large programmable machine with few peripherals but with high speed such that the data system function can be realized by an executive monitor program controlling subfunction programs which time-share the computer. Other options could be a different breakdown of special-purpose and programmable hardware or a different degree of multiprogramming. The approach is to assess the complexity and relative performance of such alternative data system organizations, considering both hardware and software aspects. Typical telemetry and command functions required by the TOPS will be initially used in the evaluation. This work unit works closely with a related OTDA SRT work unit concerned with ground multiprocessor for station monitor and control, DSN Systems Development, 150-22-12-10-55.

PROGRESS

This is a new work unit for FY 69. Progress has included discussions and exchanges (we received NASA-X-562-68-387 and -388) with Goddard SFC personnel regarding the OAO spaceborne guidance and data handling computer, and discussions at length with members of the TOPS design team regarding the telemetry needs of various TOPS subsystems. The latter activity has turned up several facts: (1) people from other spacecraft subsystems are so conditioned to the rigid and inflexible Mariner-class data system design that it is difficult to get them to ask for the measurements which are really needed for diagnosis, (2) a flexible-format system with a large number of selectable inputs would be an immensely valuable diagnostic tool for the TOPS, (3) so would a data-compressive method of acquiring transients, and (4) the existence of really significant diagnostic power in the telemetry system would make a difference in the way other TOPS subsystems are designed.

Other activity has included the study of some pertinent results from the DSN Systems Development work unit, 150-22-12-10-55; a simple multiprocessor technique has been demonstrated there on an SDS 910 machine. This is interesting because the 910 is a small machine such as one would use on a spacecraft, yet it has been shown that it can be multiprogrammed. Also under study are the new fast, small, cheap third-generation GP computers with short word lengths, oriented to real-time control, which have recently appeared on the market in abundance. The characteristics and organizations of these machines are interesting and might shed light on the telemetry and command data system problem.

PLANS

Coordination with the TOPS program will continue.

PUBLICATIONS

None

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AUTOMATED LIGHT MICROSCOPE

NASA Work Unit 125-23-02-18-55

JPL 325-32101-2-3240

R. H. Nixon

OBJECTIVE

The work unit objective is to provide a facility which will enable the technology for computer-automated experiments to be evaluated on actual hardware and to reduce to practice those techniques which may be successfully applied to a remote planetary laboratory.

The immediate objective is to automate the control and data-acquisition functions of a light microscope. The IBM 1130 and the IBM 360-44 computers will be interfaced with a light microscope to ultimately provide a completely automated analysis capability. The automated functions include: translation, focusing, magnification change, search, video data acquisition and data analysis.

PROGRESS

The development of the system is suffering from a lack of resources and, as a result, an interim configuration is being reached which makes maximum use of existing equipment but which compromises the ultimate capabilities desired. For instance, the Surveyor BB camera is being used because of its availability and is not expected to allow the SN ratio required by the users. Further, a hard-line connection to the 360 will be slow in coming because of budget limitations. This means that data analysis must be done off-line. The interim system will exercise all control and data acquisition functions, however, and therefore is a meaningful step foward. The 1130 interface is not compromised in that regard.

Digital stepping motors have been connected to the x and y axis drives on the microscope as well as the focus control. A driver circuit design has been completed and breadboard circuits fabricated. Through a simple interface with the 1130, the stepping-motor operation and driver circuit designs were verified.

Other modifications to the microscope include: the mounting of a RETMA camera, the mounting of a surplus Surveyor camera, and the addition of microswitches to limit the x and y translation.

Designs for a filter wheel and magnification changer are in process and their stepping motors have been ordered.

A preliminary functional design of the microscope interface has been made. The necessary logic cards have been ordered. These are circuits in addition to the computer interface equipment purchased from Digital Applications, Inc. (DAI).

The sweep circuits for the Surveyor camera have been modified to provide a 0.5-second scan and a 6-second scan. These are not the final rates, but this does demonstrate the ability to change sweep speed.

The data acquisition mode will rely on cycle stealing into the 1130 computer. This option was not a part of the DAI equipment, therefore, a design was undertaken by JPL engineers. A design has been accomplished which is compatible with the DAI equipment and the necessary logic cards have been ordered.

FUTURE ACTIVITIES

During the next reporting period it is expected that the DAI equipment plus the cycle steal will be installed and that some microscope control functions will be operational.

Further studies will be made to determine to what extent other data sources besides the Surveyor camera system can be made available to the system. In addition, standardized scanning modules which have application to other systems such as the SEM and IPL camera will be investigated.

Provided that adequate manpower is available, the following tasks will be undertaken:

(1) Shock mount the microscope.

(2) Complete the mechanical modifications to the microscope.

(3) Modify the Surveyor camera sweep circuit.

(4) Design and fabricate the test and control panels.

(5) Modify slow scan display system (high persistence tube and Polaroid camera mount).

(6) Generate software.

PUBLICATIONS

None.

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SOLID STATE MEMORY TECHNOLOGY

NASA Work Unit 125-23-03-02-55

JPL 325-31401-2-3240

R. Frazer

OBJECTIVE

The long-range objectives remain as previously stated: to develop the technology of solid state memory systems leading to reliable storage capability up to 10^6 bits emphasizing low power, weight, and volume.

The short-term objectives are basically unchanged:

(1) Evaluation of large-scale integration and thin-film techniques as applied to scratch pad memories.

(2) The application of the electron microscope to mapping of magnetic and electric field gradients in solid-state storage elements.

(3) The development of specialized scanning electron-beam techniques for visualization of fields associated with memory elements.

PROGRESS

Memory Investigations

There is no progress to report with regard to the evaluation of LSI memories. This portion of the task has suffered from a lack of proper talent to carry out this function. The 0151's for this task have been revised downward, resulting in the elimination of the proposed small memory contract. The support for the SEM was not affected.

Scanning Electron Microscope Development

The in-house development of the scanning electron microscope proceeded without serious delays in spite of the vacations of some of the principals.

Electron Optical Column

The design of the basic parts is complete, and all heavy machine work is done and awaiting furnace-brazing and finish-machining. Peripheral components of the gun and deflection yoke are still in process awaiting purchased parts.

Vacuum System

The design of the vacuum system is complete and combines the features of ultra-high vacuum ion pumping and high-speed differential diffusion pumping with provision for later addition of eryo-pumping. Major parts are on hand, but assembly awaits some purchased parts and fabrication.

Supporting Frame

A non-magnetic aluminum frame featuring pneumatic vibration isolation has been designed and fabricated in-house.

Electronics

The electron beam-forming power supplies are defined and an interim high-voltage supply has been modified to provide filament power. The lens supplies are on order. The scan-drive electronics are being designed, but await definition of manual controls and computer interfaces.

FUTURE ACTIVITIES

This work unit will be closed out as of January 1, 1969. The on-going work related to the development of the Scanning Electron Microscope will be transferred to the Automated Light Microscope task, Work Unit 125-23-02-18-55. The future activities described below will be conducted under that task.

The digital scan drive system will be designed to produce a 1024 x 1024 element raster with logic to provide selected area scan and reduced scan density. The resulting design will be adaptable to other image processing requirements including the digitizing of images from the Automatic Microscope (ALMS). It will be capable of accepting commands from the 1130 computer or from manual inputs.

Detectors of several types are being evaluated under a consulting agreement with a worker at the University of California at Berkeley. It is hoped that a channel electron multiplier can be used to detect secondary electrons in the SEM and result in better collection efficiency and specimen-detector geometry.

Evaluation of hermetic packages for large-scale integrated circuits continues, and a ceramic package with an aluminum ultrasonic interconnect scheme is becoming the likely candidate.

PUBLICATIONS

None

INSTRUMENTATION (125-24)

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ADVANCED SIGNAL CONDITIONING

NASA Work Unit 125-24-01-08-55

JPL 325-41001-2-3220

J. A. Daniels
J. R. Locke

OBJECTIVE

The long-range objectives of this task are to conceive, design, develop, and demonstrate signal-conditioning circuitry having application to planetary and landed scientific instrumentation and the maintenance and advancement of in-house technology. FY 69 efforts are directed at the support of gas chromatography and mass spectrometry instrumentation. These efforts include: (1) a log electrometer, (2) charged particle counting, (3) power law compression, and (4) microminiaturization of the peak detector—analog to pulse width converter (PD-A/PWC).

SOLID STATE LOGARITHMIC ELECTROMETER

This electrometer possesses the desirable data-compression characteristic that the encoding requirements are uniform throughout the circuits range of operation. In contrast, the encoding requirements of a linear electrometer are determined by low level accuracy requirements. All signals above that level are encoded in excess of accuracy requirements.

This effort is a carry-over from FY 68 to develop a circuit that would meet the stringent requirements of a spaceborne mass spectrometer, which exceeds the performance capabilities of all logarithmic electrometers presently known. Such an electrometer was successfully developed, and has been built and tested, which meets the design objectives as follows:

Dynamic Range:	$I_{in} = 10^{-11}$ amps to 10^{-5} amps
Temperature Range:	T = 0°C to 50°C
Speed of Response:	1 decade/millisecond
Accuracy:	1% uncertainty over the dynamic and temperature ranges at the maximum input current rate

Prompted by state-of-the-art device advances, reliability considerations and a rigorous analysis of the effects of operational amplifier drift sources, all the amplifiers in the system have been replaced and new input stages added. A dual matched JFET with extremely low leakage replaces the MOSFET stage used for the electrometer input, eliminating the MOSFET reliability problem. The LM 102 buffer stage has been replaced with a buffer stage using the JFET front end. This eliminates the need for compensating component selection previously required to correct for the LM 102's bias drift. Use of the newly developed NH0001 as a replacement amplifier for several of the electrometers gain stages has reduced the power dissipation of the electrometer from 337 mW to 155 mW.

An ion source was instrumented to simulate the output of a mass spectrometer, and speed of response tests were performed. To meet the speed of response requirements, it was necessary to use bifilar techniques in winding the copper coil used for linear temperature compensation.

CHARGED PARTICLE COUNTING TECHNIQUE

This technique is being developed for use with a Lunar Mass Spectrometer. The need for this approach stems from the need to measure the low ion currents (associated with mass spectrometer analysis of the rarefied atmosphere of the moon) which are below the practical limits of present spaceborne electrometers. This approach has as its objective, measurement of current in the range from 10^{-17} amperes to 10^{-13} amperes. Because of the complexity of the system involved, a major problem which must be overcome is limiting the power to a level compatible with spaceborne instrumentation. The design objective is 1 watt.

The hyperbolic function generator developed under this task in FY 68 (discussed in SPS 37-47, Volume III) will be used to control the ion acceleration voltage of the mass spectrometer. By stepping the generator, counting the charged particles leaving the mass spectrometer exit aperture, and comparing this count with the count from the previous step successively, mass peaks can be detected. By reading out the word in the control register of the digital generator, the mass can be identified. Verniering of the ion acceleration voltage will provide a more accurate focus of the ion beam which will then be followed by an ion count of 10,000 impacts or more to insure 1% statistical accuracy. At the completion of 10,000 impacts, a timing source which was turned on simultaneously at the start of the count will be turned off. The counter, which the timing source was driving, will be read out as a measure of the ion current. The dynamic range of the system is achieved by successive cycling of the hyperbolic function generator and systematically increasing the clock window time and generator step period. It is tentatively planned that a channeltron will be used as the charged particle detector.

Preliminary testing of curved and helical channeltrons, using an 18 keV titanium tritide electron source indicated the curved channeltron provided the larger signal. Attempts to operate the units in the saturated mode, which is the method best suited for the counting technique, were unsuccessful. Further testing of the channeltrons has been suspended until a more sophisticated test system is available. Design of the system has been completed and most of the parts have been machined or purchased, and some parts are assembled. The proposed system will allow injection of specific ions of different mass, variable count rate and ion energies. The overall counting system design has been completed and detail design started. Research of digital semiconductor manufacturers indicates that Amelco Semiconductor has just recently developed a new ultra-low power logic series particularly well suited to the low power requirements of this system. The digital-to-analog converter of the hyperbolic function generator has been redesigned to minimize power. Initial breadboard testing indicates the power will be reduced from 900 mW to less than 80 mW. (It should be noted that the earlier efforts in developing the digital hyperbolic generator were primarily directed at showing the feasibility of using the uniquely large diode matrix and no effort was made to minimize power consumption.)

POWER LAW COMPRESSION TECHNIQUE

The power law compression technique has application to instruments like the mass spectrometer, and promises data compression in a range below that possible using the logarithmic electrometer. The design objectives of this technique will be to measure six decades of input current with the lower threshold at 10^{-15} amperes as a one decade change in output voltage.

Power law compression can be achieved by exploiting the current gain relationship of an electron multiplier. This relationship shows that the gain varies as an Nth degree function of the voltage applied across the dynodes, where N equals the number of dynodes. By regulating the current gain of the multiplier by means of negative feedback, the regulating voltage becomes a compressed measure of the input current.

In developing this technique, ac and dc control techniques will be investigated. Discrete dynode electron multiplier and modified channeltron engineering models will be studied and tested. Because noise is the probable limiting factor in determining the lower threshold, it is anticipated that signal-to-noise optimization methods will be required.

A computer analysis of this technique has been made which indicates that six decades of input current can be compressed to provide an output signal that changes by a factor of 9 to 1 when seven dynodes of a sixteen dynode electron multiplier are controlled. System stability requirements are related to system accuracy requirements by the number of dynodes controlled.

Both discrete dynode electron multipliers and channeltrons have been obtained. The discrete dynode engineering model has been modified to evaluate its controllability. A problem area encountered is the design of a feedback transformer of reasonable size and weight which can carry a sizable bias current through its high voltage winding.

MICROMINIATURE PEAK DETECTOR – ANALOG TO PULSE WIDTH CONVERTER IN HYBRID FORM

The peak detector – analog to pulse width converter (PD-A/PWC) was developed under this task at an earlier time. This circuit finds particularly valuable application in both mass spectrometry and gas chromatography. Both instruments require detection of peak time of occurrence and peak amplitude to determine what has been detected and how much. The PD-A/PWC performs both of these functions simultaneously. Since only the desired data points are encoded, data compression is achieved.

Fabricating the circuit in hybrid form will optimize the performance of the circuit because it will minimize the thermal gradient seen by the components of the circuit. The significance of this consideration lies in the circuit design requirements of input symmetry. Additional advantages associated with the hybrid conversion are: minimal circuit volume, weight and increased circuit reliability.

Component specifications were prepared for the PD-A/PWC statement of work. The specifications are based on computer simulations of the circuit. These simulations provided parameter sensitivity data that was used in expressing the allowable pulse width change in a total differential expression. From this expression and known technological limits of materials and devices, tolerances, temperature coefficient matching, and tracking requirements were determined. A contract was awarded for fabricating and testing six units.

PUBLICATIONS

SPS Contributions

1. Locke, John R., "Peak Detector – Analog/Pulse Width Converter Analysis," 37-52, Volume III, Aug. 31, 1968.

Technical Memorandum

1. Overbey, John L., and Locke, John R., "Computer Aided Analysis of a Peak Detector—Analog to Pulse Width Converter," TM 33-401, Nov. 1, 1968.

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RADIOMETRY INSTRUMENTATION DEVELOPMENT

NASA Work Unit 125-24-03-05-55

JPL 325-40801-0-3710

M. Berdahl
J. M. Kendall, Sr.
R. C. Willson

OBJECTIVE

The long-range objectives of this task remain as last reported. These are to:

(1) Develop the art of quantitative radiometry to the degree required for testing spacecraft in simulators. This has not yet been done elsewhere. Methods of measuring total energy flux and its spectral distribution will be studied.

(2) Develop standard procedures for calibrating radiometric devices and to set up a laboratory, which, on a routine basis, can maintain a family of calibrated devices.

(3) Develop certain radiometric experiments which can be used to check the actual performance of space simulators, and which can be used to test the radiant energy transfer properties of spacecraft surface coatings.

The current objective is to establish the JPL cavity type radiometers as primary standards of total irradiance measurement. If this can be accomplished, it will provide an absolute scale rather than an arbitrary scale to which irradiance measurements may be referred. Since the arbitrary scale is defined by an angstrom pyrrheliometer presently held in Stockholm, preliminary comparisons will be made with locally held instruments of this type under various levels of solar irradiance prior to a comparison with the Stockholm instrument. A secondary objective (one that automatically falls out of using a solar source at low air mass) is the determination of the solar constant.

STATUS

During the first half of FY 69 several experiments were performed. The JPL vacuum enclosed radiometer was compared with the Eppley Angstrom Pyrheliometer on a series of flights of the NASA Airborne Meteorological Expedition. The solar energy input was steady at the near 40,000-foot altitudes and several good comparisons were made. In addition to the standard vacuum enclosed cavity radiometer, JPL was able to test a newly designed version of the cavity radiometer, which is capable of operating at atmospheric pressures. This radiometer performed exceptionally well. It is now selected as the unit with which the International Pyrheliometric Standard will be compared. A sophisticated model of the atmospheric pressure type radiometer, together with a solar tracking unit and associated instrumentation, has been built for making the comparison in late FY 69 or early FY 70 (see Fig. 1). It is now undergoing rigid laboratory and field tests to qualify it for this most important task.

The vacuum-enclosed version of the JPL Standard Cavity Radiometer was used in the month of August to determine the solar constant. Two units were sent aloft to the 80,000-feet altitude on a balloon experiment. The radiometers performed satisfactorily for several hours at that altitude (Fig. 2). Results of the test, after being corrected for atmospheric and sun-to-earth distance effects, indicated an irradiance level of 139.0 ±0.9 mw/cm^2. This is in close agreement with previously made measurements based on the scale established by the Smithsonian Institute.

Another future experiment to determine the solar constant will be performed when Mariner 69 is launched and the JPL radiometer, known as a thermal control flux monitor, will make a measurement of the sun's energy.

PUBLICATIONS

None

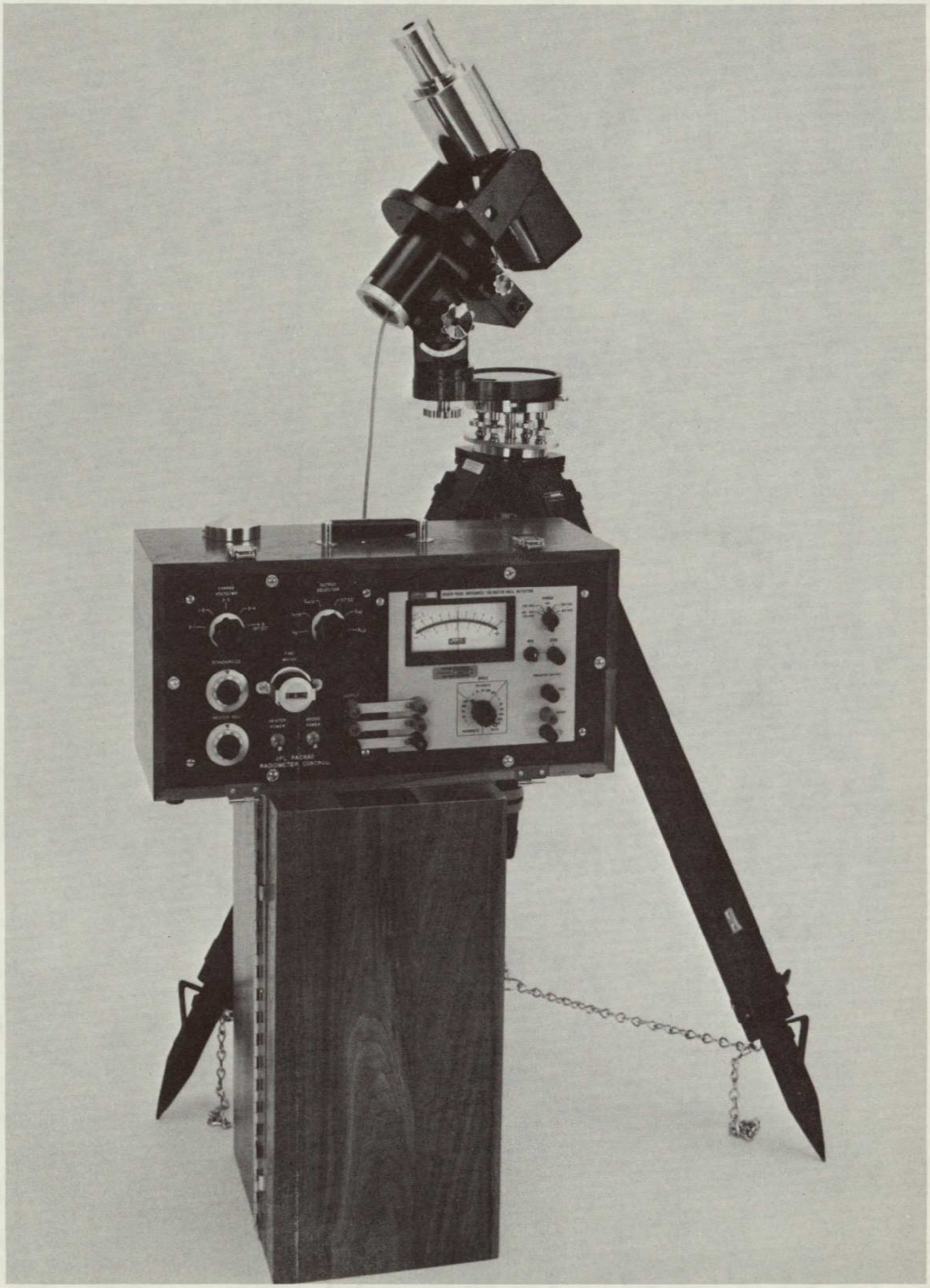

Figure 1. Primary Absolute Radiometer with Solar Tracking Mount and Measuring Instrument

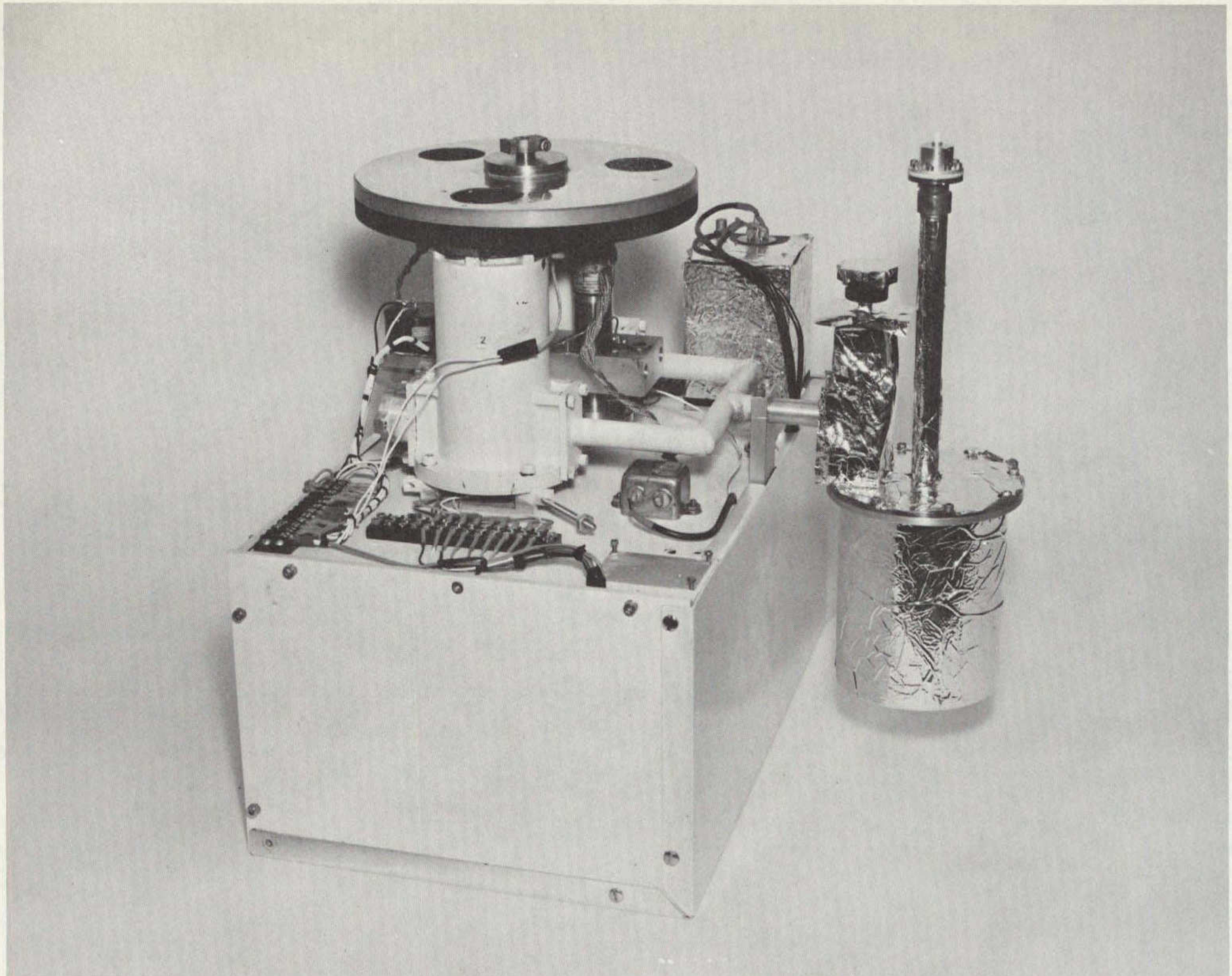

Figure 2. Twin Vacuum Enclosed Standard Cavity Radiometer Balloon Flight Package

ELECTRON MICROSCOPE

NASA Work Unit 125-24-03-06-55

JPL 325-41101-2-3240

R. Nathan

OBJECTIVE

The objective of this work unit is to investigate the feasibility of improving the normal 10 Å resolution of a commercial electron microscope to a 1 Å resolution (atomic distances) thereby revealing molecular geometry of biological materials. The electron microscope will also be modified to reduce specimen contamination and destruction rates in order to lengthen specimen stability. An image-intensifying system also becomes necessary for reduction of exposure times and improvement of contrast.

PROGRESS

The SEC camera to be used in the image intensifier still appears the most useful approach. The tube we were given by Dr. Ando turned out to be defective, whether by our doing or not is not clear. We have since arranged to have Apollo-reject SEC tubes sent to us by Mr. Bordelon of Houston (HASA). One tube has just been received and will soon be installed.

These tubes are even higher performers than the commercial cameras and are presently under military restriction (Confidential). We are arranging accordingly to have the entire electron microscope facility made appropriately secure.

Debugging of the video amplifier has progressed during this quarter after receiving circuit corrections and apologies from Westinghouse.

In a separate effort, X-ray crystallographic equipment has been set up to obtain related diffraction information which shall be incorporated into the early crystal structure work to be used in the microscope.

The decontamination equipment has just been received and installed.

FUTURE

With the decontaminator and SEC tube installed, new vistas should be very imminent. We shall transmit these images to a video tape recorder located in the Image Processing Laboratory where they can be stored for playback. As the image converter becomes operational, these images can be converted for digital analysis.

PUBLICATION

A portion of this period has been taken up by the writing of a chapter for the series "Progress in Biological Electron Microscope Techniques," edited by Professor D. F. Parsons. The chapter is near completion and concerns the "Computer Processing of Electron Micrographs."

ELECTRONICS TECHNIQUES AND COMPONENTS (125-25)

FAILURE MODES IN MULTI-FUNCTION SEMICONDUCTOR DEVICES

NASA Work Unit 125-25-02-01-55

JPL 325-50501-0-3540

L. W. Wright

OBJECTIVE

The long range objective of this work unit is to identify and investigate the fundamental physical and chemical phenomena underlying degradation and failure processes in multi-function semiconductor devices. The results from these studies will then be used as a basis for the improvement of device reliability and the prediction of device reliability with a minimal need for large scale test programs.

ACTIVITIES DURING REPORT PERIOD

In June 1967, a contract was awarded to Semiconductor Products Division of Motorola for an evaluation and development study of methods and materials for bonding large area silicon wafers. During this reporting period, further investigation and development of solid-solid and solid-liquid low temperature diffusion bonds, using gold-indium and/or gold-tin, has been accomplished.

Successful bonding of 2-inch silicon wafers to a molybdenum substrate, using gold-tin and gold-aluminum, has been achieved. The minimum thickness of the wafer has been limited to 20 mils to achieve a successful bond.

The current problems with this type of bond are surface roughness of the wafer and uneven plating of the bonding materials. Studies are continuing to discover a suitable solution to these problems.

Thermal conductivity studies have been completed for gold-tin, gold-silicon, gold-germanium, aluminum-silicon, and lead-tin.

Stress studies performed by superposition of the "stresses-in-joined bodies" indicate that the gold-silicon eutectic solder, when used to bond silicon to molybdenum, is somewhat "transparent" to the stress field.

This study also indicates that a stress-free silicon wafer bond, using gold solder, is impossible, and in order to decrease the stress in the wafer to one-half, the wafer thickness must be doubled.

PUBLICATIONS DURING REPORT PERIOD

Contractor Reports, Interim

1. Fourth Quarterly Report on Bonding Large Area Silicon Wafers, Motorola Inc., August 1968, JPL Contract 952022.

ADVANCED DEVELOPMENT OF ELECTRONIC INTERCONNECTIONS

NASA Work Unit 125-25-03-01-55

JPL 325-50101-0-3570

E. R. Bunker, Jr.

OBJECTIVE

The long range objectives of this work unit are:

(1) To maintain awareness of state-of-the-art cabling technology for unmanned spacecraft including applicable documentation.

(2) To demonstrate advanced cabling and interconnection approaches which will provide substantial improvements in weight and noise reduction, ease of fabrication, maintainability, and reliability of spacecraft subsystems.

(3) To develop format and to employ machine data processing techniques for the generation of wire and connector tabulation and routing.

FY 69 Objectives

Immediate objectives for this fiscal year are:

(1) To determine the present status of cabling technology being used in unmanned spacecraft by various agencies and contractors.

(2) To develop advanced interconnection technologies for interconnection between micro-electronic modules, discrete component modules, subassemblies and assemblies, and combinations of these interconnections.

(3) To demonstrate a punched card documentation system for a cable harness, and to compare this system with presently used documentation.

PUNCHED CARD CABLING DOCUMENTATION

Further work was accomplished on the approach of using two cards for each wire, and the results of this work are presented in the report listed at the end of this summary.

Cards simulating engineering changes in the connections of the CSAD harness were prepared and substituted for the obsolete cards to demonstrate that updating was a simple procedure. The completed tabulations for each connector were assembled in a booklet, and then shown to cable technicians and other personnel concerned with cable fabrication and test. The consensus of opinion was, once personnel became familiar with the method of presentation of information, the print-out would be adequate for fabrication of cables now used in spacecraft subsystems. The additional advantage of providing information such as lengths of wire, and other information which is not presently shown on the wiring diagrams, would be of assistance in stock maintenance.

Additionally, a set of 120 cards were prepared which, when printed out in order, gave a semi-pictorial representation of the cable harness and showing the relative locations of the connectors and all significant dimensions from the datum lines including angles, connector types, and designations. The connectors were blocked out on the cards using the 'I' and '-' with the '0' indicating a socket and the 'X' indicating a pin. Dots were used to indicate the horizontal and vertical runs of the cabling with asterisks used to represent the dimensional arrows. While not as smooth and pictorial as an illustration, all the necessary information was provided using only the conventional symbols available on the key punch. Further work will be done with this approach to achieve a more complete pictorial representation of a cable harness.

CSAD LANDER HARNESS

A work statement and a request for proposal was prepared and submitted to outside vendors for the art work, and for fabrication of a two-sided flexible printed conductor harness which could be substituted for the conventional CSAD harness. Facilities of vendors under consideration were visited to evaluate their product lines, and to evaluate their expertise in the fabrication of this cable harness.

After awarding the contract, it is expected that a flexible cable harness will be available before the end of FY 69, and that this harness can be substituted for the conventional wire harness for the CSAD Lander. When received, a functional operation of the CSAD Lander with a flexible harness will be compared with a functional operation using the conventional harness.

Also, another approach will be used and tested with the CSAD Lander if it can be completed in time. This approach consists of using off-the-shelf flat cable with the connector terminals attached to the conductors in sequence, without regard for pin callouts. The other end of the flat cable will be cut to length and terminated in one or more junction boxes where the proper routing and interfacing with other cable connectors can then be made. The cable conductors will be terminated in terminals suitable for employing the coldwelding technology being developed under the Modular Electronic Packaging Advanced Development, NASA Work Unit 186-68-10-09.

PUBLICATIONS

JPL Technical Reports

1. Kloezeman, W. G., and Hicks, W., "Documentation of Wiring Harnesses by Use of Punched Card Techniques," JPL TR 32-1326, October 15, 1968.

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MICROELECTRONIC PACKAGING ADVANCED DEVELOPMENT

NASA Work Unit 125-25-03-02-55

JPL 325-50201-0-3570

L. Katzin

OBJECTIVE

The long range objective of this work unit is to develop better techniques for packaging cased integrated circuits and miniature discrete components. A further long range objective is to develop better wire routing and joining techniques, and to evolve a process for effecting all shielded and, subsequently, all coaxial interconnections with a batch system for the integrated circuit module developed at JPL. This module is a packaging technique developed under this work unit during FY 65 and FY 66.

The FY 69 objectives include the further development of the folded stick module, and the development of hybrid component interconnecting techniques.

FOLDED STICK INTERCONNECTION

As previously reported, the folded stick module is an extension of the stick module which was developed and extensively used by JPL. The first folded stick modules were molded of polypropylene which was ideally suited for the two molded hinges which constitute an integral part of the stick module. In optimizing the hinges, it was found that other needed properties in the stick module composition were deficient. To correct these shortcomings, other materials are being tried and will be evaluated during the first calendar quarter of 1969.

A folded stick module was assembled with terminals and completely wired to demonstrate the feasibility of the concept. New terminals, having a spherical rather than a flat top, have been tried and appear to be good. These new terminals have the advantage of automatically clearing all interfering wires from above by the down stroke of the concentric electrode. Because of the spherical geometry of the top of the terminals, any previously routed wire passing over the top of the terminal is deflected aside when pushed by a descending electrode against the curved surface. An additional improvement which has been designed into the terminal is the "U" shape or double shank. This design permits the terminals to snap into the stick module and be retained mechanically. On one side of the module web, the two legs will protrude for the wire attachment, while the other side of the web will have the connecting bar of the two legs of the "U" for attaching the I. C. lead. Each terminal is capable of accepting two wires in continuing series connections which is equivalent to four wire-wrap connections per I. C. lead.

In the second half of FY 69, more terminals will be fabricated and tried, and the new materials for the folded stick module will be evaluated.

CONCENTRIC ELECTRODE WELDING OF MAGNET WIRE

The concentric electrode technique for welding insulated magnet wire, as described in the previous report, has continued to progress since the last reporting period to the point that some of the earlier work is now marketed commercially by welding equipment manufacturers. A new double concentric electrode, where the "bottom" electrode is now the external concentric ring of the upper electrode, was built and tried with good results. Additional testing and some design improvements are yet required.

During the next six months, the bottomless concentric electrode should be completed, and test data should have been obtained on various insulating materials of the magnet wire.

MINIATURE HEAT PIPE FOR MICROELECTRONIC COOLING

The need for a thermally conducting and electrically insulating material is becoming more important for microelectronic application. A variation on the conventional heat pipe could provide these two conflicting properties in a single component. . The last six months were devoted to studying the state-of-the-art in conventional heat pipes, and working with thermodynamicists at JPL who are involved in conventional heat pipe projects.

The next six months will be devoted to a preliminary design and a prototype construction of a miniature heat pipe for microelectronic application.

PUBLICATIONS

Meetings and Symposia Papers

1. "Simplifying Complex Miniature Interconnections," paper was presented at the first International Packaging Convention in Brighton, England, October 1968.

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IN-FLIGHT FAILURE RATES OF SPACECRAFT ELECTRONIC PARTS

NASA Work Unit 125-25-04-03-55

JPL 325-50601-0-3540

W. R. Scott

OBJECTIVE

The long range objective of this effort is the investigation of the preflight treatment of the electronic and electromechanical parts employed in Mariner IV and Mariner V, and the effect of such treatment on the in-flight failure rate displayed by the parts. The objective is being pursued in three phases: (1) a survey of Mariner IV and Mariner V data; (2) an analysis of the data; and (3) an extension of the first two phases to cover Mariner 69 data such as the design of experiments to yield and update actuarial data on parts life expectancies, and correlation of real life observations with analytically derived prediction criteria.

ACTIVITIES DURING REPORT PERIOD

The efforts of this period dealt with the first two phases. In pursuit of the first phase, the parts control activities contributing most to success were identified, some improved parts control techniques were delineated, and cost burdens which might have been reduced or obviated by suitable planning and funding schedules were indicated.

The second phase efforts included the verification of the validity of premises and criteria from experimental and failure report analyses, and the determination of what experimental data and observations were lacking which could most enhance reliability techniques and associated cost-effectiveness.

Work will be started on the third phase during the third quarter of FY 69.

PUBLICATIONS

None

HYBRID PACKAGING ADVANCED DEVELOPMENT

NASA Work Unit 125-25-04-04-55

JPL 325-50901-0-3570

E. R. Bunker, Jr.

OBJECTIVE

The long range objectives of this unit are:

(1) Maintain awareness of hybrid packaging technology by studying requirements of unmanned spacecraft subsystems, and studying present techniques being employed by industry and NASA centers so that problem areas can be determined and recommendations made.

(2) Develop knowledge of processes of hybrid packaging so that preparations of specifications, monitoring of procurements, and participation in design reviews will be effective.

The FY 69 objective is to become faciliar with the work of others in new thick-film technology, active device attachment, environmental protection for hybrid circuits, and hybrid circuits interconnecting and intraconnecting. This task covers all aspects of developing thick film circuits, including mask preparation, firing, resistor and capacitor trimming, registration, termination, and protection.

HYBRID MICROELECTRONICS FACILITY

Originally designated the Thick Film Facility, the name was changed to "Hybrid Microelectronics Facility" to more accurately represent the work planned in the hybrid microelectronic field. Additional equipment such as a transistor/diode curve tracer, digital multimeter, environmental chamber, and microscopes have been received. The facility was completed and major pieces of equipment installed. As the equipment was being set up, various shortcomings were noted and steps taken to correct these problems.

Conductor test patterns have been selected for the initial work. Art work will be prepared, then photographically reduced so that proper screens can be made to make the test patterns. Various types of configurations will be tried to obtain the basic knowledge. A consultant of many years experience with ceramics and thick film processes has been retained to assist in the starting-up procedure which will commence when the cognizant personnel are released from M'69 project activities.

Various methods of obtaining the temperature profile of the furnace, other than the conventional method of using a thermo-couple with long wires, are being investigated. An approach, using an optical pyrometer to observe the temperature of a target mounted on the moving belt as it travels through the furnace, was found to be impractical because, at the lower end of the temperature range, the target was not in the visible range. Equipment using infrared principles to measure the temperature of a spot as small as 0.030 inches at a distance of one foot appears to have possibilities. Further work will be done on this in the last half of FY 69 so that a method of continual monitoring of the furnace profile may be obtained. Maintenance of a given profile, or becoming aware if the temperature profile has changed, is one of the major problems in thick film resistor fabrication.

PUBLICATIONS

None

HIGH VOLTAGE PACKAGING ADVANCED DEVELOPMENT

NASA Work Unit 125-25-04-05-55

JPL 325-51001-0-3570

E. R. Bunker, Jr.

OBJECTIVE

The long range objective of this work unit is to develop the technology of high voltage packaging by developing procedures, materials, uses and hardware geometries so that breakdown will not occur in high voltage circuits.

The FY 69 objective is to demonstrate the effectiveness of the packaging technology for high voltage power subsystems which will be applicable for present and future spacecraft systems.

CORONA DETECTION NETWORK

The present configuration of the Type III Corona Detection Network is shown in Figure 1. Like previous Corona Detection Network configurations, the Type III is connected in the ground return of the high voltage load. A microammeter, which measures corona current, is connected to a bridge rectifying circuit utilizing Zener diodes. A milliammeter in a similar configuration is used to measure arcing current. At low current levels, the Zener diodes in the microammeter circuit rectify the ac voltage, producing an indication of corona current on the dc microammeter. Under arcing conditions, the Zener breakdown voltage protects the microammeter from excessive currents. The Zener diodes also protect the milliammeter from excessive arc current. The corona and arcing voltages are developed across an impedance which is a function of frequency as shown in the graph. This impedance is essentially zero at the high voltage power frequency, and large at the higher RF frequencies of corona or arcing.

As shown, this Corona Detection Network will operate equally well with dc voltage or ac voltage. It is capable of detecting dc corona even though no radio noise is generated. In this case, where no RF noise is generated, the oscilloscope would not be used. Only the readings on the microammeter would

BLOCK DIAGRAM TYPE III CORONA DETECTION NETWORK

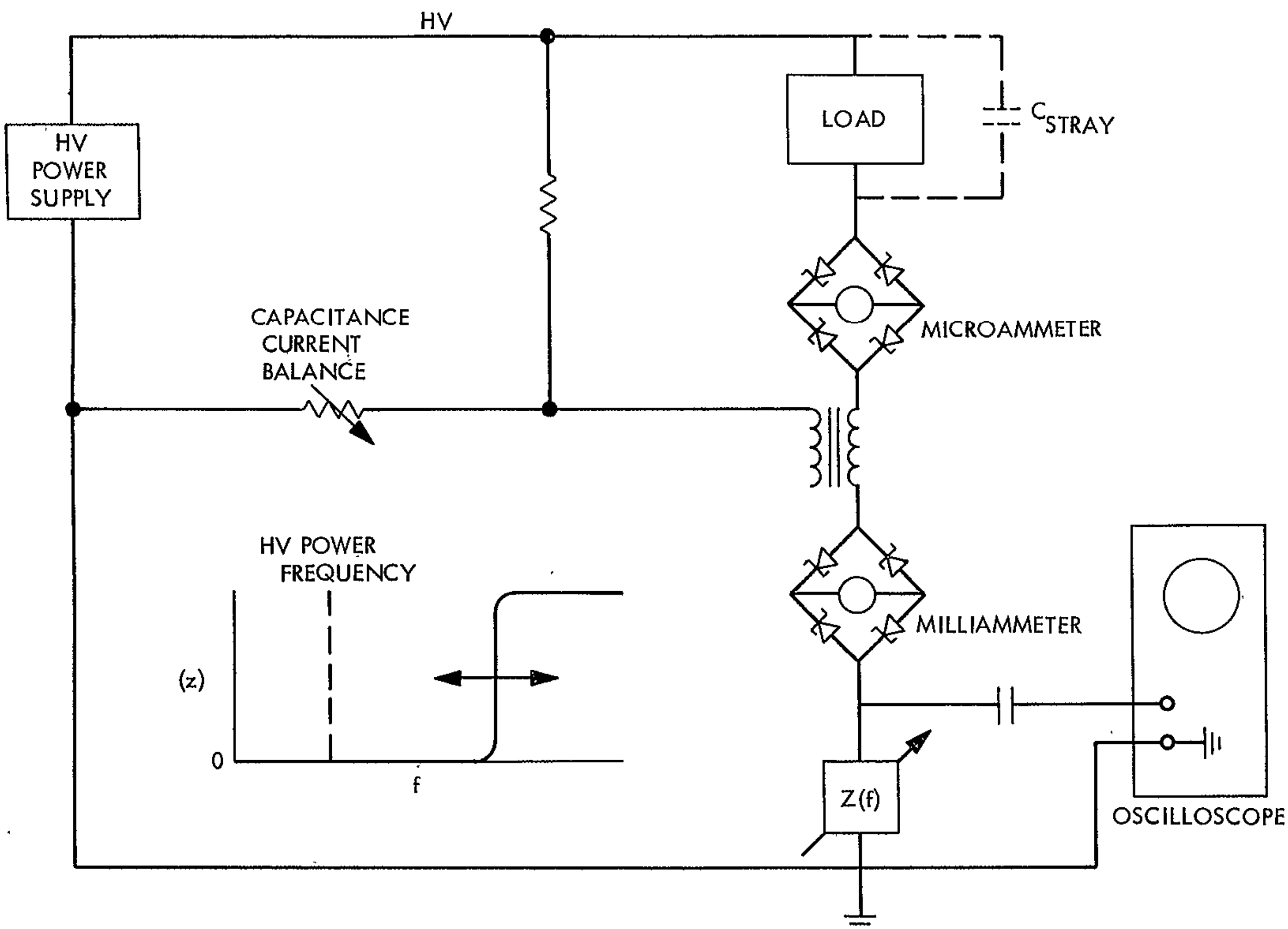

Figure 1. Block Diagram Type III Corona Detection Network

be used. A capacitance current balance adjustment is provided in the Corona Detection Network to buck-out the ac voltage which is coupled into the network by the stray capacitance. Thus, the microammeter indication will remain at zero as the ac voltage is increased. After the corona region is reached, the additional higher frequency corona current would then be rectified and shown on the microammeter.

Because of phasing problems, the method of picking off a voltage proportional to the applied high voltage did not completely balance out the stray capacitance current. A phase shifter was provided, but harmonics in the high voltage output made it impossible to zero the microammeter completely.

Modification and improvement of the Corona Detection Network has not been undertaken for two reasons. It was desired to have a method of high voltage testing available for project work as required. Also, it was decided to wait until a high voltage supply (described in the next paragraph), having a pure sine wave output, would become available. Sensitivity calibration would not be attempted until the final configuration of the network was achieved.

VARIABLE FREQUENCY POWER SUPPLY

A unanimous "no-bid" response was received from nearly 30 power supply vendors. Consequently, it was decided to build this test power supply at JPL. It would appear that the low power requirements of this supply could be met by an unconventional approach, that of using a power amplifier driving a step-up transformer. Variation of frequency during operation was not a requirement. Consequently, several step-up transformers, each covering a particular frequency range, could be employed.

A 75-watt, 20-Hz to 20-kHz power amplifier with a 110 volt output was procured from surplus. A step-up transformer which would give 10-kv, rms output at full voltage input from the power amplifier was designed and fabricated. An oil filled construction was used to eliminate corona problems and yet make it possible for modification. The frequency range was designed from 60 Hz to 2.5 kHz with a pure sine wave output. If this transformer is successful, other transformers will be fabricated to cover the complete frequency range of the power amplifier.

An additional advantage of this approach is that wave forms other than sine wave may be used to drive the power amplifier. Thus, corona breakdown as a function of both wave shape and frequency may be determined. The high voltage transformer also has a winding closely coupled with the high voltage secondary to serve as a metering and feedback winding for the amplifier. This winding could also be used to buck out the capacitance current flowing in the Type III corona detection network.

HIGH VOLTAGE WIRE

After several delivery delays were encountered, the vendor finally provided 855 feet of high voltage wire in accordance with a JPL Specification. The features of this wire configuration include a conductive plastic coating immediately surrounding the stranded wire to minimize the voltage gradient, a polyolefin dielectric between the center conductor and the outside braid shield which is embedded to eliminate air spaces or voids, and a cover of polyvinyl over the shield. This wire, rated at 7 kv, rms, ac will pass heat sterilization requirements of 135°C for 600 hours without damage or degradation. The materials used as insulation in the high voltage wire are bondable with the transformer encapsulation materials presently being investigated. Voltage tests and bonding tests will be made on this wire as a next step in evaluating its performance. If these various tests are successfully completed, specifications for higher voltage wire will be written and samples procured.

HIGH VOLTAGE TRANSFORMER EMBEDMENT

After receiving the high voltage wire, test samples were fabricated as shown in Figure 2 for various encapsulating materials such as Stycast 1090, Solithane, Scotchcast 280, 281, 235, and 241. The test configuration shown in Figure 2 simulates the interface between the high voltage lead and the encapsulation material used to seal the high voltage components. Using five foot lengths, 3 sets of 2 wires each were prepared for embedment of each sample. Since the wire is continuous throughout the sample, this results in four interfaces undergoing tests for each pair of wires. Each of the two samples shown on the left in Figure 2 were prepared in the following manner. The inner conductor was exposed for 1/4 of an inch, followed by 1/4 of an inch of the insulation exposed on each side of the center conductor, which in turn has 1/4 of an

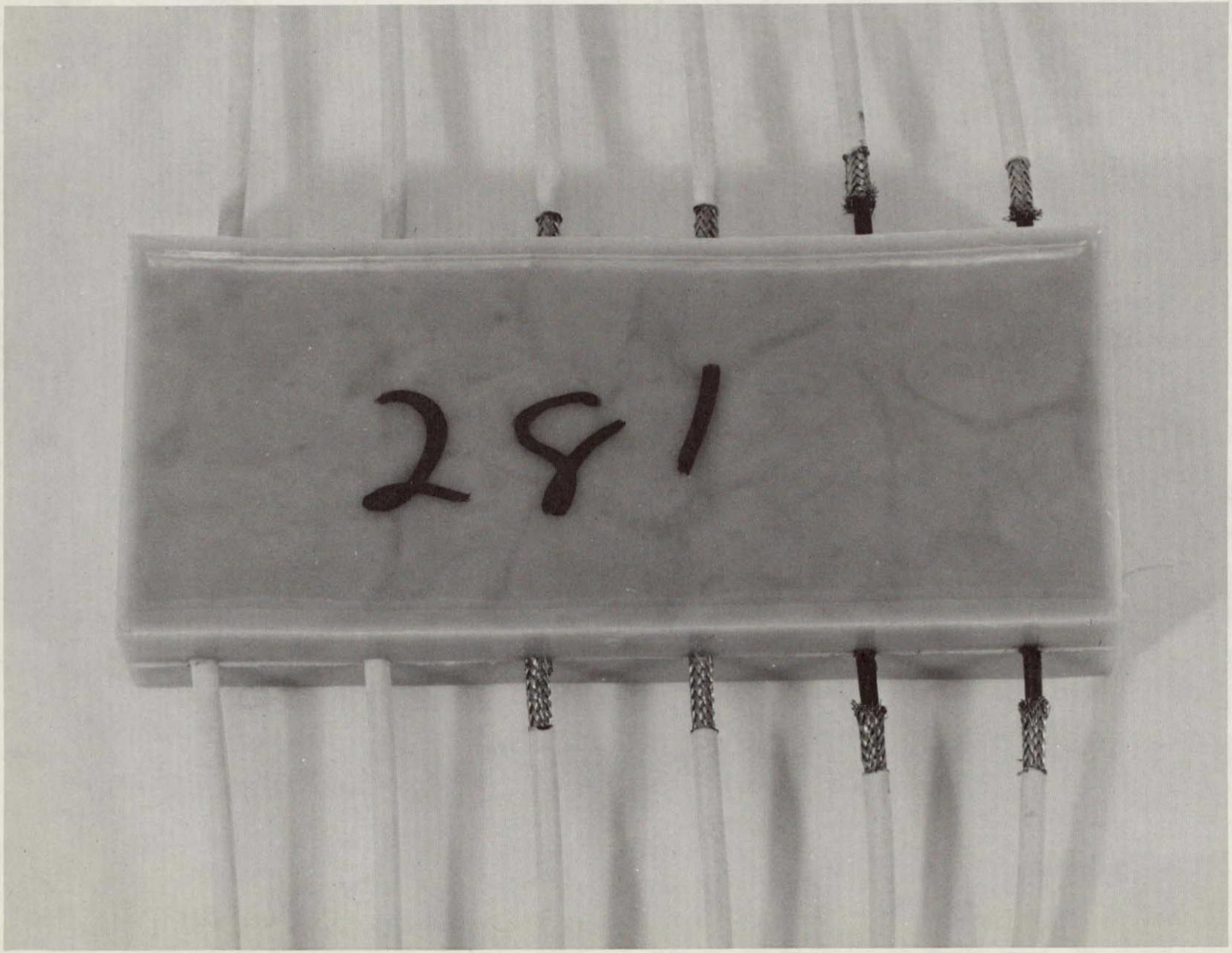

Figure 2. Test Samples of High Voltage Wire

inch of the braid exposed. The width of the mold is such that 1/4 of an inch of the jacket on each side serves as the interface between the encapsulation compound and the high voltage wire.

The two wires in the center have 1/4 of an inch of the jacket removed thereby exposing the shield to the ambient air pressure. One-fourth of an inch of the braid and 1/4 of an inch of the insulation are embedded in the compound. If voids exist in the shielding, this exposure will allow the air to bleed out while the sample is in the critical pressure region. One-fourth of an inch of the shield and 1/4 of an inch of the inner insulation is exposed and in contact with the encapsulation.

The two samples shown on the right in Figure 2 determine the degree of bonding of the encapsulation material to the inner insulation of the wire. One-fourth of an inch of the insulation on each side is in contact with the encapsulating material. The rest of the length is the exposed center conductor.

During the next half of the fiscal year, these samples will be exposed for a period of time to the critical pressure region, and 10-kv, ac voltage will be applied to determine the defectiveness of the bonds between the various layers of the high voltage wires.

VOLTAGE BREAKDOWN WORKSHOP

A second Voltage Breakdown Workshop, similar to the one held at JPL in August 1965, is being organized and will be held March 5, 6, and 7, 1969. A mailing list of nearly 300 names, obtained after the previous workshop, was used for mailing out the information. To date, eighteen (18) abstracts have been received and more are expected. After the first of the year, a selection of the papers will be made based on the abstracts submitted. Preliminary programs will then be printed and sent to the individuals on the mailing list. The proceedings of the workshop will be recorded and published and sent to those attending.

PUBLICATIONS

None

N70-39646

HUMAN FACTORS SYSTEMS SRT (127)

127

MAN-SYSTEM INTEGRATION (127-51)

MAN-MACHINE FUNCTIONS IN CONTROL OF AN UNMANNED ROVING VEHICLE

NASA Work Unit 127-51-01-02-55

JPL 327-10201-2-3430

V. F. Anthony
J. W. Moore

OBJECTIVES

The objectives of this unit are to (1) develop an understanding of man-machine concepts pertinent to the remote control of unmanned planetary and lunar roving vehicles, (2) investigate and establish requirements and techniques for integrating man-machine functions into the control system, and (3) apply this knowledge to laboratory studies and projects.

BACKGROUND

The feasibility of using unmanned roving vehicles for lunar and planetary exploration is directly dependent upon the capability for effectively and safely controlling vehicle motion over long distances and for extended periods of time. The control function must include human participation in the system control loop to provide judgment, reasoning, diagnosis, perception, and reaction to unexpected circumstances while operating the vehicle in unfamiliar and severe environments. Because these human functions are intimately interrelated with other elements of the complete control-mobility system, this work unit is being carried out in mutually beneficial association with OSSA developmental task, "The Remote Operation of a Roving Vehicle," NASA Work Unit 186-68-02-25-55.

PROGRESS

Two series of remote operation field tests have been performed:

(1) Determination of vehicle location from landmark identification.

(2) Determination of vehicle location and remotely maneuvering the vehicle to a preselected destination.

In the first series of tests, each operator was given an aerial photo map of the test site, a separate transparent plotting board, a television monitor view of the scene as viewed from the vehicle, and a vehicle camera-pan remote control (Fig. 1). The control test model (CTM) vehicle was placed within the area covered by the photo map, but at a location and heading unknown to the operator. The operator was expected to scan the scene, and pick out landmarks identifiable on the photo map. The azimuth direction and estimated range from the vehicle to the landmark was plotted on the plotting board. By overlaying the plotting board on the photo and matching landmarks and azimuth lines, the operator determined vehicle location and heading. In general, the operators were quite successful in determining the vehicle position. They were not so successful in estimating distance to the landmark. They tended to overestimate short distances and underestimate long distances. The errors in judgment of distance had a pronounced effect on the operator's efficiency in correlating information pertinent to the location.

Of the twelve operators tested to date, seven were successful in determining the vehicle position within reasonable accuracy.

In another test, the operator was asked to first determine the location of the vehicle and to then remotely drive the vehicle to a preselected destination (Fig. 2). Each of the above techniques is considered feasible for locating and keeping track of the remotely operated vehicle. More work will be done in this area. Figure 3 shows the vehicle on the test site. The television camera is on the mast. The lower photo is the view as seen by the operator at the console in the laboratory.

An engineering documentary color film clip of these tests ("Man-Machine Functions in Roving Vehicle Motion Control," JPL 822-2, 15 minutes) was shown to representatives of the sponsoring NASA agencies at a presentation in Washington in November 1968. A detailed report, which includes operator performance analysis, is in preparation.

The roving vehicle laboratory/control center has been moved from temporary quarters in Building 158 to Building 198, Guidance Laboratory, which is further from the test area. The quality of television reception was marginal at

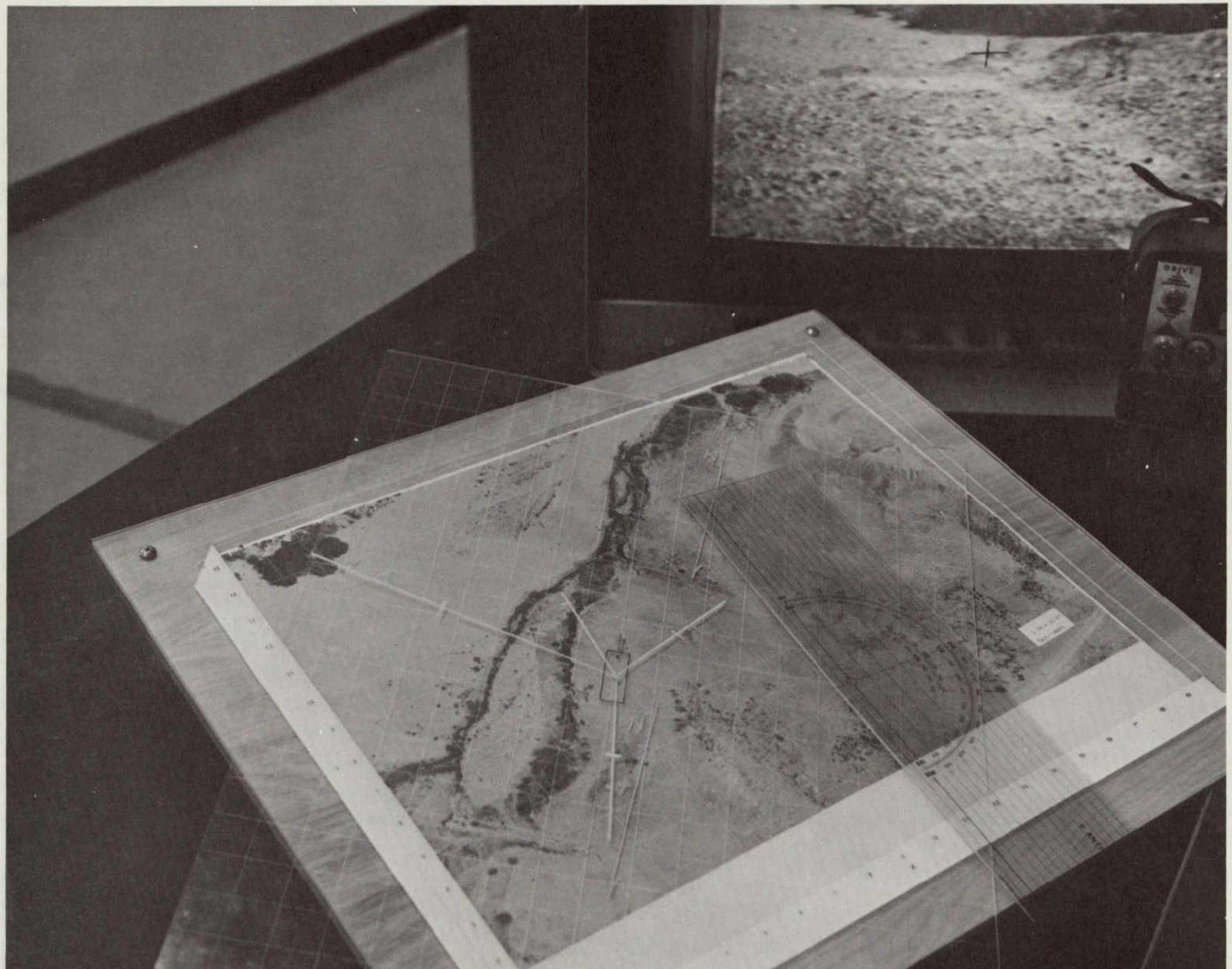

Figure 1. Plotting Equipment

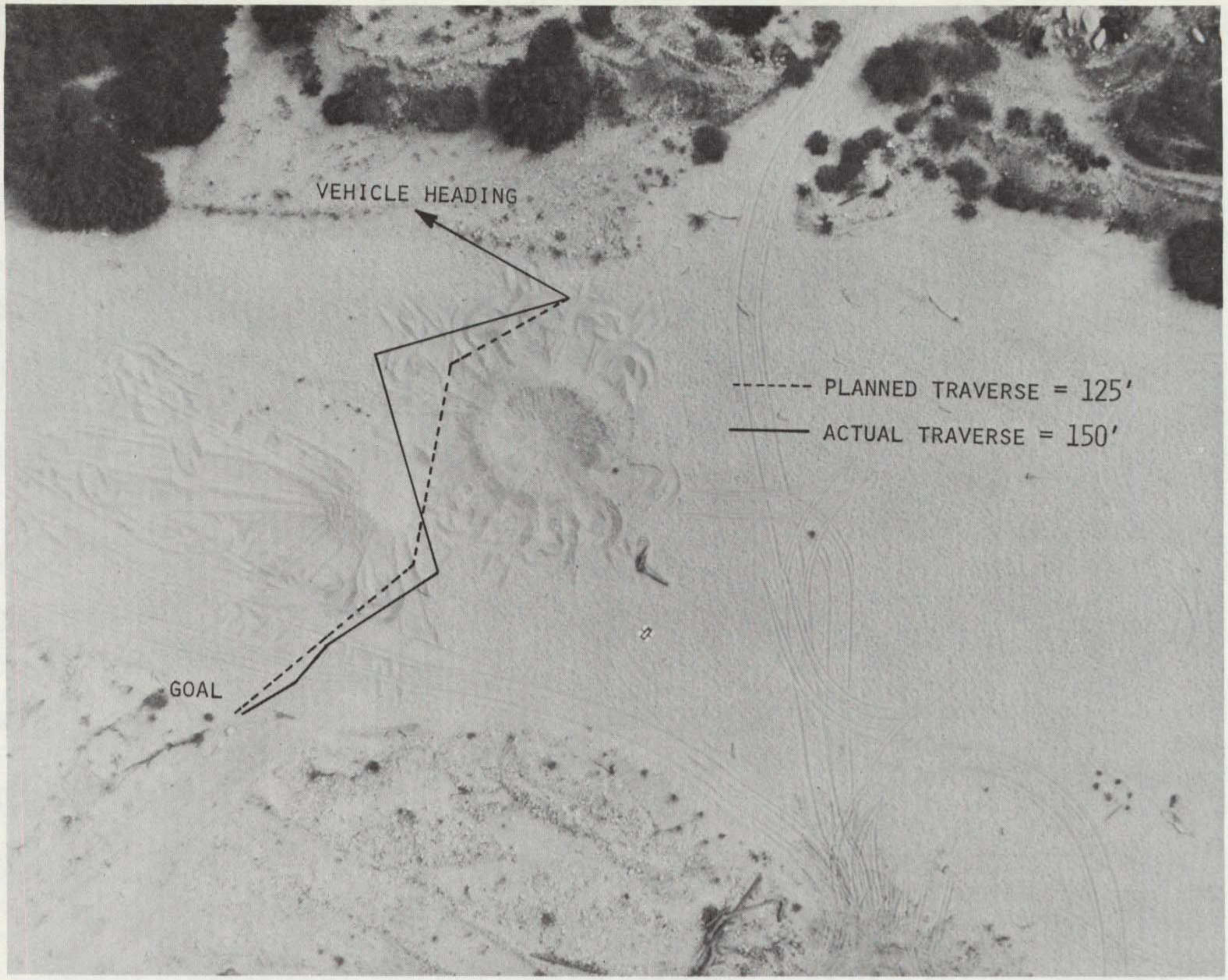

Figure 2. Traverse on Test Site No. 1. Crater

CHEMICAL PROPULSION (128)

128

LIQUID ROCKET TECHNOLOGY PROGRAM (128-31)

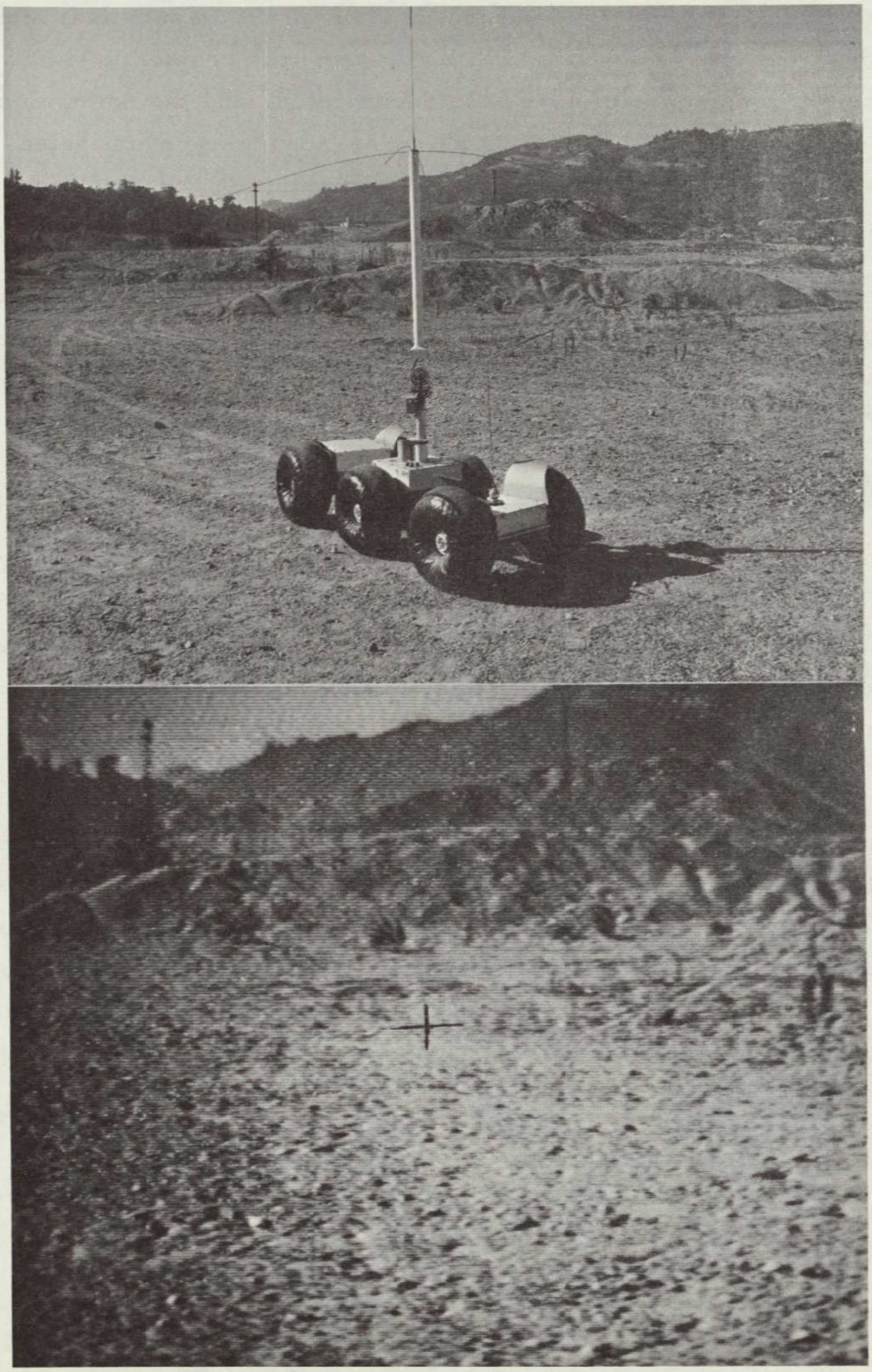

Figure 3. View B on Test Site No. 2

the shorter distance because of the low transmission power. Also, communication with the vehicle is line-of-sight and the location of 198 is such that most of the East Arroyo Test Site is obscured. To overcome the problems, a new set of communication requirements have been documented, and the communication system definition and implementation are presently being investigated. The implementation must be completed before resumption of the navigation and motion control tests.

Most of the surplus Surveyor flight and operational control equipment requested early in 1968 was received in October and November. The control equipment is in place in the Building 198 roving vehicle laboratory. Equipment intercabling is in process, with turnon and checkout to follow.

PLANNED ACTIVITY

The work for the remainder of FY 69 will be directed toward establishing the communication link between the Building 198 control center and the test sites, and to processing additional operators through the tests described above. The data sample from operators tested to date is too small to determine population trends with confidence.

For the motion control tests, some work remains to be done in specifying the test requirements and procedures. Data from these tests will be used to measure the operator's ability to control the vehicle motion over both specified and unspecified traverses. Of particular interest will be the time of execution, the number of commands transmitted, traverse deviation, and methodology employed by each operator. Operators selected for these tests will be from both trained and untrained classes.

PUBLICATIONS

1. Engineering documentary color film clip, JPL 822-2: 15 minutes, "Man-Machine Functions in Roving Vehicle Motion Control."

ADVANCED TECHNOLOGY CONTRACT MANAGEMENT FOR RPL

NASA Work Unit 128-31-20-01-55

JPL 328-10401-2-3840

C. R. Foster

OBJECTIVE

The purpose of advanced technology contracts, sponsored by the Liquid Propulsion Technology Program (RPL) office at NASA headquarters, is to advance the technology of all phases of liquid propulsion through contracts to industrial aerospace firms.

DESCRIPTION OF ACTIVITIES

Under this work unit, JPL engineers experienced in the liquid propulsion field provide the technical management of some of these advanced technology contracts. These advanced technology contract management tasks are supplementary to the normal JPL assignments of these engineers on research, advanced development, or flight projects.

In general, the engineer's work consists of visits to the contractor's plant for technical information and direction, review of monthly progress reports, and quarterly reviews of progress at the contractor's plant, normally in company with the NASA project manager. In addition, the engineer participates in planning and recommending new work, prepares the statement of work for proposed new (or continuing) advanced technology contracts, provides technical evaluation of proposals received, and gives technical review and approval to the final reports submitted by the contractor. On a semiannual basis, the engineer submits an informal report to the NASA headquarters project manager to give his technical judgement on the status of the contractor's effort and results.

STATUS

Thirty-three advanced technology contracts in liquid propulsion have been in effect during the first half of FY 69 that were technically managed by engineers in the Propulsion Division (38) of JPL. It is expected that technical management of advanced technology contracts will continue at approximately the same level of effort during the second half of FY 69.

PUBLICATIONS

None

APPLICABILITY OF LASER DIAGNOSTICS TO ROCKET ENGINES

NASA Work Unit 128-31-21-01-55

JPL 328-10701-1-3840

J. H. Rupe
R. S. Rogero

OBJECTIVE

The objective of this experimental program was to demonstrate the feasibility of producing laser holograms of the reacting environment in liquid propellant rocket engines. A joint effort using JPL propulsion personnel and equipment and TRW's expertise in laser technology has been completed. The results have been documented in a final report (TRW No. 68.4712.2-024, dated July 31, 1968) which, in summary, concluded that it was feasible to obtain such holograms.

The JPL effort also provides support of other work units in the form of studies of nonreactive sprays.

PROGRESS

Laser Holograms

Although a number of holograms of good quality, covering a range of operating conditions, were obtained during FY 68, there was little or no effort expended in analysis and/or interpretation of these results. (This task was purposely omitted from the original work statement in order to concentrate on feasibility.)

However, a cursory evaluation of the records revealed certain anomalies that required explanation prior to attempts to apply the technique for quantitative analysis. In particular, under certain operation conditions there was no evidence of the anticipated droplet cloud that has historically been utilized to characterize the reacting environment. Therefore, a small supplemental effort was initiated in order to (1) "estimate" the probable resolution of the holocamera system as it was finally developed, and (2) provide a comprehensive study of the existing holograms for purposes of identifying the information that can be obtained from such records. To this end, a new contract is being negotiated. Although current estimates are that the purchase request (dated June 11, 1968) should yield a signed contract yet this winter, the work to be performed under this contract was not started during this reporting period.

Nonreative Studies

The spray booth facility in Building 78 (a replacement for the facility in Building 158 that was vacated several years ago) has been completed and the equipment installed.

An improved model of the impingement of a pair of jets has been formulated. A two-dimensional analysis based on just momentum and continuity has provided valuable insight into the probable spray properties. In particular, the analysis indicated the existence of an unstable operating condition that holds broad implications for spray characterization. An initial photographic study with three-dimensional jets failed to verify this phenomenon, but it is believed that a second attempt based on direct sampling will be more successful. These experiments are continuing.

$OF_2 + B_2H_6$ Engine Experiments

A small rocket engine (a so-called pancake engine utilizing only five elements with radial injection), being utilized to demonstrate the appropriateness of available design criteria to rocket engines utilizing $OF_2 + B_2H_6$, has been test fired eight times. In the single run for which performance data were obtained at design operating conditions ($r = 3.0$, $p_c = 180$), the uncorrected c* was greater than 95% of theoretical. This measure has yet to be verified.

PUBLICATIONS

Contractor Reports, Interim and Final

1. TRW Report No. 68.4712.2-024, Final Report, July 31, 1968.

TRANSPORTABLE SUPPLY MODULE FOR OF_2/B_2H_6

NASA Work Unit 128-31-21-02-55

JPL 328-14601-1-3840

J. H. Rupe

OBJECTIVE

The objective of this work unit is to provide for the design, fabrication, and testing (under contract) of a transportable supply module intended for use at any one of several JPL test facilities where the OF_2 + B_2H_6 propellant combination is required. It also provides for training of the JPL personnel required to operate that facility.

PROGRESS

The procurement action required to implement this work unit has progressed to the point of preparing a contract. The proposals have been evaluated, a vendor selected, and negotiations should begin in the near future.

PUBLICATIONS

None

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ADVANCED EXPULSION DEVICES TECHNOLOGY

NASA Work Unit 128-31-33-04-55

JPL 328-11901-2-3840

H. B. Stanford

OBJECTIVE

The objective of this work unit is to advance the technology of phase separators for liquid propellant control in spacecraft applications. This is to be accomplished through investigation of the problems associated with various materials and types of devices suitable for use with both earth and space storable propellants for missions of up to 10 years duration. The work is concerned with:

(1) Mechanisms to control propellant sloshing.

(2) Development of materials of construction for expulsion bladders (such as laminates and composite structures).

(3) Fabrication techniques required to produce these devices.

The goal is to furnish information for engineering application that will result in designs with more reliable performance.

PROGRESS: JPL ACTIVITY

The JPL activity consisted of technical management of the contracted expulsion devices tasks.

PROGRESS: OFF-LAB ACTIVITY

Teflon Aluminum Laminate Bladder Materials

Contract No. 952091, chemical vapor deposition of aluminum (Dilectrix Corp.) purposes are to:

(1) Investigate the process of chemically depositing aluminum onto Teflon substrates, and to design and build equipment with which to produce representative samples for test and evaluation.

Consideration is to be given in design of this equipment to the eventual requirement of depositing aluminum onto bladders of cylindrical or spherical shape.

(2) Select metal foils and develop techniques for preparing the surface of these materials to produce laminations with Teflon substrate that will demonstrate improved bond strength, and resistance to peeling, blistering, delamination and permeation.

Status

The effort as defined by Contract 952091 is completed and the final report published.

Phase I. Samples of chemically-vapor-deposited aluminum on Teflon substrates which showed no detectable permeation to N_2O_4 in 96 hours when tested by the JPL permeation test method (Vango). By the use of proper suppressant gases, aluminum layers having either lamellar or columnar crystallite structure are produced. Tests have indicated the lamellar structure to be the most resistant to permeation.

Also, a study was made and a method proposed for extending the chemical vapor deposition process from the current equipment, capable of only producing small test pipes, to equipment capable of applying coatings to the interior of bladders which are as large as 36 inches in diameter.

Phase II. The cause of delamination and blistering of Teflon-aluminum foil laminate structures has been determined to be outgassing from the TFE Teflon substrate. This type of defect can be prevented by interposing a sufficiently thick (1/2 mil or more) layer of FEP Teflon between the TFE and the metal foil.

Expulsion Bladder Material Development for Earth- and Space-Storable Propellants

Contract No. 951484 (Stanford Research Institute) objectives are:

(1) To develop control parameters for the production of liquid-propellant expulsion bladder materials, such as Teflon films.

(2) To improve techniques of cladding or laminating these materials.

(3) To provide improved test methods and apparatus for detection of long-term permeation of nitrogen tetroxide and hydrazine through materials.

(4) To investigate the compatibility of materials with oxygen difluoride and diborane.

Status

This contract ran out of funds and has been technically dormant other than for publication of the final report on Teflon fabrication techniques. Negotiations for refinancing this effort have been completed and studies relative to materials for use with oxygen difluoride and diborane as well as earth-storable propellants (nitrogen tetroxide and hydrazine) will be continued.

PUBLICATIONS

Contractor Reports, Interim and Final

1. "Improved Positive Expulsion Bladders with Laminar Wall Construction," Commonwealth Scientific Final Report, Dilectrix Corp., JPL Contract 952091 under NAS7-100, Oct. 1, 1967 – Oct. 1, 1968.

2. "Development of Techniques to Improve Bladder Materials and Test Methods," Stanford Research Institute Final Report, JPL Contract 951484 under NAS7-100.

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SPACE STORABLE PROPELLANTS COMBUSTION DEVICE TECHNOLOGY

NASA Work Unit 128-31-34-04-55

JPL 328-11501-2-3840

R. Y. Oshiro

OBJECTIVE

The primary objective of the program is to create, optimize, and demonstrate the feasibility of new concepts related to liquid rocket engine injector and thrust chamber technology using the space-storable propellant combination of oxygen difluoride (OF_2) and diborane (B_2H_6). Immediate short-range objectives are to gain first-hand experience in propellant handling, to determine cryogenic feed systems operational characteristics, and to develop compatible high-performing injectors with extended duration capability that are also scalable to higher thrust ranges and amenable to throttling operation.

APPROACH

Injector-chamber compatibility hot-fire screening tests will be conducted using the instrumented copper heat-sink thrust chamber and employing several types of injectors. Performance and heat transfer characteristics will determine the optimum engine-assembly configuration, the chamber of which will be constructed of the advanced thrust chamber material. This engine will then be tested to demonstrate sustained duration capability.

STATUS

The major effort during this reporting period has been devoted to system rework, resolving feed system operational difficulties at cryogenic temperatures, and test hardware fabrication. However, several short-duration tests were conducted, with the five element, unlike impinging doublet, radial flow injector, using the instrumented copper chamber. Transient thermocouple plugs on the chamber provided the thermal data. Indications are that a large variation in heat flux exists as measured in line with and between injector elements. All data from these tests must be verified by additional testing. However, the preliminary performance level is approximated at 93 percent equilibrium C* at the injector design conditions.

During the test series, a leak was detected at the diborane (B_2H_6) propellant tank flange. Since only a small amount (less than 4 lb/min) of fuel remained, the propellant was disposed of and the system secured for repairs. It had been previously planned to rework the diborane system upon propellant depletion, and this opportunity was used to undertake the rework. The major rework consisted of replacing the existing fuel valves with new valves and installing them into an up-graded system-conditioning trough that allows easy accessibility to all components after the unit has been permanently installed in the feed system. Two flowmeters in series were installed in the line, upstream of the fire valve arrangement, to improve the liquid flow measurement capability. The flange seal has been replaced, and the diborane tank has been helium leak checked to 900 psig pressure without leakage. The liquid level detector device in the oxidizer (OF_2) run tank has been repaired and is now functional.

Due to priority projects and a heavy work load onthe laboratory's electro-discharge machine, the fabrication of the like-on-like injector has been delayed Both impinging sheet injectors have been completely cold-flow characteristized and are available for test. Testing will resume as soon as system rework has completed. The test stand is expected to be operational early inthe next reporting period.

PUBLICATIONS

None

LIQUID PROPELLANT MATERIAL COMPATIBILITY

NASA Work Unit 128-31-37-01-55

JPL 328-11801-2-3840

L. R. Toth
O.F. Keller

OBJECTIVE

The broad objectives of this work unit are (1) to advance the technology of materials of construction for liquid propulsion systems for future space missions (2) to determine acceptably inert materials having high reliability after periods of up to two years storage in the mission environments while in contact with hydrazine (N_2H_4), nitrogen tetroxide (N_2O_4), or monomethylhydrazine (MMH) liquid propellents, (3) to understand the implications of extended storage periods of two, five, and ten years, such as those associated with an advanced mission to the outer planets, and (4) to generate data upon which to base flight commitments.

STATUS

Phase II (Earth Storables)

Fabrication and preparation of material compatibility test specimen/capsules continues. To date, 120 hydrazine test-specimen/capsules have been delivered to JPL/ETS for long-term storage test (see Fig. 1). These test-specimen/capsules have been temporarily placed in cold storage until the instrumentation wiring of the fuel side Lazy Susan has been completed and is operational.

A certain amount of "learning" has been required in connection with JPL Contract 952004 to reduce JPL procedures to industrial practices.

The specialized nature of the work includes: (1) fabrication and preparation of the test specimens, per JPL Specification GMZ 50521-GEN-A, and the glass test capsules, per JPL Specification GMZ-50522-GEN; (2) assembling of the test specimens with the glass test-capsules and filling with liquid hydrazine,

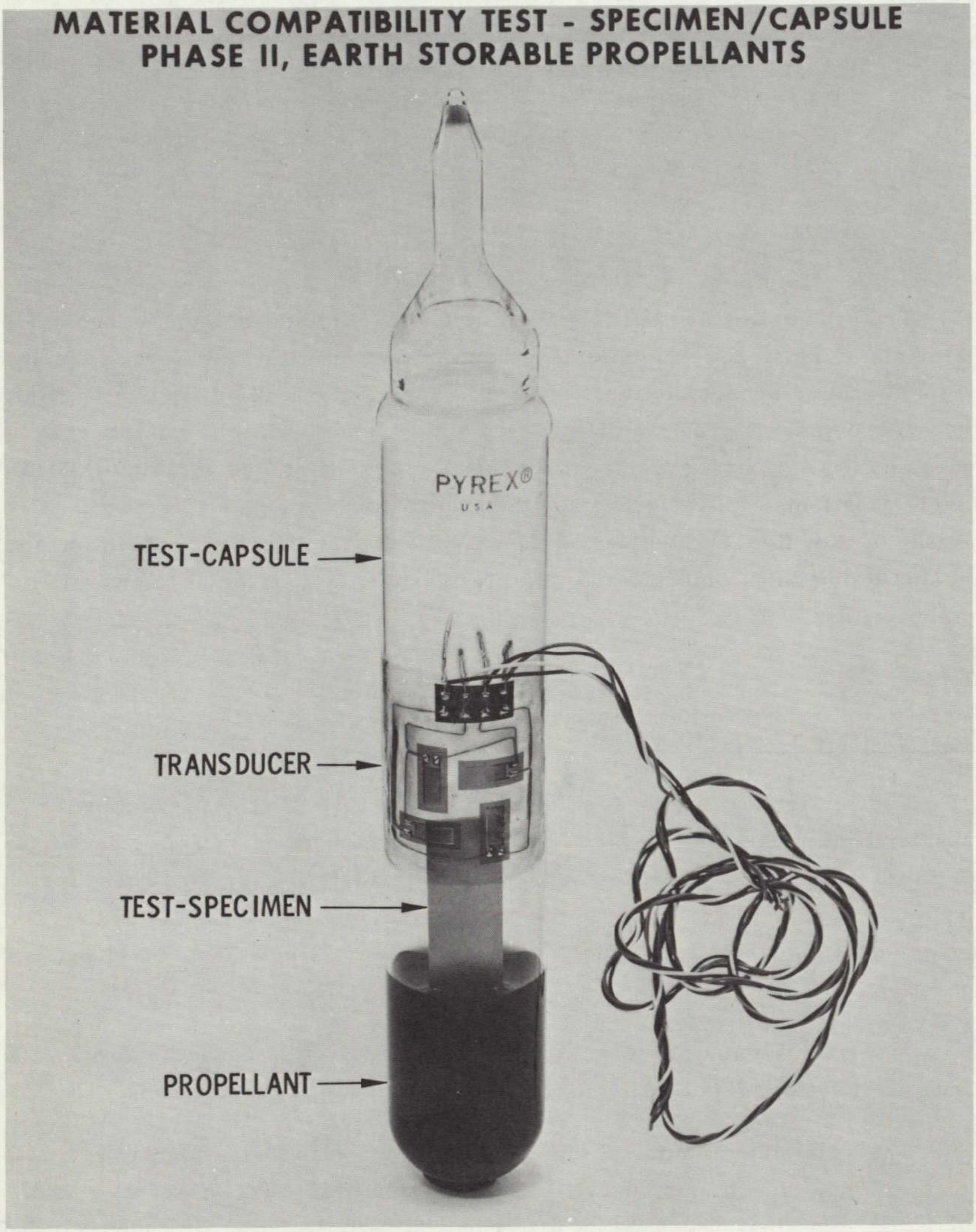

Figure 1. Material Compatibility Test Specimen/Capsule

nitrogen tetroxide, or MMH; (3) hermetical sealing of glass test capsules; and (4) shipping of hermetically sealed, fully instrumented, glass test capsules, with test specimens and liquid hydrazine or other propellant enclosed, to the JPL/ETS environmental compatibility test facility; Edwards, California, for long-term storage tests under controlled temperature conditions at 110°F.

The completion date of JPL Contract 952004 with Pressure Systems, Inc., for procurement and preparation of the material compatibility test specimens and glass test capsules was extended to December 20, 1968, and an incremental increase in funding in the amount of $20,000.00, was obligated.

Negotiations are underway to continue this contract beyond the present expiration date of December 20, 1968.

Phase III (Space Storables)

The objective of the space-storable material compatibility program is similar to the broad objective as outlined above for earth-storables except that the primary emphasis will be placed on the space-storable propellants, oxygen difluoride (OF_2) and diborane (B_2H_6). A survey of existing test facilities and equipment has been made. Preliminary planning in connection with the testing of metallic specimens in space-storable propellants, oxygen-difluoride and diborane has been started.

PUBLICATIONS

Contractor Reports, Interim and Final

1. "Monthly Reports of Work in Process," Pressure Systems, Inc., report numbers 6720-12, 6720-13, 6720-14, 6720-15, 6720-16 and 6720-17, July through November 1968, respectively, JPL Contract No. 952004.

2. Muraca, R. F., Whittick, J. S., Neff, J. A., "Treatment of Metal Surfaces for Use With Space Storable Propellants: A Critical Survey," SRI 951581-8, Stanford Research Institute, Menlo Park, Calif., August 15, 1968.

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COMBUSTION EFFECTS IN SPRAYS

NASA Work Unit 128-31-50-01-55

JPL 328-10901-1-3840

J. Houseman

OBJECTIVE

The objective of this work unit is the experimental verification of several theoretical models for predicting the presence (or absence) of stream separation, i.e., the separation of the fuel and oxidizer jets due to gas evolution at the impingement point.

Recent experiments conducted at JPL with highly reactive propellants have shown that rapid chemical reactions occurring at the interface formed by a pair of unlike impinging jets play a key role in the establishment of the mass, mixture ratio, and drop size distributions achieved in an actual rocket engine. Thus, it is essential that a quantitative evaluation of these effects be obtained so that the range of applicability of the nonreactive data can be established and the reaction effects correlated with the design parameters.

A procedure has been developed to measure the mixture ratio distribution produced by a single unlike impinging doublet injector element using reactive fluids in a combustion chamber. The combustion gas in the chamber is sampled continuously by means of a scanning probe. On-line chemical analysis of the gases is carried out by a fast-scanning quadrupole mass spectrometer. The end result is a mixture ratio distribution across the chamber for a combusting spray.

STATUS

Experimental

An additional 23 test firings were carried out during this period. Stream separation was observed over a wide range of injection temperatures and chamber pressures with the 0.073-inch diameter element. A few data points with a 0.050-inch diameter orifice also showed separation. The mixture ratio variation usually ranges from 0.6 to 2.1 across the chamber for an overall input of 1.2.

The experimental program suffered a delay of about two months because of repainting (including sandblasting) and clean-up of the test facility.

Equipment

Some trouble was experienced with the sampling probe. The 0.008-inch diameter orifice in the tip closed up, probably due to flowing of the gold brazing. A modified design has since worked satisfactorily.

The water pump in the hot water probe-cooling circuit failed and was replaced by a new one. Two probe burn-outs have since occurred. Formation of steam bubbles and subsequent failures in the future would be prevented by increasing the pressure level of the cooling water.

A set of 0.040-inch diameter orifices and a corresponding small nozzle were manufactured and are now in operation. A set of 0.020-inch diameter orifices are being made by electrostatic machining.

The helium bleed Kistler pressure transducer, which continued to show zero drift, has been replaced by a water-cooled photocon.

A time-averaging amplifier now gives an average chamber pressure based on the Tabor transducer. To express the roughness of the combustion, the photocon signal is fed to an RMS meter and, in this manner, a single meaningful number for roughness or chamber pressure fluctuation is obtained. It is suggested that this practice be adopted by the industry.

Mass Spectrometer Operation

Further refinements were made in the computer-controlled operation of the mass spectrometer. The method has proved to be quite successful; both a cost reduction and a new technology application were filed. A cost reduction of $20,000 was awarded.

A new computer program to enable simultaneous recording of both mass spectrometer output, probe position, and engineering data on tape is now in operation. The data reduction program to process the tape is now being prepared. This will eliminate the hand calculations of the mass spectrometer output.

Consideration has been given to the feasibility of building a molecular beam sampling device. This should enable identification of the actual chemical species in the chamber. In addition, operation of a traversing probe during firing is then possible with a considerable reduction in the number of test firings.

Theoretical Models

Another theoretical model for stream separation was introduced. A total of three possible mechanisms for stream separation are now postulated:

(1) Local boiling of the propellant due to heat released by liquid phase reaction.

(2) Gas evolution due to gaseous products of liquid phase reactions.

(3) Formation of a gas film between the jets due to gas phase reaction.

At this time more data points are needed to firm up these models.

FUTURE ACTIVITY

Plans for the future are to:

(1) Obtain more data points, particularly with small diameter orifices, to check out the theoretical models of stream separation.

(2) Convert sampling probe to molecular-beam type.

(3) Plan modification of equipment and procedure to the OF_2/B_2H_6 system.

(4) Check out possible correlation between combustion roughness and stream separation.

PUBLICATIONS

Meetings and Symposia Papers

1. "Combustion Effects in Sprays," ICRPG Combustion Conference, Oct. 1-3, 1968.

RESONANT COMBUSTION

NASA Work Unit 128-31-51-01-55

JPL 328-10601-1-3840

R. M. Clayton

OBJECTIVE

The overall objective of this work unit is to evolve liquid rocket injector/combustor design criteria which will yield high-performance steady combustion with a high margin of stability against transitions to destructive resonant combustion. The general approach is to:

(1) Elucidate the properties of the early reaction environment which enhance finite wave support.

(2) Relate the control of these properties to injector design variables.

(3) Ascertain the critical relationships between baffle geometry and these properties for prevention of wave growth and the development of resonant combustion.

The baffle device is emphasized here for stability control because of its inherent effectiveness against the transverse modes of wave travel, especially the spinning tangential mode. The latter mode is generally the most destructive by virtue of its potential for high amplitude shocklike behavior, but the transverse can be an important transitory step in development of the sustained tangential wave. Additional control over less severe chamber gas oscillations may be achieved with acoustic cavity devices located at the chamber boundaries, but these devices are not presently of primary interest to this program.

Intermediate objectives for FY 69 are:

(1) Completion of initial experiments with an 18-inch annular engine to lend experimental support for a contractual analytical effort under work unit 128-31-51-03-55.

(2) Conduct an order of magnitude analysis of the potential for developing high amplitude shock fronted waves during the first pass of a disturbance across the chamber.

(3) Design and fabrication of an injector for producing controlled degradation of injection hydraulic properties.

(4) Developing suitable pulsing devices for introducing controlled initial disturbances to the steady combustion environment.

(5) Evaluating the dynamic stability of baffled versions of the two 11-inch-diameter and the 18-inch-diameter cylindrical engines previously studied in this program.

STATUS

Annular Engine Experiments

The resonance characteristics of the unbaffled annular engine were described in the last semiannual report. Experiments to determine the effectiveness of baffles for stabilizing the engine were conducted this period. Using a four-baffle array dividing the annular cross section into unequal size cavities, a 5-inch length was found to be effective in eliminating the 200 psi spinning waves which were typical of the unbaffled engine. Intermediate lengths did not appear to produce large effects on the amplitude of the resonance. However, all baffle lengths tested eliminated the counterrotating wave nature of the unbaffled engine, restricting the resonance to a 2-wave spinning mode. A residual low-level (~20 psi) oscillation appears to be present intermittently even with the "stabilized" engine; however, it is not a destructive mode. Analysis of these results and of the unbaffled-engine results is continuing.

"Pop" (spontaneously generated high-amplitude pressure wave) is a characteristic of the annular engine as it was for the cylindrical engine. It appears to be related to the operating conditions of the boundary injection scheme (separate system from the main injected flow). Boundary propellant temperature and mixture ratio seem to be the critical variables controlling the occurrence of pops, which act as triggers for resonant combustion. Experiments to further define the influence of these variables are presently under way with the baffled annular engine. It is believed that the dependence of pop disturbances on the temperature and injected flows occurs through a lack of stability of the boundary element impingement processes, and may be the result of either rapid liquid phase reactions or hydraulic instability, or both.

Analysis of High Amplitude Wave Development

The occurrence of spontaneously generated high-amplitude pressure waves during otherwise steady combustion is a common phenomena, especially with the N_2O_4-hydrazine family of propellants. It is also common to assume that the wave is essentially a blast wave originating from the explosion of pockets of accumulated propellant. However, estimates based on blast wave theory indicate that local energy release of the order of the total energy available in the chamber would be required if the observed waves were simply blast waves. In addition, other observations indicate that wave growth occurs as the wave traverses the chamber, a situation which is converse to the required decay of a blast wave with travel distance. Thus, the question of chemical enhancement of initially small disturbances becomes important and was the subject of the present analysis (performed by Professor Arthur Kovitz, a summer 1968 employee).

The objective of this analysis was to explore the potential for chemical augmentation of small initial disturbances under realistic liquid rocket combustion environments. In this sense, it was complementary to an earlier effort by Dr. J. Bonnell (see publications list) in a study of relatively larger amplitude blast waves as generated by combustion chamber bombing techniques.

A technical report is in preparation covering the present analysis and no attempt to describe it will be given here; however, the principal conclusions from the work are:

(1) For chemical induction times of the order of 10^{-6} sec (believed reasonable for N_2O_4 - N_2H_4 propellants under rocket conditions), spherical detonations can be initiated with an initial energy release as small as 0.1% of the total chamber energy.

(2) The detonation wave may not be large amplitude due to the high thermal energy level of the environment, but the low temperature gas near the chamber wall can significantly amplify the reflected wave amplitude to values approaching JPL observations on pops.

(3) Conditions of high temperature and nearly complete combustion enhance the probability of initiating a detonation.

These conclusions provide additional support to the underlying hypothesis of the JPL resonant combustion program that detonative processes are involved in the initiation and character of destructive combustion resonance, and thus are not solely dependent upon acoustical resonance phenomena. Hence, the application of baffles for achieving stability must be based on their ability to inhibit finite wave growth through detonation-like processes by insuring that the properties of the combustion environment retain a reproducible spatial relationship with the baffles. The quantification of these spatial requirements is, of course, a primary objective of this program.

Injector Design and Fabrication

Design specifications for a variable orifice-geometry injector (to be designated RC-2) have been defined and its basic layout has been established. The element centerline geometry and scale (200 lb_f/element) of RC-1 injector (18-inch-diameter) will be retained and the following variables will be incorporated: (1) $3 < \text{orifice } L/D < 30$, (2) variable orifice entry contour, and (3) variable manifold cross velocity and gross turbulence.

The purpose of this injector is to provide a means for degrading the injection hydraulics and hence the control over the early reaction environment. Ultimately, it is anticipated that a correlation will be achieved between baffle effectiveness and injector design parameters.

It is expected that design and fabrication will extend through the next reporting period.

Pulsing Devices

Two pulsing techniques are presently of interest. The first utilizes small explosive charges (bombs) of the order of 10 grains of explosive and the second involves the use of exploding wires.

The bombing technique has been used extensively in the program to date; however, in the past only one bomb per engine run was required. Test of the stability of baffled engines makes multiple bombs per run advantageous in order to reduce the number of runs. Consequently, a sequenced firing circuit has been devised to allow firing as many as six bombs per run. The bombs may be of different sizes and placed in as many different positions within the combustor.

The energy release from such bombs is relatively large for even small charges and, at best, is difficult to control. The exploding wire technique appears to offer substantial advantages when small initial disturbances of the order studied by Kovitz is required. Therefore, the feasibility of using this technique is being investigated. Energy release levels of the order of 10^3 joules or less are of interest for simulating the origin of a pop-like disturbance.

It is anticipated that apparatus for exploding wires will be assembled and experimented with during the next reporting period.

Baffled Engine Stability

The stability margin of the baffled versions of the two 11-inch engines has never been determined, Consequently, these engines will be bombed with the multiple bomb apparatus mentioned previously. Likewise, the 18-inch-diameter cylindrical engine will also be tested. It is expected that these tests will conclude the experimental activities for the next reporting period.

PUBLICATIONS

Open Literature

1. Clayton, R. M., Rogero, R. S., and Sotter, J. G., "An Experimental Description of Destructive Liquid Rocket Resonant Combustion," AIAA Journal, Vol. 6, No. 7, pp. 1252-1259, July 1968.

2. Flandro, Gary A., and Sotter, J. George, "Resonant Combustion in Rockets," Scientific American, December 1968.

JPL Technical Reports

1. Bonnell, J. M., "An Investigation of Spherical Blast Waves and Detonation Waves in a Rocket Combustion Chamber," TR 32-1286, August 15, 1968.

2. Clayton, R. M., "The Influence of Several Near-Wall Injection Conditions on the Combustion Performance of a Liquid Rocket Engine," TR 32-1283, September 15, 1968.

COMBUSTION LIMITS IN MIXING STREAMS
NASA Work Unit 128-31-51-02-55
JPL Work Unit 328-11601-1-3840

R. Kushida

OBJECTIVE

A new type of laminar flame burner is being utilized to measure rates of chemical reactions in combustion reactions. An objective of this program is to perfect the theory of this burner to the point where predictions of quenching, blowoff, ignition, and steady combustion can be made for systems with known rates. A second objective is to use the experimental data on these phenomena to obtain overall rates of chemical reaction, and to obtain, if possible, detailed mechanism of reaction. Studies on the rates of space-storable propellants are being carried out.

STATUS

Relatively little work has been done in the past reporting period due to manpower limitations. The propellant handling system has been designed, and long lead-time supplies obtained.

The products of combustion of the space-storable system, OF_2 and diborane, contain both solids and corrosive gases. The pump for the low-vacuum combustion tests must be compatible with these exhaust products. A Nash CL-203 three-stage vacuum pump with 70 CFM capacity at 10 torr was obtained. This pump has an air ejector stage followed by two water-sealed pumping stages. Since the pump is continually flushed with water, it is well adapted to handling the abrasive and corrosive gases.

A large bell jar and collar, which were from a surplus vacuum metal sputtering apparatus, will be used for the main vacuum chamber. The collar has eight fittings through which tools or lines can be easily inserted into the vacuum chamber.

Technical meetings attended included: (1) ICRPG Performance Standardization Committee, Theoretical Methods Subcommittee, December 3 - 4 at LTV Aerospace, Dallas, Texas; and (2) Western State Section/Combustion Institute, October 28- 29 at Stanford Research Institute, Menlo Park, Calif.

PUBLICATIONS

None

NUMERICAL ANALYSIS OF HETEROGENEOUS COMBUSTION

NASA Work Unit 128-31-51-03-55

JPL 328-11701-1-3840

J. H. Rupe

OBJECTIVE

The current effort of this work unit is directed toward the development of a solution of the complete wave equations with arbitrary sources and sinks and is being conducted under JPL Contract No. 951546 with Mathematical Applications Group, Inc. This contract is in its second year of work and the contractor has, in essence, completed the tasks allocated to the first year and is in the process of implementing the experimental verification of the efficacy of the analytical solutions that are now in hand.

This work unit encompasses three separate tasks of which only one is funded due to current budget limitations.

STATUS

The final interim report covering the first year's work has been received. This document incorporates the fluid dynamic model, the development of the nonlinear differential and difference equations, for both the pancake and annular models, and the droplet evaporation and combustion analyses. Together with the "Description of Programs" and the computer decks, this completes the documentation of the first year's effort.

It is anticipated that the additional tasks to be performed under the contract will be completed on schedule and that both letter and intent of the contract will be satisfied. However, in view of a rather substantial success that has been achieved in developing an analytic tool for simulating rocket engine resonance, it is deemed essential that the work statement be supplemented at this time so as to include several additional verification experiments. This modification was initiated in September, formalized in November, and should be consummated sometime in the spring.

PUBLICATIONS

Contractor Reports, Interim and Final

1. Burstein, S. Z. and Chinitz, W., "Nonlinear Combustion Instability in Liquid-Propellant Rocket Motors," 4th Quarterly Report, Mathematical Applications Group, Inc., July 30, 1968.

2. Burstein, S. Z. and Chinitz, W., "Nonlinear Combustion Instability in Liquid-Propellant Rocket Motors," Interim Yearly Report, MAGI, October 1968.

3. Schechter, Harold J., "Nonlinear Combustion Instability in Liquid-Propellant Rocket Motors, Description of Programs," MAGI, October 18, 1968.

THE KINETICS OF OF_2 REACTIONS
NASA Work Unit 128-31-52-01-55
JPL 328-11101-1-3840

R. A. Rhein

OBJECTIVE

The long-range objective of this work unit is to provide fundamental information regarding the reaction kinetics of advanced spacecraft propellants. Those aspects of kinetics that relate to ignition of engines in space are of particular interest.

The initial studies are concentrating on the propellant combination $OF_2 + B_2H_6$ in those low-pressure, low-temperature regimes characteristic of preignition and/or near-ignition regimes. The current emphasis is on the formulation of a mechanism for the reaction that would yield species and rates for ignition as well as provide a basis for extrapolation to other state conditions.

STATUS

The resources allocated to this work unit were permanently reassigned as of October 25, 1968, and this unit will be terminated. However, a possible mechanism for the OF_2/B_2H_6 reaction that appears plausible and is consistent with measurements made to date has been formulated and listed in Table 1.

PUBLICATIONS

None

Table 1. Mechanism, Rate Constants, and Activation Energies

Reaction	Rate Constant at 300°K, Torr/Min	Activation Energy, K Cal
$B_2H_6 \xrightarrow{K_f} 2BH_3$	0.01386	28.4
$2BH_3 \xrightarrow{K_r} B_2H_6$	3.2×10^8	0.0
$BH_3 + OF_2 \xrightarrow{K_2} HF + HBOHF$	$10^{0.702}$	0.22
$HBOHF \xrightarrow{K_3} H_2 + BOF$	$10^{-0.429}$	10.93
$B_2H_6 + HBOHF \xrightarrow{K_4} FB_3H_4O + 2H_2$	$10^{0.96}$	0.0
$OF_2 + HBOHF \xrightarrow{K_5} FBO_2 + 2HF$	$10^{-7.55}$	>40.0
$FB_3H_4O + OF_2 \xrightarrow{K_6} HBOHF + BOF + H_2BF$	$10^{0.550}$	0.0
$FB_3H_4O \xrightarrow{K_7} BOF + 2(BH_2)$	$10^{-0.512}$	10.29
$B_2H_6 + FBO_2 \xrightarrow{K_8} FB_3H_4O_2 + H_2$	*	*
$OF_2 + FB_3H_4O_2 \xrightarrow{K_9} FBO_2 + BOF + H_2 + H_2BF$	$10^{0.99}$	1.05
$B_2H_6 + FB_3H_4O_2 \xrightarrow{K_{10}} FBO_2 + H_2 + 4(BH_2)$	$<10^{-10}$	**
$\xrightarrow{K_{11}} BOF + HBO + H_2 + 3(BH_2)$	$10^{-0.935}$	9.55

*Not determined, as these rate constants do not show up in the rate expressions $-d/dt\ (OF_2)$, $d/dt\ (B_2H_6)$, or $+d/dt\ (BF_8)$.

**Not found here.

Table 1 (contd)

Reaction	Rate Constant at 300°K, Torr/Min	Activation Energy, K Cal
$3BOF \xrightarrow{K_{12}} (BOF)_3$	*	*
$(BOF)_3 \xrightarrow{K_{13}} BF_3 + B_2O_3$	*	*
$(BH_2) + HF \xrightarrow{K_{14}} (BHF) + H_2$	$10^{0.9}$	**
$(BHF) + HF \xrightarrow{K_{15}} (BF_2) + H_2$	$10^{-1.98}$	**
$\xrightarrow{K_{16}} HBF_2 + 1/2\ H_2$	$10^{-1.02}$	**
$(BF_2) \xrightarrow{K_{17}} 1/2\ B_2F_4$	$10^{-1.8}$	**
$\longrightarrow 1/2\ (BF) + 1/2\ BF_3$	$10^{3.00}$	**
$(BH_2) \xrightarrow{K_{19}} (BH) + 1/2\ H_2$	*	**
$2H_2BF \xrightarrow{K_{20}} H_4B_2F_2$	*	**
$(BF_2) + HF \xrightarrow{K_{21}} BF_3 + 1/2\ H_2$	$10^{-1.9}$	**
$H_4B_2F_2 + H_2BF \xrightarrow{K_{22}} BF_3 + 2(BH_2) + H_2$	*	**

*Not determined, as these rate constants do not show up in the rate expressions $-d/dt\ (OF_2)$, $d/dt\ (B_2H_6)$, or $+d/dt\ (BF_8)$.

**Not found as only isothermal rate data for $+d/dt\ (BF_3)$ are available.

NOZZLE FLOW AND VACUUM EXHAUST TECHNOLOGY

NASA Work Unit 128-31-53-01-55

JPL 328-12101-x-3840

W. Simon

OBJECTIVE

The objective is to collect and formalize the analytical techniques necessary for design of nozzles and determination of plume characteristics including boundary layer effects, condensation, shock wave interaction, heat transfer, and the effects of plume impingement. This effort is to augment and consolidate the existing analytical tools into a useful form for spacecraft applications.

STATUS

The literature on nozzle exhaust plume analysis has been extensively reviewed. A nozzle plume calculation program has been obtained from Lockheed Missiles and Space Company and checked out on the JPL computing facilities. Test plans have been made to experimentally measure small nozzle boundary layer and plume characteristics in the JPL 25-foot simulator and the JPL MOLSINK facility. Calibration of both facilities is now in progress.

PLANNED ACTIVITY

After the calibrations of the simulator and the MOLSINK have been completed, nozzles will be fabricated and tested. Plume characteristics experimentally obtained will be checked against analytical predictions. Plume analysis methods will be modified, if necessary, and recommended for future use. Review of the literature and technical information exchange with the investigators in the field will continue throughout the next period.

PUBLICATIONS

None

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REDUCTION OF TURBULENT HEAT TRANSFER IN NOZZLES

NASA Work Unit 128-31-54-02-55

JPL 328-11001-0-3830

P. F. Massier

OBJECTIVE

The primary objectives of this task are: (1) to determine the parameters that govern the reduction in turbulent heat transfer that has been found to occur in supersonic nozzle investigations, including rocket engine tests, and (2) to establish the limiting conditions for which this phenomenon takes place so that it may be used advantageously for the design of rocket nozzles that may be either cooled, uncooled, or ablative.

A description of the four nozzles and their contours used in this investigation appears in JPL TM 33-322, Vol. II, July 1 - December 31, 1966, pp. 365-367. Measurements that have been obtained have contributed to establishing realistic predictions of flows through convergent-divergent nozzles. This information has considerable bearing on the performance standards effort of the Inter-Agency Chemical Rocket Propulsion Group. Prior publications associated with the investigation appear in JPL TM 33-353, Vol. II, January 1 - July 1, 1967, pp. 373-376; JPL R&D Program Document 701-6, Vol. II, July 1 - December 31, 1967, pp. 459-462; and JPL R&D Program Document 701-15, Vol. II, January 1 - June 30, 1968.

STATUS

During FY 69 the nozzle which has 10° half-angle of convergence and divergence is being investigated. This nozzle represents the low-angle end of the spectrum of conical angles and resembles a configuration that would be used for engines in which the combustion chamber is an integral part of the convergent portion of the nozzle. Simultaneously, heat transfer and pressure measurements are obtained along the wall of a second-throat diffuser attached to the exit end of the convergent portion of the nozzle. The diffuser investigation supplements the diffuser performance effort that was completed several years ago at JPL. Heat transfer data pertaining to exhaust diffusers are virtually unavailable even though they are used extensively during ground level tests of rocket engines. Some wall static pressure and heat transfer measurements have been obtained and are reported in Refs. 1 and 2. These results contain information on single shock wave and multiple shock wave boundary layer interaction where the heat transfer can be very high locally.

Boundary layer measurements have been made at three locations in the convergent section of the 10°-10° nozzle with heated air operation. The stagnation temperature was 1500°R and two stagnation pressures were investigated, 20 and 150 psia. At the lower stagnation pressure or Reynolds number where a 50% reduction in heat transfer was found, both the velocity and temperature profiles become laminar-like near the wall. Consequently, the turbulent transport of heat and momentum is less, and this is consistent with the observed reduction in heat transfer. Farther away from the wall some turbulent transport still exists in the outer part of the boundary layer. Apparently, the laminarization process proceeds outward from the wall and is associated with the suppression of the production of turbulence in the wall vicinity in an accelerating flow. Laminarization occurred when the parameter $K = \nu_e/u_e^2 \, (du_e/dx)$ exceeded about 2×10^{-6}. At the higher stagnation pressure, the boundary layer remained turbulent so that it was also possible to study the structure of a turbulent boundary layer and how it is affected by acceleration and wall cooling. A paper on cold-flow boundary layer measurements previously made has been submitted and accepted for publication in the AIAA Journal (Ref. 3).

To complete the investigation on the laminarization process and the history of the boundary layer development, the boundary layer probes, are being positioned at a fourth and last location in the convergent section. Boundary layer measurements at this new location are planned next.

To gain an understanding of the boundary layer structure at the exit of a supersonic nozzle, boundary layer measurements also have been made in the divergent section of the 10°-10° nozzle at a location where the Mach number is about 3.5. These measurements, which are of interest to the performance standards effort of the Inter-Agency Chemical Rocket Propulsion Group in establishing boundary layer momentum losses in nozzles, were obtained for cold-flow and heated-flow operation.

The paper on transonic flow measurements in another nozzle (45°-15°) has been submitted and accepted for publication in the AIAA Journal (Ref. 4).

A paper has also been prepared on the effect of cooling on the structure of a low-speed, turbulent boundary layer (Ref. 5). In this paper, measured velocity and temperature profiles and friction coefficients are discussed in connection with semiempirical turbulent boundary layer theories. These measurements were made in the tube upstream of the nozzle, where the free-stream velocity variation was negligible, in order to appraise the effect of cooling. Satisfactory agreement was found between the magnitude of the increase of the friction coefficient found with cooling and predicted values. Fair agreement was found between the measured profiles and predicted profiles. This information, along with the cold flow nozzle boundary layer measurements, Ref. 3, is now being used to appraise the simultaneous effect of cooling and acceleration on the structure of the boundary layer in the nozzle.

REFERENCES

1. Back, L. H., Cuffel, R. F., and Massier, P. F., "Pressure and Heat Transfer Distributions in a Duct, a Supersonic Nozzle and a Diffuser," SPS 37-49, Vol. III, February 29, 1968.

2. Back, L. H., Cuffel, R. F., and Massier, P. F., "Pressure and Heat Transfer Distribution in a Duct, a Supersonic Nozzle and a Diffuser," SPS 37-50, Vol. III, April 30, 1968.

3. Back. L. H., Cuffel, R. F., and Massier, P. F., "Laminarization of a Turbulent Boundary Layer in Nozzle Flow," to be published in the AIAA Journal.

4. Cuffel, R. F., Back, L. H., and Massier, P. F., "The Transonic Flow Field in a Supersonic Nozzle with Small Throat Radius of Curvature," to be published in the AIAA Journal.

5. Back. L. H., Cuffel, R. F., and Massier, P. F., "Effect of Cooling on the Structure of a Low-Speed, Turbulent Boundary Layer," paper prepared.

PUBLICATIONS

None

SOLID PROPULSION TECHNOLOGY PROGRAM (128-32)

ADVANCED TECHNOLOGY CONTRACT MANAGEMENT

NASA Work Unit 128-32-20-01-55

JPL 328-20101-2-3810

W. Gin

OBJECTIVE

The unit objective is to provide technical management of contracts and grants which are under the program management of NASA Office of Advance Research and Technology, Solid Propulsion Supporting Research and Technology, Code RPS.

STATUS

Under this task, the following contracts and grants were technically managed for RPS during this report period:

1. "Chemistry of Solid Propellant Chemistry," NGR 45-003-019, University of Utah
2. "Nozzle Transition Arc Ratio," NAS 7-706, Thiokol-Wasatch
3. "Solid Propellant Explosive Effects," NAS 7-480, SRI
4. "Heterogeneous Combustion Kinetics," NAS 7-481, UACRL
5. "Advanced Fuel Synthesis," NAS 7-551, Unified Sciences, Inc.
6. "NP Stability Evaluation," NAS 7-561, Midwest Research, Inc.
7. "High Energy Propellants for Controllable Motors," NAS 7-661, Rocketdyne
8. "Laser Pyrotechnic Ignition," NAS 7-670, Space Ordnance Systems
9. "Metal Combustion," WO 6032, Naval Weapons Center
10. "Binder Model System," NAS 7-689, SRT
11. "Fuel-Oxidizer Concept," NAS 7-655, Rocketdyne
12. "Advanced Binder Synthesis," NAS 7-669, Thiokol-Elkton.

An oral semiannual report was made on all contracts and grants being managed by JPL to NASA headquarters RP personnel and NASA Center representatives on November 21, 1968, at JPL.

PROJECTED ACTION

During the next report period, it is anticipated that contracted work will be initiated on the investigation of burning rate modification for Saturethane propellants, and the study of novel solid or hybrid propulsion systems for ten-year spacecraft missions to the outer planets.

PUBLICATIONS

None

ROCKET MATERIALS AND COMPONENT DEVELOPMENT

NASA Work Unit 128-32-36-01-55

JPL 328-20201-2-3810

R. L. Bailey
R. A. Grippi, Jr.

OBJECTIVE

The long-range objective of this work is to evaluate new and promising materials for possible solid-propellant motor component applications, such as nozzles, chamber insulation, TVC systems, and low-acceleration, long-burning-time motor systems. Fabrication techniques and component design, using the more promising materials, will be evaluated.

STATUS

LMH_2 Nozzle Performance

The final test results of the ARC and Hercules LMH_2 propellant systems, conducted at AEDC, Tennessee, have been received. Nozzle performance analysis of the tests is currently underway.

Multicomponent Test Stand

Initial axial calibration tests of the multicomponent test stand indicated that several side load interactions were occuring. It was determined that a modified axial calibration loading technique would reduce the interactions. Revere Corporation fabricated the required hardware and reinstalled it on the test stand. The stand was then recalibrated. The calibration data showed that the modified loading technique reduced the interactions to acceptable limits.

Sterilization Materials

Sterilization tests, including motor firings, are continuing on candidate nozzle materials. The most promising material tested to date is Narmco's 4085, which is a high-purity silica fabric with an unfilled, modified, phenolic nitrile resin system. The nozzle exhibited a low charring rate and a negligible erosion rate when tested with a nonaluminized, sterilizable propellant system.

Long-Burning-Time Nozzle Materials

Materials felt to be compatible with long burning (200 sec), low acceleration (1 g) motors are being evaluated. Promising candidate nozzle materials for this application are the reimpregnated fibrous graphites. Procurement was initiated for small test nozzles and insulation pieces fabricated from Carbitex and Fibergraph. These test articles have been received and are scheduled for testing, using the UTM-12 motor. Material heat transfer rate data will be obtained from these tests.

Ethylene Propylene Insulation

An ethylene-propylene terpolymer rubber (EPR) chamber insulation material is being evaluated. This EPR material is designated GTR 4010 and is produced by the General Tire and Rubber Company. GTR 4010 will be useful in high-performance rocket motors, since both the density and thermal diffusivity are 20% lower than nitrile butadiene rubber (NBR) insulators.

A technique has been established for bonding the EPR insulator to steel or titanium substrates. This process uses a two-coat primer and vulcanizing system. This system has been proven effective by peel tests. Material failure always occurs in the insulation material. No bond interface failures have been observed.

Eight 5 in. diameter by 6 in. long heavyweight rocket motors have been insulated, using a hand lay-up technique, with GTR 4010. Two of the motors have been successfully loaded with a fully case-bonded, end-burning grain configuration. The Saturethane propellant was bonded directly to the EPR insulator without a liner interface. One motor, containing 3.2 lb of propellant, has been successfully static tested. The unit operated at a pressure of 185 psia for 24 seconds. This test demonstrated the adequacy of both the insulation to case bonding and Saturethane propellant to EPR insulation bonding techniques.

Noncoating Nozzle Inserts

Ballistic test firings of the Saturethane propellant (4600° F) at low motor operating pressures result in aluminum oxide coating of the nozzle throat. The throat coating results in inaccurate ballistic data calculations. The conventional ballistic check motor used a high-heat-sink type throat insert, which kept the throat cool and allowed the aluminum oxide to adhere to the surface. A series of tests is under way using small graphite inserts backed up with low thermal conductivity material (asbestos/phenolic). This technique keeps the nozzle throat hot so that the aluminum oxide will not adhere to the graphite throat. Preliminary tests have shown that this technique can reduce the postfire throat area coating from 10% to 1% in some configurations. Several of the tests have indicated that the coating thickness is sensitive to the graphite throat insert geometry. Further tests will define and evaluate this parameter.

Pyrolytic Graphite Coated Nozzle Inserts

A second approach to the coating problem is the use of pyrolytic graphite (PG) coated inserts. Pyrolytic graphite is a highly anisotropic material, a good conductor along the grain, and a good insulator against the grain. The use of a graphite insert coated with PG on the gas side surface turns the PG coating into a "heat-barrier." This scheme allows the nozzle throat to operate hot. One test has been conducted using the PG-coated nozzle. The motor contained a polyurethane aluminized propellant (5200° F) and operated for 8 seconds with an initial and final pressure of 150 and 80 psia respectively. Postfire measurement of the nozzle throat indicated a coating of less than 1%.

Long-Burning-Time Motor

A motor design has been established to produce a long-burning-time, low-pressure, low-acceleration rocket motor using existing flight-weight Applications Technology Satellite (ATS) apogee motor chamber hardware. Two designs, one using the present ATS apogee motor propellant system (polyurethane-JPL 540) and a second design using a slower burning Saturethane propellant, were established. The designs consist of a flight-weight titanium chamber, an ablative or radiation-cooled fibrous-graphite nozzle, ethylene-propylene rubber insulation and a fully case-bonded end-burning grain configuration.

PLANNED ACTIVITY

Multicomponent Test Stand

It is planned to conduct a hot firing on the multicomponent test stand as a final acceptance check for the stand. After the test stand has been accepted, it is planned to conduct some thrust misalignment firings on it.

Sterilization Materials

Development of advanced insulation and nozzle materials will continue, particularly with respect to motor sterilization requirements. The Narmco 4085 material will be evaluated in a more meaningful nozzle size. Also, the carbon reinforced counterpart of this material will be evaluated for use on aluminized sterilizable propellant systems.

Long-Burning-Time Nozzle Materials

If the initial tests on the Carbitex and Fibergraph materials are successful, then flight-weight nozzle designs with this material will be tested. The main concern with the use of this material in a nozzle is a suitable motor attachment technique due to its high heat transfer characteristics. The heat transfer data obtained from the UTM-12 tests will be utilized in designing the nozzle attachment ring.

Ethylene Propylene Insulation

Further evaluation of the GTR 4010 EPR is planned to determine the best propellant-to-insulation bonding technique for the polyurethane-JPL 540 and Saturethane systems in conventional and sterilizable (Saturethane only) applications. A secondary insulation-to-case bonding system will be evaluated. Several Syncom rocket motor cases (60 lb propellant) will be insulated and tested.

Noncoating Nozzle Inserts

Hot motor firings will be conducted with both small graphite inserts and PG-coated nozzles using the two current JPL propellant systems. The PG nozzle will also be evaluated for restart application, since it will be refired numerous times until the coating erodes beyond use.

Long-Burning-Time Motor

Further design and analysis will be performed on the ATS end burner. Several small motor tests will be conducted to evaluate new concepts and materials to be used in the ATS motor. Procurement will be initiated for motor components (nozzle, insulation, auxiliary hardware, etc.) and services.

PUBLICATIONS

None

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PROPELLANT FUELS

NASA Work Unit 128-32-40-01-55

JPL 328-23301-2-3810

F. A. Anderson
R. A. McKay

OBJECTIVE

The long-range objective of this work unit is to develop a propellant family based on beryllium and on LMH-2 for use in spacecraft midcourse and terminal maneuver motors. Included in this objective is the performance evaluation of these propellant systems as they become available. An intermediate objective is to provide a self-contained in-house facility at JPL for small-scale development and testing of nondetonatable beryllium propellants. A facility design goal is to provide for complete containment of all accidental emission from deflagrating propellant.

STATUS

JPL Beryllium Facility

Construction of the proposed JPL beryllium facility was started July 9, 1968. At the end of this report period, the construction is estimated at 80% complete. The concrete block walls are laid and all concrete floors and pads are poured. The first-floor roof decking is nearly finished and the caulking operations are proceeding. The second-floor roof joists are in place, but the roof remains open to allow installation of the heavy or large equipment on the second floor. The exterior utilities are complete, interior mezzanine plumbing is approximately 75% complete, and the rough electrical work is approximately 97% complete. The completion date for the construction is scheduled for January 6, 1969, but early or mid-February is probably more realistic.

The laboratory flume hoods, the glove boxes, and the propellant conditioning chambers are on order. The procurement for the modifications and installation of the existing motor test tank is being processed. The procurement of a propellant mixer was delayed but will now proceed.

Propellant Performance Evaluation

The results from the BATES motor firings of the double-base/Beane propellants have been evaluated. As was reported in the previous report, these eight motors were fired at AEDC under simulated altitude conditions. All eight motors were fired successfully. The four motors, loaded with ARCOCEL-332A-propellant, yielded a delivered specific impulse of 91% (average of the four motors). The average delivered I_{sp} for the four motors loaded with VIY propellant, was 92% of theoretical. The theoretical I_{sp} refers to the theoretical specific impulse calculated at the motor firing conditions and an expansion ratio of 50/1. These eight motor firings concluded the planned BATES motor tests of Beane propellant. A report of this program is in process. No further BATES motor testing of propellants is planned until such time as improved or new propellant formulations become available.

Meetings and Symposia Papers

It is planned to present a paper on high energy fuels at the 4th ICRPG Solid Propulsion Conference to be held in Chicago in May 1969.

PUBLICATIONS

JPL Technical Reports

1. Anderson, Floyd A., and Bailey, Richard L., "Performance Evaluation of Beryllium Propellant Systems," TR 32-1272, June 1968. (Confidential)

PROPELLANT BINDER
NASA Work Unit 128-32-40-02-55
JPL 328-21501-2-3810
H. E. Marsh, Jr.

OBJECTIVES

The primary objective of this program is to develop a new propellant binder suitable for advanced solid propellants for space application. Additional objectives are evaluation of new binder curing reactions and investigation of model polymerization systems leading to the determination of the functionality of reactive group-terminated prepolymers.

The program consists of two parts: (1) studies by Union Carbide Corporation, Chemicals and Plastics Division, under JPL Contract 951210, and (2) JPL research.

STATUS

Union Carbide Contractual Research

Work on this program during the last six months was conducted in the following areas: (1) production of a scaled-up quantity of the ethylene-neohexene prepolymer for characterization and curing studies, (2) studies of the separation of the desired difunctional fraction of raw prepolymer from the lower-functional fractions, (3) investigation of low-temperature property improvement by the substitution of other co-monomers for neohexene, and (4) writing of a triennial report.

At JPL's direction, a large quantity of ethylene/neohexene prepolymer was synthesized for evaluation as a binder material. Two runs were made in the Unit II continuous stirred autoclave reactor, producing 106 and 549 grams of crude, respectively. The new telagen, methyl α-bromoisobutyrate, which is the best found so far, was used. Properties of interest for the two products were: molecular weight, 800 and 883; average functionality, 1.87 and 1.89; and viscosity, 2600 and 2750 centipoise.

Both column chromatography and liquid-liquid countercurrent distribution were found to be effective in separating difunctional fractions from fractions consisting mostly of mono- and zero-functional polymer. Crude prepolymer samples of 1.24 and 1.34 average functionality were upgraded to 2.1 and 1.8 by the two methods. If necessary, liquid-liquid extraction can be applied practically in a production process. A qualitative method of functionality distribution analysis, based on thin layer chromatography, was developed.

Based on the theory that improved polymer chain flexibility would be obtained if the pendant side chains were linear instead of bulky (as in the case of neohexene), propylene was substituted for neohexene as co-monomer with ethylene. The expected results were evident in a decrease in viscosity of almost one magnitude and a lowering of glass transition temperature by about 20°C. Limited tests with the higher homologues (1-butene, 1-pentene, and 1-hexene) gave even better results.

A report summarizing the first three years' work on this program, ending September 30, 1968, has been written and submitted. After review, it will be printed by JPL and distributed to from 75 to 100 interested parties in the industry.

JPL Research

Work is continuing with polymer network theory, both to extend our understanding of cross-linked polymers and to provide useful tools for propellant binder technology. These studies are being coordinated with an experimental program that has the objective of developing a method for determining the functionality distribution of prepolymers based on network theory. This latter program is being done by Stanford Research Institute under an Advanced Technology Contract NAS 7-689, entitled Binder Model System (Work Unit 128-32-40-03-56).

Based on Flory's statistical method of predicting polymer network structure, equations for calculating systems containing mono-, di-, and trifunctional components of both chemical polarities have been derived. This is a general case which covers all simpler combinations. Comparison of these equations with Stockmayer's equation, which is more general in terms of functionality combinations, but restricted to incipient gelation conditions only, shows the two theoretical routes to be equivalent for all cases except those which have trifunctional components of both polarities. A fundamental experiment, using model compounds and esterification as the polymerization reaction, is under way to determine which prediction is correct.

PUBLICATIONS

Meetings and Symposia Papers

1. Marsh, H. E. Jr., "Recent Developments in Solid Propellant Binders Symposium: "Polymers in Space Research" sponsored by The Polymer Group of the Southern California Section of American Chemical Society and the Jet Propulsion Laboratory, July 15-17, 1968.

Contractor Reports, Interim and Final

1. Potts, J. E., "Saturated Hydrocarbon Polymeric Binder for Advanced Solid Propellant and Hybrid Solid Grains," Quarterly Report No. 10, Union Carbide, Corporation, Chemicals and Plastics Division, Bound Brook, N. J., April 1, 1968 - June 30, 1968.

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HIGH ENERGY PROPELLANT

NASA Work Unit 128-32-41-01-55

JPL 328-20801-2-3810

F. A. Anderson

OBJECTIVE

The objective of this work is to investigate classes of high-energy propellants based on NP, HAP, and HP_2 for use in spacecraft motors.

STATUS

There is no work being done at the present time involving either NP or HP_2, and no future work is being planned with either of these two oxidizers. The present effort is being concentrated on HAP (hydroxyl ammonium perchlorate) in an attempt to characterize the HAP oxidizer and develop a propellant system using it.

As was stated in the previous report, HAP is extremely sensitive to moisture; therefore, all work involving HAP must be done under very carefully controlled atmospheric conditions. The tolerable moisture limits have been established. If the HAP is allowed to come in contact with moist air, however, it can be redried without deleterious effects on the HAP.

HAP's thermal properties have been fairly well established. Its melting point is at approximately 80° C, and it begins to decompose at 197° C.

HAP is considerably more sensitive to impact than ammonium perchlorate (AP). HAP detonates at a drop height of approximately 17 in. with a four-pound ball as compared to 33 in. for AP under the same conditions.

Compatibility tests between HAP and potential binder ingredients have been conducted, and a number of candidate ingredients selected. Based upon these selected candidate ingredients which appear to be compatible with the oxidizer, a reference HAP propellant formulation has been established. This formulation contains 80% solids by weight. Several 10-gram mixes have been made as part of a preliminary processing study. It is hoped that with improved processing techniques the total solids loading can be increased to at least 84%. While studies are continuing with the current candidate formulation, other potential binder ingredients are being investigated.

PUBLICATIONS

None

PROPELLANT IMPROVEMENT AND CHARACTERIZATION

NASA Work Unit 128-32-42-03-55

JPL 328-21701-2-3810

C. L. Robillard

OBJECTIVE

The objective is to improve and characterize the performance, ballistics, mechanical properties, processing, and ingredient quality control on newly developed propellants or of existing propellants for new applications.

STATUS

Low-Modulus Aluminized Propellant

A low-modulus, high-elongation Saturethane propellant is being developed for use in a case-bonded end-burning motor. Saturated binder (Saturethane) propellants exhibit inherently low burning rates at 15 to 500 psi; therefore, they are expecially desirable for use in low-g applications such as spacecraft orbit-retro motors. Aluminized propellants with elongations of approximately 85% at tensile strengths of 150 to 400 psi have already been obtained. The objective is to obtain elongations of over 100% at tensile strengths of 100 to 150 psi and to achieve these properties with a low-temperature cure.

Heat-Sterilizable Propellants

Previously, several candidate solid propellants were developed and evaluated for use in heat-sterilizable propulsion systems as reported in Ref. 1. The existing type approval specification requires that a propulsion subsystem survive six 53-hr heat cycles at an equilibrium temperature of 275°F. Several 2-lb motors containing saturated binder (Saturethane) propellant, fully case bonded, were successfully fired after being subjected to these six 53-hr cycles at 275°F.

All of the work reported in Ref. 1 was performed using one lot of oxidizer. Subsequent work has shown that propellant stability is variable and that this variable propellant stability is the consequence of sample-to-sample (and lot-to-lot) variations in ammonium perchlorate (AP) characteristics. To review, the propellant survival has varied from none to ten 53-hr cycles at 275°F. One of the chief propellant variables is the AP itself; survival of a low-modulus propellant has been increased from 0 to 6 cycles by changing the oxidizer lot alone. It has been found that propellant stability with a given lot of oxidizer can be improved by grinding or sieving the oxidizer to smaller particle sizes, or by increasing the propellant modulus (primarily by increasing the binder cure ratios). In addition, it has been found that there is a very strong temperature dependence for the net reaction in the propellant, and a weak dependence on x-radiation dosage for net reaction in the propellant. Raising the temperature 10°C (from 125 to 135°C) decreases the time to failure by a factor of 4.

Table 1 shows many of the AP and propellant treatments that have been attempted in order to control propellant stability. Of these, only grinding and sieving the oxidizer and increasing the degree of binder cross-linking have improved propellant stability.

Curious but true, there is no test which correlates AP characteristics with propellant stability. In particular, no correlation exists between AP stability, in terms of DSC exotherm or high-temperature weight loss, and propellant stability. Several of the AP treatments shown in Table 1, i. e., recrystallization and cocrystallization, have made significant improvements in AP stability, but no improvements in propellant stability. And finally, the effect on propellant stability of treating AP in some given manner varies among AP samples.

REFERENCE

1. Robillard, C. L., Dowler, W. L., Shafer, J. I., and Udlock, D. E., "Heat Sterilizable Solid Propellants," JPL TR 32-1187, October 1, 1967.

PUBLICATIONS

None

Table 1. AP and Propellant Treatments

A.	**AP TREATMENTS**
	Drying (<0.003% Total H_2O)
	Preheating to 275°F
	Coating (PTFEO)
	Grinding
	Sieving
	Recrystallizing
	Cocrystallizing
	NH_3 Treatment
	Slurrying with NaCl
B.	**PROPELLANT TREATMENTS**
	Antioxidants
	Wetting Agents
	Cure Ratios

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RHEOLOGICAL PROPERTIES OF PROPELLANTS

NASA Work Unit 128-32-43-01-55

JPL 328-20301-1-3820

R. F. Landel
R. F. Fedors
B. G. Moser

OBJECTIVE

The long-range objective of this work unit is to evolve and substantiate a theory of viscoelastic behavior that will permit the prediction of the response of a solid propellant to a generalized stress-time-temperature field. This requires studies of:

(1) Finite deformation under (at least) unequal biaxial loads.

(2) The origin of rupture and its dependence on factors such as time, temperature, crosslink density, and type of polymer.

(3) Effects of the type and concentration of filler particles on the rheology of filled systems over this same range of small deformation, finite deformation, and ultimate behavior.

Once a general understanding of these areas is obtained, attention will be turned to more complex systems.

STATUS

Work on finite deformation behavior has been set aside for the time being to concentrate on the viscosity of slurries and the uniaxial behavior of filled rubber. A new parallel plate viscometer for measurements on low viscosity liquids is under construction. The movable upper plate is attached to a long counter-balanced arm so that the stress applied to specimens can be varied over very wide ranges. The plate displacement is monitored with a set of linear variable differential transformers. The whole apparatus can be placed in an existing air thermostat for studies as a function of temperature. Considerable difficulty has been encountered with the readout system and the computer program to handle the output, but these problems are essentially all resolved and measurements should commence early in the new year. Initial measurements will be on slurries prepared from blends of various sizes for comparison with and extension of existing literature data and also for comparison with the Landel, Moser, Bauman (LMB) equation for relative viscosity.

As for studies on elastomer, essentially all of the time has been occupied with experimental measurements of styrene-butadiene rubber (SBR) filled with glass beads, SBR filled with carbon black, and unfilled natural rubber, but the results have not been reduced to the point where a comprehensive report can be given. The SBR-beads system is an extension of earlier work to higher glass bead concentrations (from 35 up to 50 volume %), and to a range of bead sizes (diameters from 0.001 to 0.018 in.), plus one system containing a blend of the smallest and largest beads. These studies are intended as a test of our theory for the behavior of easily dewetted systems (Space Programs Summary 37-41, Vol. IV). In this theory, the void which develops on dewetting was assumed to be conical, for simplicity. An extension of the theory has now been developed to allow for a more realistic cavity shape — A paraboloid of revolution (Space Programs Summary 37-54, Vol. III). The original, admittedly over-simplified, cone model gave the following equation for the relative modulus:

$$E_{rel} = \left\{ \frac{\phi_m}{\phi_m - \frac{\phi_o}{1 + C}} \right\}^2$$

where ϕ_m is the maximum possible volumetric loading, ϕ_o is the volumetric loading used and C is a function which depends on ϕ_o, on the applied strain, and on a constant k whose value can be determined by measuring the volume increase which occurs as the specimen is strained. The corresponding expression in the modified theory is

$$E_{rel} = \left\{ \frac{\phi_m}{\phi_m - \phi_o\left[\left(1 + C_1\right) - \left(C_1^2 + 2C_1\right)^{1/2}\right]} \right\}^{2.5}$$

where C_1 again depends on ϕ_o and the strain plus a similar constant k_1, also determinable from volume change measurements. However $k_1 \neq k$. Yet, it turns out that when $k_1 = 1.93k$ (or $C_1 = 1.93C$) then the volume changes predicted by either model are not markedly different and hence either can be used to describe experimental data over limited ranges. The corresponding relative modulus versus strain expressions are also very similar for systems which dewet easily, except in the region of relatively high loadings and small strains, or for systems which do not dewet easily. Unfortunately, reliable data in this region are not available. For the SBR glass bead system, it appears that either model is acceptable.

Because the SBR-carbon black system is one which will not dewet so easily, experiments were set up to measure its tensile and volumetric behavior. Thermax, a rather poorly reinforcing block was used; ϕ_o ranges from 0 to 40 volume percent. It is anticipated that the results will help distinguish between the two models.

The natural rubber specimens were obtained from Dr. P. Thirion, of the French Rubber Institute of Paris, France. Much information is available on these identical specimens from a cooperative program being carried on by Dr. Thirion, Prof. J. D. Ferry at the University of Wisconsin, and Prof. D. J. Plazek of the University of Pitsburgh. In particular, Prof. Ferry has studied the dynamic mechanical properties of this material, and we plan to compare his data obtained at small strains with the rupture data according to our recently proposed theory (Ref. 1).

Creep data previously obtained on the system polyisobutylene-glass beads, in which the polymer is uncrosslinked, have been reanalyzed. An apparently anomalous dependence of the tensile viscosity has been shown to be a direct consequence of the time dependence of the system. Even in unfilled polymers, there is a dearth of information on tensile viscosity. The relative viscosities may not follow the LMB equation, originally derived for nonviscoelastic fluids, but the results are not sufficiently accurate to be sure. If this is true, it could be an important question in understanding flow behavior of solid propellants during casting.

REFERENCES

1. Landel, R. F., and Fedors, R. F., "Rupture of Amorphous Unfilled Polymers in Fracture Processes in Polymeric Solids," Chapter IIIB, pp. 408-413 and Figure IIIB-26, Rosen, B., editor, J. Wiley and Sons, New York, (1964).

PUBLICATIONS

Meeting and Symposium Papers

1. Landel, R. F., "The Rheology of a Model Filled System: Polyisobutylene-Glass Beads II. Behavior at Long Times," Fifth International Congress of Rheology, Kyoto, Japan, October 1968.

DEGRADATION MECHANISMS

NASA Work Unit 128-32-43-02-55

JPL 328-20401-1-3820

J. D. Ingham
D. D. Lawson
J. A. Miller

OBJECTIVE

The objective of this work unit includes (1) studies of the mechanisms of thermal degradation of polymers, (2) investigation of the synthesis of new polymers as potential binders, and (3) determination of the molecular structure of polymers by NMR spectrometry and other methods.

STATUS

Polymer Degradation

To attempt to improve the thermal sterilizability of saturated poly-(butadiene)-urethane (SPBU) propellant, some oxidizer was coated with poly-(tetrafluoroethylene oxide) before formulation. Results to data indicate that sterilizability has not been significantly improved, but that mechanical properties are better than for uncoated oxidizer. An AT contract has been negotiated with Rocketdyne ($20, 000) to initiate work on determination of the chemical interaction of saturated hydrocarbon binder materials with oxidizer.

Polymer Synthesis

Several cationically polymerized isobutylenes have been prepared and submitted to Section 328 for proton NMR analysis. Although spectra have been obtained that indicate the structure of some terminal groups, quantitative results are not yet available. An isobutylene polymer — one that appears to have a relatively high concentration of terminally unsaturated end groups and a molecular weight in the desired range (1000-2000) — was prepared by heterogeneous catalysis with use of molecular sieves as catalyst.

Polymer Molecular Structure

Polymers (perfluorobutadienes) have been characterized by F^{19} nuclear magnetic resonance and infrared spectroscopy. A method of estimating solubility parameters from refractive index measurements has been developed and evaluated for a large number of different types of polymers.

FUTURE ACTIVITY

Results derived from the AT contract on hydrocarbon-oxidizer interactions will be analyzed to determine and implement appropriate structural modifications, or stabilizer additions, that should inhibit solid propellant degradation. Polymers prepared by heterogeneous cationic polymerization will be characterized with respect to terminal groups, and the effect of temperature on heterogeneous polymerization will be investigated. NMR structural characteristics and low-temperature properties of other fluorocarbon and hydrocarbon polymers will be determined within the next reporting period.

PUBLICATIONS

Meetings and Symposia Papers

1. Toy, M. S., and Lawson, D. D., "Poly(perfluorobutadiene) III: Homogeneous Polymerization in Bulk," 156th National ACS Meeting, Atlantic City, September 1968.

Open Literature

1. Ingham, J. D., "Free-Radical Spin Labels for Macromolecules," Macromol, J., Sci., Rev., C-2, 279 (1968).
2. Lawson, D. D., "Characterization of the Diastereoisomers of 2, 4-Dimethyl-3-Oxapentane-1, 5-Diol," J. Chem. Eng. Data, 13, 575 (1968).
3. Toy, M. S., and Lawson, D. D., "Poly(perfluorobutadiene) I: Polymerization of Perfluorobutadiene by Nitroxide and Peroxide," Polymer Letters, 6, 639 (1968).

SPS Contributions

1. Ingham, J. D., "Saturated Hydrocarbon Prepolymers," 37-52, Vol. III, June-July 1968.

2. Lawson, D. D., and Ingham, J. D., "Estimation of Solubility Parameters from Refractive Index Data," 37-53-, Vol. III, August-September 1968.

PROPELLANT STRESS ANALYSIS

NASA Work Unit 128-32-43-03-55

JPL 328-20501-1-3820

G. W. Lewis
E. N. Duran

OBJECTIVE

The long-range objective of this work unit is to integrate material characterization studies, experimental and analytical stress analysis techniques, and to evolve satisfactory failure criteria into a rational designer-usable stress analysis. The short-range objectives are the improvement of the tools and techniques of experimental stress analysis, the adaptation of the JPL in-house Structural Analysis and Matrix Interpretive System (SAMIS) Program to propellant grain analysis, the continuing study of finite deformation theory, and the development of satisfactory failure criteria for elastomeric materials.

STATUS

Motor Modeling

The use of experimental techniques to predict the state of stress within flight motors continues with the use of live propellant and stress freezing epoxy. The propellant motors being studied are the case-bonded, end-burning deorbit motors currently under development. The experimental techniques used are case-mounted strain gage rosettes to measure the strain at points of interest. The first two motors have completed their cycle and work has started on instrumenting a second set of motors. Initially, results have given an insight into the role of the propellant in reinforcing the motor case at low temperatures.

A salvaged quarter-scale Surveyor motor case has been used for the stress freezing study. The internal configuration has been simplified from a seven-point star to a cylinder, and a large front burning face has been introduced. These changes will make the photoelastic analysis simpler and the large burning area will introduce the problem of the end burning motor. At present, the photoelastic material is being evaluated.

Stress Transducer Development

A contract has been let to Whittaker Corporation in Pasadena to perform the first stage of improving the thermal characteristics of the JPL-developed miniature stress transducer.

ELAS Computer Program

The present two- and three-dimensional elastic programs are being used to predict the results of the motor modeling studies on the epoxy and end-burning propellant grains. Verification is also being sought for determination of the proper parameters, i.e., Young's modulus and Poisson's ratio, for use in unknown cases.

Work has been completed in expanding the two-dimensional automatic mesh generation program to the three-dimensional case. The result is FEDGE (Finite Element Data Generator) which generates a three-dimensional mesh for use directly in ELAS. Once the initial mesh is generated, changes in design, materials, etc., can be made with ease. Advantages of this automation are:

(1) Mesh generation that would require 30 man-days when manually prepared would take 1 man-day when FEDGE prepared.

(2) Once the mesh is generated, it can be used for a variety of problems by simply changing the input cards.

(3) Design changes can be incorporated with considerable saving time and expense.

(4) The probability of human error involved in the preparation of data is greatly reduced.

(5) The overall accuracy of ELAS is increased by the use of a regular mesh which best fits the boundary conditions.

FUTURE ACTIVITY

The motor modeling studies will continue until good correlation is found between experimental and analytical methods. Design changes on the case bonded, end-burning motors will be evaluated and experimentation will continue on propellant tests to verify these evaluations.

At the completion of the first stage of the stress transducer contract, a second stage will be initiated to improve the electrical and packaging design.

The ELAS program will be extended into the region of linear viscoelastic properties.

PUBLICATIONS

Meetings and Symposia Papers

1. Duran, E. N., "Stress Analysis in a Model Motor Program," ICRPG Mechanical Behavior Working Group, 7th Annual Meeting, November 14-15, 1968.

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SOLID ROCKET COMBUSTION STUDIES

NASA Work Unit 128-32-50-01-55

JPL 328-22701-2-3810

R. Klaus
D. Norton
W. Dowler

OBJECTIVE

The objective of this work unit is to develop a sound theoretical understanding of the sources of combustion inefficiencies peculiar to solid rockets and to develop computer programs to predict these effects.

STATUS

Work in this period was directed toward developing an understanding of the effects of condensation and freezing of condensable species on calculated and measured performance parameters such as characteristic velocity (c*) and specific impulse (I_{sp}). It was theoretically shown that propellants with higher flame temperatures (equal molecular weight of the products) may actually have lower values of theoretical c* if condensation and/or freezing takes place beyond the throat and if the latent heat is sufficiently large. This effect is probably not noticeable in the actual measured c* of a real rocket motor because of lags in condensation or freezing, but the effect will show up as a "combustion inefficiency" which is really a condensation or freezing inefficiency.

An SPS article is planned that will detail the theoretical work and computer calculations.

MEASUREMENT OF SOLID PROPELLANT BURNING RATES DURING RAPID PRESSURE TRANSIENTS

Objective

This program is to develop a technique for determination of burning rates under transient conditions and obtain transient burning rate data.

Status

Several experiments were conducted for the transient burning rate under varying depressurization conditions. The data thus obtained indicate that the burning rate under rapid depressurization is not that which is predicted by the pressure alone. Before additional tests were conducted it was decided that attempts should be made to reduce the fixed reflections in the microwave system. This will be accomplished by improving the transition region between the wave guide and the propellant sample. By reducing the fixed reflections, the interpretation of the data will be simplified and the uncertainty in the results will be reduced.

Additional tests for various propellant formulations will be made in the improved microwave system.

MEASUREMENTS OF THE ADMITTANCE FUNCTION OF A SOLID PROPELLANT IN A T-BURNER

Objective

This program is to study the T-burner as a means of measuring the dynamic response of burning solid propellants in the presence of oscillatory pressure changes.

Status

Approximately 200 firings have been conducted to date. Burners of various lengths and diameters and at several mean pressures were used. Almost all of these have used two composite propellants, A-13 and A-35, provided by the Naval Weapons Center, China Lake, Calif. The data taken – both during the burning when acoustic modes are driven in the burner, and after burnout when the waves decay –. seem to be acceptably reproducible.

It was anticipated the losses in the burner would be principally due to viscous dissipation at the walls. The frequency dependence of the results supports this view, but, to the contrary, it was learned that the expected influence of diameter appears not at all. At the present time, this observation remains unexplained. In order to obtain more information about the flow in the burner, and perhaps to resolve the dilemma, motion pictures are to be taken of firings in plastic or glass burners.

Two preliminary tests of the equipment have been successful.

A series of measurements have also been started on a second composite propellant, T-17, mixed and cured at JPL. The principal reason for choosing this propellant is that it was used several years ago in very extensive measurements of the stability boundary for small cylindrical rockets at JPL. Thus, it will be possible to assess the usefulness of data taken in a T-burner, for studying the stability characteristics of a rocket. This connection has not previously been completed experimentally.

PUBLICATIONS

None

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SOLID PROPELLANT DETONATION RESEARCH

NASA Work Unit 128-32-50-02-55

JPL 328-23201-2-3810

O. K. Heiney

OBJECTIVE

The goals of this unit are to analytically and experimentally investigate high-rate phenomena occurring in solid propellants. This effort is currently being channeled into two main areas. The first area is the investigation of shock, deflagration and detonation wave onset and propagation through solid propellants. (This implies an analysis of the coupling between the chemical energy and pressure release waves and the mechanisms of propellant ignition.) The second area of research is that of applied unconventional interior ballistics for space application to propellant actuated devices.

STATUS

A Beckman and Whitely simultaneous streak and framing camera has been procured and installed. Operational familiarity with this intricate piece of test equipment is now being acquired. An analytic formulism for deflagration wave propagation over slab propellant has been designed and computer coded. This theory, as well as different approaches developed at Princeton and by AFRPL, will shortly be correlated with experimental window motor firings designed to test the validity of the various analyses.

Future effort in these areas will be an attempt to photograph the transition from a deflagration to a detonation wave in a granular propellant bed and also mathematically describe the process. Additionally, the flame spread during an ignition process will be experimentally evaluated with various ignition materials acting on a propellant, JPL 540, whose thermal properties are well known.

In the field of unconventional interior ballistic development, a high-low propellant actuated device formulism has been completed, computer coded, and experimentally verified. This technology was then applied to a high-low operated parachute mortar for potential application as a planetary lander deceleration system. This mechanism has been fabricated and successfully tested.

PUBLICATIONS

None

SOLID ROCKET GASDYNAMICS STUDIES
NASA Work Unit 128-32-52-01-55
JPL 328-21101-2-3810

O.K. Heiney
D. Norton
L. D. Strand

OBJECTIVE

The objectives of the individual gasdynamic study programs are detailed under their discrete entries in the following paragraphs.

ROCKET EXHAUST CXIDE PARTICLE SIZE MEASUREMENT

Objective

The objective of this program is to determine the validity of the photometric measurement of the average particle size of aluminum oxide exhausts.

Progress

Calculations were performed that showed that the photometic measurement technique was sensitive only to the continuum portion of the overall aluminum oxide particle size distribution, but the tank system tests also indicated the presence of discrete particles in the large-size region of the size spectrum. These calculations suggested that the mean particle sizes indicated by the spectrophotometric tests should be compared with size distribution data obtained from the tank tests that were truncated at the end of the continuous portion of the distribution function. Data reduction for the tank system tests were, therefore, recalculated after the discrete spectrum was truncated. Comparison of particle sizes measured by the spectrophotometric system with the truncated tank system data yielded quite good agreement, suggesting that the actual distribution function does indeed possess a bimodel character.

Preparation of a final report for this project was completed. Condensed versions of the report were prepared for presentation at the 6th ICRPG Static Test Working Group Meeting and the 6th AIAA Aerospace Sciences Meeting.

NOZZLE THROAT CONTOUR OPTIMIZATION

Objective

This program is to determine the gasdynamic effects of varying the throat contour ratio r_c/r_t on mass flow, nozzle thrust, and specific impulse.

Progress

The computer program for nozzle throat contour studies was modified to determine the flow field for submerged nozzles. This program was employed for submerged nozzles. However, it was found that the series expansion used in the analysis did not permit an accurate description of the streamlines for upstream of the nozzle throat. Therefore, a new computer program was developed to solve the flow equations by finite difference techniques developed without resorting to series expansions. The equations are solved by imposing the Cauchy boundary conditions at the centerline and the Dirichlet conditions at the nozzle inlet. This technique works well for conventional nozzles with entrance half-angles up to 80 degrees. For submerged nozzles it will be necessary to transform the coordinates to avoid multiple value points.

The result of the cold flow tests on five nozzles of varying throat contour radii is that the performance of the nozzles was not adversely affected for r_c/r_t ratios as low as 0.5. Application of these results will make shorter and lighter weight nozzle designs without loss in expansion efficiency.

SOLID ROCKET MOTOR EXHAUST PLUME IMPINGEMENT STUDY

Objective

This program is to develop engineering data on the effects of the impingement of exhaust gases and solid particles upon a spacecraft.

Progress

The first two high-altitude firings of the six motor test series at the Arnold Engineering Development Center (AEDC) were performed in July. The results of these tests with 12% aluminized propellants were highly severe erosion and heating of the instrumented targets in the exhaust plume. Reduction of the particle flux density to levels closer to those of practical interest was deemed necessary. Two means of readily doing so are to (1) increase the separation distances between the motor nozzle exit and the targets, and (2) reduce the aluminum concentration in the solid propellant. The second method was used because the first method would result in the targets being located in a less well-characterized region of the plume. The propellant aluminum concentrations for the final four tests were reduced to 0.0, 0.08, 0.40, and 2.0%, respectively – the nonaluminized propellant firing measuring the gaseous component of the target heating. Two of these last four tests have been conducted. The remaining two were tentatively scheduled to be performed near the end of December.

The contract with Aeronutronics has been extended an additional four months to allow for preparation of a final report following the completion of the AEDC tests.

NOZZLE THRUST MISALIGNMENT

Objective

This program is to determine whether or not a protrusion to the flow in the nozzle expansion region and asymmetry in the nozzle throat displace the thrust vector and, if so, to what magnitude?

Progress

A first draft of a report covering the cold-flow studies was prepared.

SELF-OBTURATING PROPELLANT ACTUATED DEVICE

Objective

This task was oriented toward developing a gas-sealing propellant-actuated device to provide a technology base for the design of payload launchers for planetary lander vehicles. The entire system was to be sterilizable. An ejector-free ballistic cycle was required to prevent lander area contamination or potential degradation of optical surfaces.

Progress

To provide a remote-payload-deployment, self-sealing, propellant-actuated launcher, a fully sterilizable system was designed, fabricated and tested. A self-swaging payload piston was employed to provide for positive ejector containment. This unique mechanism has been the subject for a new technology report. The squibs and propellant used were fully sterilizable. The squibs were surplus from the Surveyor program, while the main charge propellant was an experimental HMX oxidized formulation developed by Hercules. Subsequent to the successful system tests, the goals were reached; no further effort will be expended on this task.

PUBLICATIONS

Meetings and Symposia Papers

1. Dobbins, R. A., and Strand, L. D., "A Comparison of Two Methods of Measuring the Particle Size of Al_2O_3 Produced in a Small Rocket Motor," 6th Annual Meeting of the ICRPG Static Test Working Group, October 16-17, 1968.

SPS Contributions

1. Heiney, O. K., "Molecular Transfer From Regressing Solid Propellant Surfaces," SPS 37-51, Vol. III, June 30, 1968.

N70-39648

CHEMICAL ROCKET EXPERIMENTAL ENGINEERING (731)

LIQUID SPACE PROPULSION SYSTEMS (731-12)

LIQUID PROPULSION COMPONENTS

NASA Work Unit 731-12-03-03-55

JPL 331-10201-2-3840

W. F. MacGlashan

OBJECTIVE

The broad objective of this work unit is to advance the technology of liquid propulsion components for future space missions. Emphasis is placed on space-storable components, although earth-storable components are still considered for specific requirements. Current objectives are to develop solutions to problems identified in the space-storable module work unit, 731-12-04-01, and the combustion devices development work unit, 731-12-02-11.

PROGRESS

Fill Valves

Originally there were eight valves each in aluminum, stainless steel, and titanium.

One of the aluminum valves had an electron-beam-weld leak. Rewelding to correct the leak was not successful. During burst test, rupture occurred at 11, 900 psi in the leak area.

Two of the stainless steel valves leaked at the electron-beam weld. Both valves were successfully rewelded.

One of the titanium valves had excessive leakage caused by irreparable porosity of the seat metal.

One each of the stainless steel and titanium valves was subjected to the maximum available pressure (20, 000 psi) without damage.

The current stock consists of seven aluminum, eight stainless steel, and seven titanium valves. Some of these will be tested during the last half of FY 69 at the Edwards Test-Station Facility in pressurized space-storable propellants (oxygen difluoride and diborane). The special test equipment for these tests is being completed and will become operational during the third quarter of FY 69. The initial leak rate of each valve was less than 8×10^{-5} standard cu-cm/sec when pressurized with zero to 3000 psi helium gas in a mass spectrometer. Prior to the leak test, each aluminum and stainless steel valve was torqued shut with 10 inch-pounds. The titanium valves were torqued shut with 20 inch-pounds because of the coarser finish of the lapped titanium seats.

Service Connection

Testing of the bobbin-type seal connectors is planned to be initiated during the last half of FY 69. Leakage and long-term storage tests will be conducted with oxygen difluoride and diborane using the special equipment indicated above.

Belleville Spring Redesign

A series of Belleville springs has been designed for development purposes to give a predetermined load versus deflection curve and also to be interchangeable with the springs in the Mariner midcourse propulsion system pressure regulator. A pilot order totaling 24 springs from two materials was completed. The order consisted of six springs each with height/thickness ratios of 1.29 and 1.51 made from 0.0225-inch-thick 17-7 PH stainless steel and ELGILOY strip stock. Load versus deflection curves for each spring will be obtained, and the data will be used to determine the configuration for the production run.

Lapped Valve Seat Study

Scanning electron-microscope (SEM) photos of a lapped valve seat show considerable detail. Preliminary results reveal that this photo method will be very effective in evaluating seat surface treatments and determining seat surface finishes. In the latter case, photos of the seat in question would be visually compared with photos of test specimens of known micro-inch finishes. As part of the component subdetail improvement program, we have studied SEM photos of plain-lapped seats, diamond-impregnated seats, and also ceramic and sapphire seat balls.

A plain-lapped seat is formed by rotating a diamond-impregnated ball on a square-edged orifice to produce a spherical land, which is the sealing surface.

Diamond-impregnation is accomplished by impacting a diamond compound into the spherically lapped land. The purpose of impregnation is to eliminate galling between the seat and the closure ball and to increase the resistance of the seat to erosion and corrosion. At 2000X magnification, there is slight difference in appearance between a plain-lapped seat and a seat impregnated with 1/100 micron diamond particles. If excessive pressure is used during the diamond-impacting procedure, extensive surface cratering occurs. Each pit averages about one micron in diameter. The cause of this cratering is not known, but it is not believed to be related to the diamond particles, since it is not likely that a 1/100 micron particle could make a one micron crater. No galling was evident when a dry sapphire ball was loaded against the dry diamond-impregnated seat and then rotated.

The continuation of the seat and ball study will consist of selective effort in the following areas:

(1) Investigate the cause of the seat cratering which occurs during excessive pressure seat impregnation.

(2) Determine the optimum particle distribution for diamond-impregnated seats.

(3) Develop a technique for a controlled impact procedure during impregnation.

(4) Determine the effect of seat treatment on seat leakage and seat life.

(5) Determine the increased resistance of the treated seat to erosion and corrosion.

Components for Space-Storable Propellants

Preliminary design data sheets for tanks, fill valves, and a bipropellant shutoff valve have been initiated. These components are oriented toward a specific space-storable propulsion system in the 1000-pound thrust range. The requirements include consideration of thermal control constraints and the mission environments. To effectively cope with the problem, the work will be covered in the following manner:

(1) Establish suitable materials of construction for each component application.

(2) Design components based on the material investigations of Phase I and system requirements.

(3) Fabricate and test the components.

PUBLICATIONS

SPS Contributions

1. Keller, O. F., "Heat Sterilization Compatibility of Ethylene-Propylene Rubber in N_2H_4," JPL SPS 37-51, Volume III, pp. 137-141, June 30, 1968.

SPACECRAFT PROPULSION MODULE USING SPACE-STORABLE PROPELLANTS

NASA Work Unit 731-12-04-01-55

JPL 331-10701-x-3840

D. L. Young

OBJECTIVE

The objectives of this unit are to: (1) develop an experimental prototype propulsion module using space-storable propellants, (2) coordinate advanced development efforts in the space-storable field, and (3) contribute to the broad technology base required for use of space-storable propellants.

STATUS

During this reporting period, the propulsion module requirements were established. Schematic designs were established for a two-tank system, and generic component classes were selected. Work has been initiated on thermal control and structure and their interrelationship with the module and a Mariner derivative spacecraft. Design layouts of the major volumetric components have been completed. Definitions have been outlined for the establishment of an SRAD project for the space-storable propulsion module and related activities.

PLANNED ACTIVITIES

During the next reporting period, a four-tank schematic design will be established. The two-tank or four-tank configuration designs will be carried in parallel for at least a year. Work will continue on the structures and thermal control aspects of the module. The module requirements will be refined and formalized into a reportable document. The SRAD project will be formally established.

PUBLICATIONS

None

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PROPULSION FEED SYSTEM DESIGN ENGINEERING

NASA Work Unit 731-12-04-03-55

JPL 331-11101-2-3840

L. R. Toth

OBJECTIVE

The objective of this work unit is to advance the technology of liquid propulsion systems for spacecraft for future space missions and to furnish data upon which to base future flight project commitments. This work area consists of evolving basic propulsion system concepts for unmanned-type spacecraft that can be applied to foreseeable space and planetary missions, and that will maximize life and reliability because of the mechanical simplicity inherent in their design.

STATUS

During the first quarter of FY 69, there was no effort on this work unit. Based upon revised plans, the funding level was reduced to zero; effectivity is September 12, 1968.

PUBLICATIONS

None

ADVANCED COMBUSTION DEVICE DEVELOPMENT

NASA Work Unit 731-12-04-04-55

JPL 331-10301-2-3840

R. W. Riebling

OBJECTIVE

The objective of this work unit is to utilize recent advances in injector and thrust-chamber technology in the development of advanced, high-performance rocket engines to near-flight-prototype status. Problem areas associated with the application of this recently developed technology will be exposed, and problems will either be solved as they arise or made the subject of further technology studies. The program is sufficiently flexible that new technology may be incorporated as it becomes available, or promising concepts exposed during development may be pursued further. This integrated approach is intended to produce basic engineering information, and to demonstrate the performance and reliability of advanced rocket engine concepts so that new high-energy, space-storable propulsion systems will be ready for inclusion in forthcoming space flight project planning. Primary emphasis is being placed on the propellants oxygen difluoride (OF_2) and diborane (B_2H_6).

A number of injectors and chambers, all based on concepts already proven in OF_2/B_2H_6 service, are being fabricated. To conserve costs, and also because of the possibility that a spacecraft engine of this proven scale may be required, these components have been designed to produce a vacuum thrust of approximately 200 lb_f. All elements of this hardware are interchangeable, so that various injector-chamber combinations can be made up and tested. Thousand-second-duration firings will be attempted for each combination, and, based on measured combustion efficiency and durability, the most promising concept will be selected for further development. This future development will take place at the 1000-lb_f-thrust level because of potential application to a 1000-lb_f-thrust, space-storable propellant propulsion module being studied concurrently. It will incorporate refinements as necessary, based on the results of the 200 lb_f studies.

STATUS

Fabrication of two 200-lb_f-thrust injectors is nearing completion. Their designs are based on criteria developed for OF_2/B_2H_6 propellants under Contract NAS 7-304, "Chamber Technology for Space-Storable Propellants." Both are self-impinging doublet-type injectors made of nickel, and contain multiple injection elements arranged in such a way that the spray consists of a high-mixture-ratio, high-performance core region containing the bulk of the propellant mass flux, surrounded by a low-mixture-ratio barrier zone adjacent to the chamber walls. The purpose of this barrier zone is to minimize wall and throat erosion by reducing the temperature, heat flux, and concentrations of corrosive species adjacent to the wall. The two injectors are nearly identical, differing only slightly with regard to their specific pattern arrangements.

One 200 lb_f thrust chamber is being fabricated at JPL, while contracts have been let with three outside contractors for the design and fabrication of three alternative chamber concepts. All these chamber designs incorporate liners made of carbonaceous or graphitic materials to withstand the high combustion temperature of the OF_2/B_2H_6 propellants. The use of such materials for chamber liners with these propellants has been successfully demonstrated on the NASA 7-304 contract. Chamber cooling is completely passive, relying primarily on the barrier zone and the superior high-temperature properties of the carbonaceous materials. In the event that such engines must eventually be used in a "buried" configuration, the thrust chambers are all being insulated so as to reduce the outside wall temperature to a nominal value of 600°F.

One of the chambers being made by a contractor is basically a free-standing Carb-I-Tex chamber with its inner surface impregnated with a layer of pyrolytic graphite. (Carb-I-Tex is a fiber-reinforced, graphite composite material.) This is surrounded by a standoff shield of lightweight, multilayer insulation encased within a thin sheath of silica-phenolic ablative material. A second contracted chamber consists of an ATJ graphite liner, and pyrolytic graphite heat conduction wedges which conduct a portion of the heat from the throat area to a region of the chamber near the injector, where it is rejected. The wedges are surrounded by two layers of insulation material in series. The third chamber being fabricated under contract consists of a graphite-phenolic ablative chamber with a throat insert of a material similar to Carb-I-Tex. The inner surface of the throat insert is impregnated with pyrolytic graphite. A fourth, being made at JPL, incorporates a free-standing graphite liner surrounded by a carbon cloth/tantalum foil multilayer insulation system of the type developed under NASA Contract NAS 7-474, "Spacecraft Rocket Engine Chamber Insulation Materials." Liners for the JPL chamber have been made of ATJ and several grades of POCO graphite. All hardware is scheduled for delivery between January and March of 1969. Test-firings at the Edwards Test Station will begin as soon thereafter as facility modifications (to permit operations with OF_2/B_2H_6 propellants) have been completed. These are being accomplished under a separate NASA work unit, Space-Storable Propellant Engine Testing, 731-12-04-05-55.

PUBLICATIONS

<u>JPL Technical Reports</u>

1. Riebling, R. W., "Experimental Evaluation of a Throttlable Impinging-Sheet Injector with Earth-Storable Propellants," Technical Report No. 32-1330, October 15, 1968.

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SPACE STORABLE PROPELLANTS ENGINE TESTING

NASA Work Unit 731-12-04-05-55

JPL 331-10601-2-3840

W. B. Powell

OBJECTIVE

The objective of this work unit is to provide a facility for development testing of rocket engines and components using the high-performance space-storable propellant combination of oxygen difluoride (OF_2) and diborane (B_2H_6) at thrust levels up to 10,000 lb_f, and for significant durations. Testing development-type engines of this scale for long duration will expose problems that should be made the subject of separate technology studies. This will contribute to the development of integrated propulsion systems matched, as far as possible, to potential spacecraft applications, and having high performance, reliability, and long life.

APPROACH

An existing test stand at the JPL Edwards Test Station is being modified to accommodate the OF_2-B_2H_6 propellant system. Temperature-controlled and insulated propellant tankage is being procured. Propellant run tank capacity corresponds to total altitude impulse of 1.35×10^6 lb_f-sec. Initial operation will be at thrust levels of up to 2000 lb_f. Straight-tube diffusers will be coupled to the motor exhaust nozzles, enabling operation at an expansion ratio of up to 5, and closely duplicating high area ratio nozzle heat flow conditions in the throat region. The diffusers will discharge into a scrubber designed to remove as much as possible of the fluorine and boron from the exhaust products.

PROGRESS

The test stand area has been prepared for the installation of new equipment by removing previous equipment which will not be reused, by enlarging the oxidizer propellant tank bay, and relocating the helium pressurizing gas tanks. A monorail hoist has been installed over the test stand and diffuser area.

The oxidizer and fuel propellant tanks (180 gal and 256 gal) are in the final stages of fabrication. Tanks and propellant valves will be delivered during January 1969, after which major piping installation can begin.

A new thrust stand has been designed to accommodate the range of test motors from 200 lb_f to 2000 lb_f vacuum thrust.

A vacuum-jacketed liquid nitrogen line has been ordered to bring LN_2 coolant to the propellant tanks and lines.

Some valves, pumps, and tanks have been acquired from surplus at Air Force RPL for use in the test stand modification. Toxic gas detectors which had been used by Lewis Lab are also being made available for use at ETS.

A decision has been made on a contractor to design, build, and install a scrubber system to remove the fluorine and boron components from the thrust chamber exhaust gases. Sufficient money was made available for the scrubber to enable initial purchase of a unit rated at 99.5% toxic product removal efficiency. Large pumps available from RPL will be used as part of the scrubber installation.

A NASA Headquarters contract has been awarded to Callery Chemical Company to design and prototype a B_2H_6 shipping container holding about 200 lb_m of product. This container will also be made compatible for use with OF_2. These shipping containers will not be available for use for at least a year. NASA Headquarters is also considering letting a contract for small-scale production of OF_2. By the time the OF_2 becomes available, the 200 lb_m shipping container should also be available.

Initial testing will be done using FLOX delivered in commercial F_2 tankers, and using B_2H_6 shipped in the current 35 lb_m bottles packed in dry ice.

Components that were ordered during the last 10 months are beginning to arrive. Overall installation will start in January of 1969. Completion of the test stand, with the exception of the scrubber, should occur during the first quarter of calendar 1969. Initial short-duration checkout firing tests should be possible at this time. Long-duration firing tests, using the scrubber, should be possible before the middle of the year.

PUBLICATIONS

None

LIQUID AUXILIARY PROPULSION SYSTEMS (731-13)

EXTENDED-MISSION GAS ACTUATOR SYSTEM DEVELOPMENT

NASA Work Unit 731-13-01-03-55

JPL 331-30301-2-3440

F. G. Roselli-Lorenzini

OBJECTIVE

The long-term objective of this task is to provide improved alternatives to the nitrogen cold-gas attitude-control system presently utilized on Mariner-type vehicles. Attitude-control thruster requirements for future planetary missions will include higher specific impulse, lower weight, and longer life.

The immediate objective of this work unit is to design, build, and evaluate the distribution subsystem and its components for utilization with several different types of gas supply systems being developed by the Propulsion Division. The first two of these new gas supply systems will be an evaporating ammonia system and hydrazine-catalytic decomposition system. Areas of improvement accomplished in the present distribution design include lower-leak-rate thruster valves, improved regulation, and new welding and cleaning techniques.

STATUS

The present distribution system under evaluation represents a design that incorporates solutions to all of the known problems associated with Mariner-type distribution systems. The new system includes an improved pressure regulator design, pressure and temperature transducers (for recording the output or distribution pressure), and valve manifolds for the clustered thrusters. The components are interconnected by welded, ultrasonically drawn stainless steel tubing with convoluted sections for flexibility where the distribution system crosses simulated hinge points to the solar panels. The distribution system was procured under JPL Contract 951988 from General Electric Company (GE) of Valley Forge, Pennsylvania, and received at the end of FY 68.

As a result of functional tests performed by GE, the contract has been extended to supply two improved pressure regulators whose response, particularly at the thermal extremes, will be a significant improvement over the

Mariner-type designs. The two additional regulators will be procured by GE From Carlton Controls, Inc., of East Aurora, New York, and from Sterer Engineering Compnay, of Burbank, California. The reason for the two different regulators is to evaluate both a hard and soft poppet-valve design. A general design critique was held between JPL and GE, and the improved hardware delivery is expected by March 1969.

A compatibility test program has been started for the distribution system utilizing spare parts from the GE system. This breadboard compatibility test will duplicate all the components of the main welded system with the exception of the filter, which has been substituted by a stainless steel wire-mesh 5-micron filter in a millipore filter holder.

In an effort to understand some of the torque unbalances observed on spacecraft in flight, an attempt has been made in the past three months to measure the thrust due to a valve leakage. The testing showed rough correlation with a theoretical approach; within the next six months another attempt will be made to test further this thrust level with improved testing techniques. Measured thrusts due to leakage have been in the order of fractions of 1 micropound (see Fig. 1).

PLANNED ACTIVITIES

The anticipated schedule for completion of this compatibility test with both hydrazine and ammonia will be during the months of January and February. Pending successful completion of the compatibility test, the integration of gas supply and distribution systems will follows.

PUBLICATIONS

None

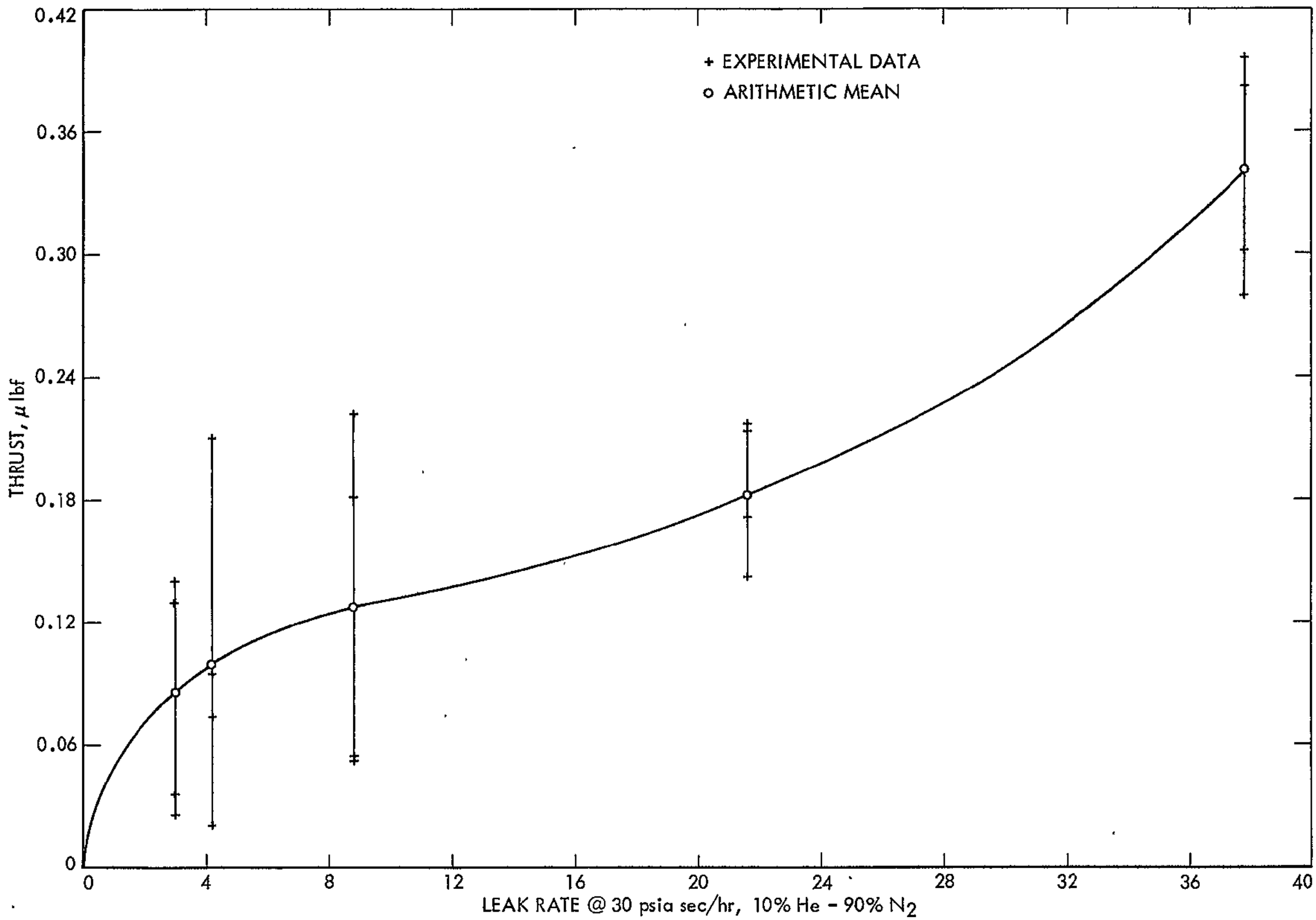

Figure 1. Thrust Versus Valve Leak Rate

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TOROIDAL TANK BELLOWS MONOPROPELLANT UNIT

NASA Work Unit 731-13-01-04-55

JPL 331-30601-2-3840

H. B. Stanford

OBJECTIVE.

The objective of the task is to demonstrate an experimental monopropellant (hydrazine) propulsion system incorporating a toroidal tank, bellows expulsion unit with length/diameter ratio of approximately 1.0. Goal of this unit is to be capable of sterilization, multicycle operation, and long-term space storage for periods of up to 10 years.

STATUS

In-House Activity

JPL activity has consisted of technical management of contracted tasks to design and fabricate a toroidal tank bellows propulsion assembly for purposes of demonstrating the feasibility of this type of integrated expulsion device for a spacecraft propulsion package.

Off-Lab Activity

The toroidal tank expulsion device for the spacecraft propulsion package is with the Solar Division of International Harvester Company under Contract No. 951940.

The off-lab activity has been completed with delivery of two assembled toroidal tank bellows units as stipulated in the contract. These units were proof- and leak-tested and subjected to 10 expulsion cycles each.

Dummy M 69 components were installed on a plate attached to the top of one unit with a rocket motor mounted in the toroidal center to demonstrate the feasibility of a unitized propulsion package.

The total weight of the tank and expulsion assembly was 26 lb. However, a substitution of low-strength material in the bellows end caps added approximately 7 lb. It is estimated that further optimization could reduce this weight to 17 lb.

PUBLICATIONS

Contractor Reports, Interim and Final

1. "Development of Toroidal Tank Bellows Expulsion Unit," Solar Division, International Harvester Company, San Diego, Calif., October 1967 — November 1968, Contract No. 951940.

REACTION CONTROL GAS SUPPLY SYSTEM

NASA Work Unit 731-13-01-07-55

JPL 331-30101-2-3840

A. Karbin

OBJECTIVE

The goal of this program is the development of advanced technology for reaction control gas supplies for planetary spacecraft.

STATUS

The initial effort to survey, analyze, and compare six types of attitude control thrusting systems was published near the end of FY 67 (STAR Reference No. N 67-32369). Three of the more promising systems were studied further and prototype systems were designed, fabricated, and tested. The vaporizing ammonia system and the hydrazine electrolysis system were investigated by General Electric Company and Hughes Aircraft Company, respectively, under contract, and work on the hydrazine plenum is being done at JPL.

Dual Mode Hydrazine Electrolysis

The Hughes Aircraft Company Aerospace Group was awarded a contract to perform a laboratory study and to fabricate and test a breadboard model of a hydrazine electrolysis system. The contract began in August 1967 and is documented in a final report published in August 1968. Included in this report is a design of a prototype dual-mode hydrazine system. Though attempts made to initiate uncontrolled reactions in the laboratory model were unsuccessful, a follow-on task is being funded to perform controllability tests of the breadboard model. These tests will consist of shorting the electrolysis cell and operating the system under conditions in excess of nominal. The follow-on controllability tests should begin during the third quarter of FY 69 and last about one and one-half months. Two problems encountered during the prototype tests — entrainment of liquid droplets in the vented gas and an increase in electrolysis cell resistance with operating time — are thought to be understood. The verification of the solution and elimination of these problems will require additional testing.

Liquid Ammonia Vaporizing System

The General Electric Company, Nuclear Systems Programs Group, has concluded a contract to study, design, fabricate, and test a vaporizing ammonia system which converts ammonia from the liquid state to a superheated vapor. As gas is demanded by the jet thrusters, the heat of vaporization is supplied mainly from the liquid sensible heat. The system temperature is returned to normal by radiation and conduction of heat from the spacecraft. A solenoid valve and a throttle valve in the supply line to the heat exchanger prevent flooding of the heat exchanger during nonoperative periods. Either liquid or vapor may enter the heat exchanger. The final report draft has been reviewed and the revised report should be ready for distribution during the third quarter of FY 69.

The ammonia system hardware has been delivered to JPL. It is being readied for additional testing at JPL and will be used to supply ammonia vapor to the warm-gas attitude-control distribution system.

Hydrazine Plenum Storage Tests

The hydrazine plenum has been reworked by incorporating hermetically sealed thermocouple lead-ins. A five micron filter has been designed and fabricated to capture the catalyst fines from the gas generator. A water absorber of calcium hydride has been designed and fabricated. The upper catalyst bed has been designed for additional catalyst support and increased catalyst surface area. The catalyst grains in the lower bed are supported in individual layers to decrease mechanical deterioration. Problems with contamination of the hydrazine feed valve and an excessive pressure drop through the bed have been delaying the resumption of testing of the assembled system. The hydrazine plenum will be used to supply gases to the warm gas attitude control distribution system. Plenum tests should start during the third quarter of FY 69.

PUBLICATIONS

Contractor Reports, Interim and Final

1. N 67-32369, "Spacecraft Attitude Control Gas Systems Analysis," Final Report, April 1967, prepared for JPL (Contracts NAS 7-100; JPL — 951720) (NASA-CR-86661:SSD-70172R), CSCLC.

2. N 68-19360, "Analytical and Experimental Investigations Concerning the Dual Mode Hydrazine System, Task IV, Summary Report," August 1, 1967 through February 1, 1968 (Contracts NAS 7-100; JPL — 951720. NASA-CR-93663: Rept. -68(22-2749/B1183-002).

3. "Hydrazine Electrolysis for Spacecraft Propulsion, Analysis and Test of a Dual-Mode Gas and Liquid System," Final Report, JPL Contract No. 951720, August 1968, SSD 80316R, Propulsion and Power Systems Laboratory of Hughes Aircraft Company Space Systems Division.

LIQUID PROPELLANT EXPULSION

NASA Work Unit 731-13-04-02-55

JPL 331-30401-2-3840

H. B. Stanford

OBJECTIVE

The objectives of this work unit include the technology advancement of liquid propellant orientation and management in spacecraft propulsion systems. Also, to understand the problems associated with (1) phase separation in a gas-liquid propellant medium, either earth or space storable; and (2) making end use application of metallic and nonmetallic phase separators to stabilize the separation of two phase media (gas-liquid) for planetary missions of up to 10 years duration.

JPL ACTIVITY

Bladder Slosh and Leak Tests

There has been no JPL slosh and expulsion testing activity throughout this reporting period. The test facility has been shut down because of major alterations to the hydraulics laboratory.

Desert Storage Test (Compatibility)

Several prospective and established bladder materials have been in compatibility test at the ETS facility. These include materials for approval from outside contracts and flight bladder materials.

OFF-LAB ACITIVITY (CONTRACTUAL) PROGRESS

Contract No. 951898 (Arde, Inc.)

This contract is for the purposes of (1) demonstrating stainless steel expulsion tank and diaphragm hardware of flight-weight configuration with multicycle and sterilization capability, and (2) the use of a propellant compatible gold braze alloy for attaching the reinforcing wires to the expulsion diaphragm. The status is as follows:

(1) Evaluation diaphragms using the Engaloy 255 gold nickel brazing compound for wire attachment were made and tested. One diaphragm was subjected to 8 reversals before it failed.

(2) Two complete wire reinforced diaphragms for expulsion testing have been delivered to JPL.

(3) The two 18-inch diameter Ard-formed tank and wire-reinforced diaphragm assemblies have been completed for shipment by December 31, 1968.

(4) Tests performed by Arde on a third 18-inch diameter unit gave an expulsion efficiency of 96% at 30 psi. Ultimate tensile strength of 235, 000 psi longitudinal and 213, 000 psi hoop stress were achieved in burst tests.

Contract No. 951939 (Accessory Product)

The purposes of this contract are to (1) evolve an ethylene propylene rubber compound acceptable for long-term space storage with hydrazine (the compounding formula is to be available to the Government so that proper quality controls can be identified); (2) prove the fabricability of this compound for one piece molded bladders of Mariner 69 design.

Although some bladders have been molded from the two noncarbon-bearing compounds previously reported, some problems still exist. The difficulties are encountered in removing the bladders from the molding die. No satisfactory mold release has yet been found to consistently permit removal of the molded bladder from the die without tearing. Two reasons are apparent: (1) the non-carbon-bearing EP rubbers have low hot strength and (2) they seem to have a greater tendency to adhere or vulcanize to the metal surface. A search for an adequate mold release continues.

PUBLICATIONS

Contractor Reports, Interim and Final

1. "Gold Braze Investigation as Applicable to Multicycle Metallic Reversing Bladders," Arde Inc. report, No. 56001-I, May 15, 1968.

LIQUID PROPULSION TEST METHODS° EQUIPMENT, SAFETY° AND SUPPORT (731-14)

ADVANCED TECHNOLOGY CONTRACT MANAGEMENT FOR RPX

NASA Work Unit 731-14-01-03-55

JPL 331-40201-2-3840

C. R. Foster

OBJECTIVE

The purpose of advanced technology contracts, sponsored by the Liquid Propulsion Experimental Engineering Systems (PRX) office at NASA Headquarters, is to advance the engineering development of liquid propulsion systems through contracts to industrial aerospace firms.

DESCRIPTION OF ACTIVITIES

Under this work unit, JPL engineers, experienced in the liquid propulsion field, provide the technical management of some of these advanced technology contracts. These advanced technology contract management tasks are supplementary to the normal JPL assignments of these engineers on research, advanced development, or flight projects.

In general, the work consists of visits to the contractor's plant for technical information and direction, review of monthly progress reports, and quarterly reviews of progress at the contractor's plant, normally in company with the NASA Headquarters project manager. In addition, the engineer participates in planning and recommending new work, prepares the statement of work for proposed new (or continuing) advanced technology contracts, provides technical evaluation of proposals received, and gives technical review and approval to the final reports which are submitted by the contractor. On a semiannual basis, the engineer submits an informal report to the NASA Headquarters project manager to give his technical judgement on the status of the contractor's effort and results.

STATUS

Four advanced-technology contracts in liquid propulsion engineering development have been in effect during the first half of FY 69 that were technically managed by engineers in the JPL Liquid Propulsion Section (394). It is expected that technical management of advanced technology contracts will continue at approximately the same level of effort during the second half of FY 69.

PUBLICATIONS

None

OPTIMIZATION CRITERIA FOR SPACECRAFT PROPULSION

NASA Work Unit 731-14-01-05-55

JPL 331-40102-2-3850

J. P. Don

OBJECTIVE

The objective of this work unit is to consolidate the propulsion subsystem optimization analyses conducted under Contract NAS 7-519. These analytical techniques are to be directed to rapid planning use for planetary spacecraft studies.

STATUS

During the past six months, the effort has been directed toward a better understanding of the broad analysis of the preceding study contract. Evaluation of abbreviated techniques, and the attendant loss in accuracy, has begun. Literature surveys are under way to provide additional (specifically planetary spacecraft) historical data to use in curve fits and coefficient evaluation.

The planned activity for the next six months includes the completion of the abbreviated analysis and activity to program the results for case study comparisons. Also planned is a library literature search of the appropriate reference data for future reference.

PUBLICATIONS

None

SOLID SPACE PROPULSION SYSTEMS (731-26)

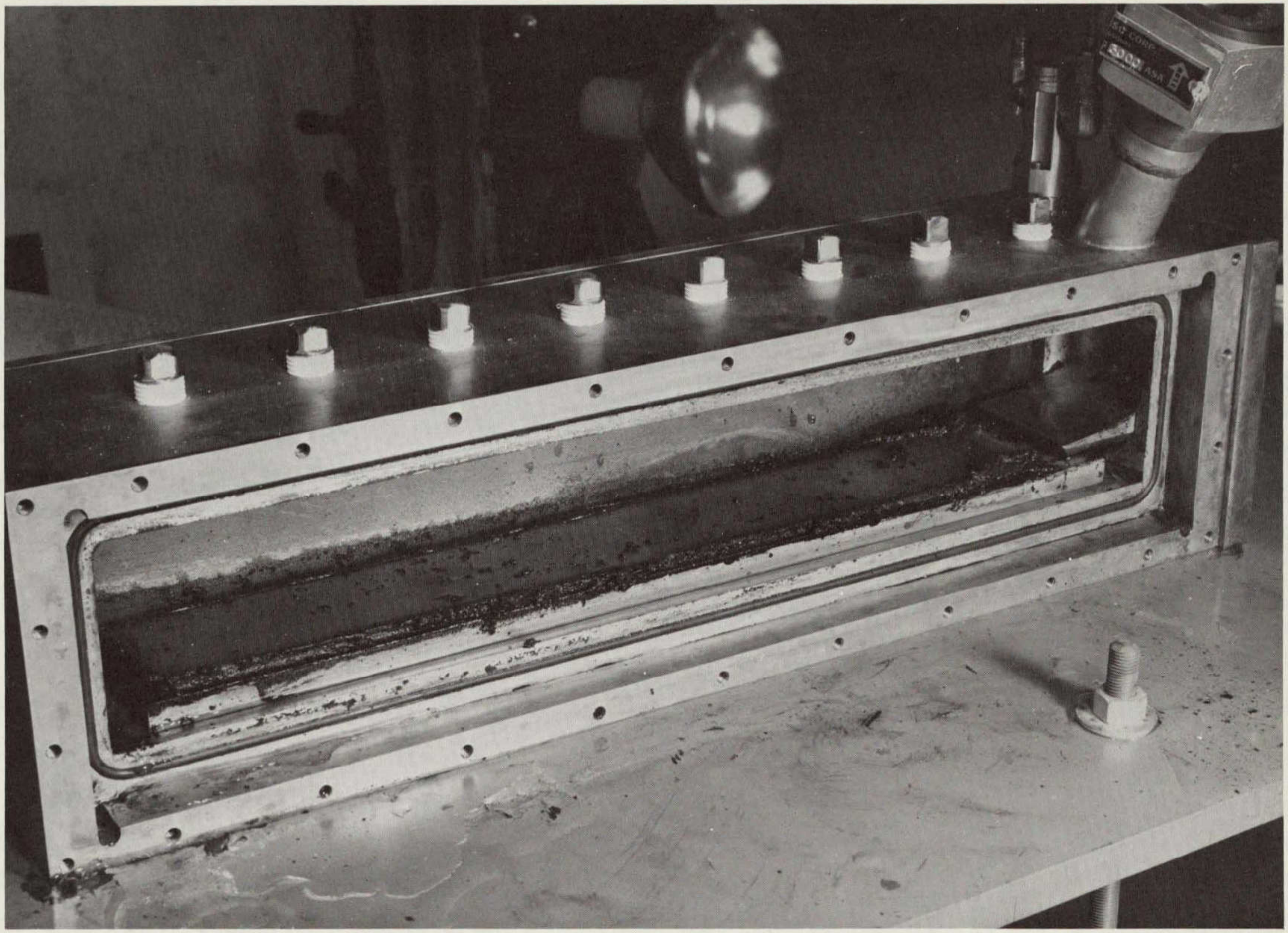

Figure 1. Slab Window Motor with Sheet Water Injector

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MOTOR CONTROL TECHNOLOGY

NASA Work Unit 731-26-02-02-55

JPL 331-60101-2-3810

L. Strand

OBJECTIVE

The objectives of this study are to: (1) determine the optimum method of water injection to obtain extinguishment, (2) better understand the quench mechanism so that it may be optimized, (3) establish means for predicting water requirements of any given motor, and (4) determine feasibility and performance of water extinguishment of flight motors.

PROGRESS

A 30-cubic-inch floating piston water accumulator was received and assembled. Following a delay necessitated by the obtaining of a new solenoid for the flow line solenoid valve, checkout of the accumulator was accomplished.

Modifications were made which allow the entire sequence of events in the motor firings to be triggered automatically following closure of the igniter circuit. When the motor pressure reaches a level of 40 psig, a pressure sensing switch starts the high speed motion picture camera. After a preset delay time required for the camera to accelerate up to operating speed, the water injection valve is triggered.

Four water quench motor firings were conducted, with successful termination occurring in three of the tests. In two of the tests a sheet water injector was used (Fig. 1). This injector sends a thin sheet of water rapidly over the burning propellant surface. If the primary quench mechanism is a thermal quench of the burning surface, this injection method should be the most efficient way of delivering the water. In both tests, termination was very rapid, progressing over the propellant surface with the advancing water flow. In the first test, the mean chamber pressure prior to extinction was 83 psig, the average water injection rate 13.7 lb/sec, and the amount of water injected up to the onset of extinction 0.046 lb. In the second test the mean chamber pressure was

73 psia, the average water injection rate 3.54 lb/sec, and again approximately 0.046 lb of water was injected up to the onset of extinction.

A series of two motor tests were conducted with fog-type injectors in an attempt to verify if the previous quench with this type of injector system was indeed due to a rapid depressurization phenomenon. The first test was conducted at a motor pressure of 72 psia and a water injection rate of 6 lb/sec. After the injection of approximately 0.08 lb of water a depressurization rate of approximately 1900 psi/sec and extinction occurred. A total of 1.23 lb of water was injected prior to and during extinction. In the second test with this injector the motor pressure was raised to 178 psia. The water injection rate was increased in an attempt to duplicate the depressurization rate of the previous test. An injection rate of 8.3 lb/sec yielded a measured depressurization rate, after the injection of 0.11 lb of water, within 10 psi/sec of that of the previous test. A total of 1.54 lb of water was injected prior to and during the depressurization period. Extinction did not occur. The motor pressure dropped to a minimum pressure of approximately 80 psia and then climbed to a pressure of approximately 130 psia before propellant burnout.

Extrapolation of the results of low-pressure L^* extinguishment studies yielded the prediction that a depressurization rate of 1900 psi/sec should be sufficient to produce extinction at the pressure level of the first test, but not at the second, in agreement with the test results.

The laboratory motor phase of the test program will be completed during the next report period, and equipment buildup for the Phase 2 motor tests should be initiated.

PUBLICATIONS

SPS Contributions

1. Strand, L. D., "Solid Propellant Rocket Motor Command Termination by Water Injection," SPS 37-52, Vol. III, August 31, 1968.

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SPACECRAFT MOTOR TECHNOLOGY

NASA Work Unit 731-26-05-09-55

JPL 331-60401-2-3810

J. I. Shafer

OBJECTIVE

The objective of this work unit is to demonstrate feasibility of use and assess approximate performance level of long-burning-time, low-thrust retro rockets, and low-thrust auxiliary propulsion systems.

STATUS

Early design studies (1) confirmed the advantages of using end-burning motors for unusually long burning time (i.e., low acceleration) applications; (2) established the desirability of using fully case-bonded designs, if feasible, in order to reduce launch vibration problems and provide higher motor performance than cartridge charges, (3) provided the charge shape that will produce the desired regressive thrust versus time program while minimizing sliver formation (see Fig. 1).

Two charges were cast with use of 60 lb Syncom flight weight motors as fully case-bonded end-burning designs that employed a JPL 540 polyurethane propellant with an unusually high propellant elongation (approximately 160% at maximum stress). This was to determine whether that type design could survive the cool-down from cure without propellant failure or insulation-propellant separation when later pressurized in a simulation of a motor firing.

The first motor was cured using standard processing techniques, 50 psi and bulk curing, as a reference and to determine whether very simple processing techniques were adequate. The second was cured at 175 psi and using zone cure, i.e., progressively cured from one end to the other.

Slow pressurization of each motor (over a 20-sec period) to 275 psi, or about 92% of the chamber yield strength, revealed no visual separation at the propellant-insulation-chamber interfaces, or propellant failure at ambient

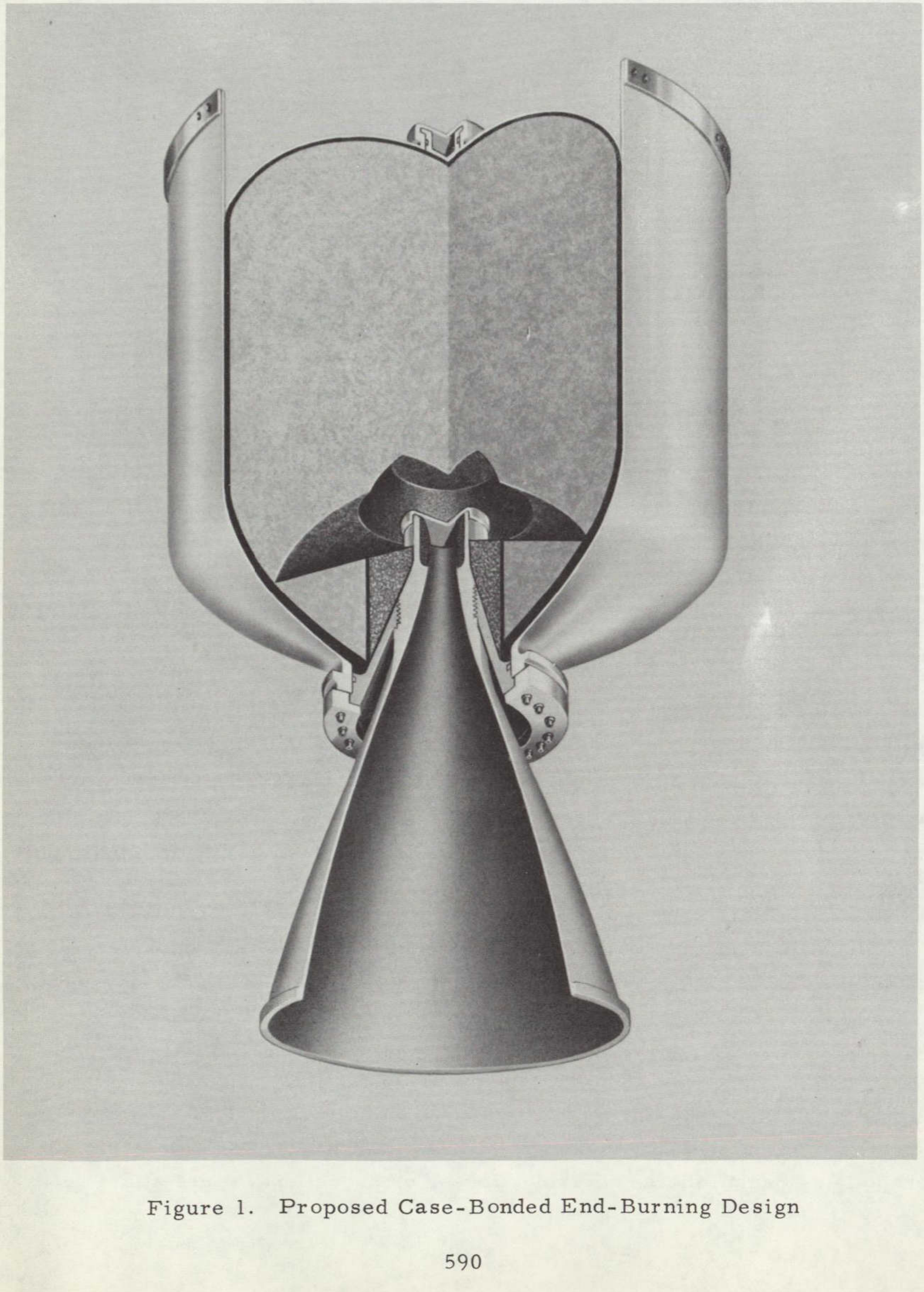

Figure 1. Proposed Case-Bonded End-Burning Design

temperature nor subsequently at 50°, 10°, -20°, -50°, and +165°F when retained at pressure for a period in excess of 3 minutes. Even after pressurization at 165°F, shock cycling directly to -65°F and again pressurizing to 275 psi, X-raying and visual inspection revealed no flaws.

It is believed these tests reveal a significant advance, being the first time a fully case-bonded end-burning charge in a flight weight case has been pressurized without failure.

A creep test with one motor stored at 175°F in an inverted position revealed negligible distortion after 48 hours, but revealed pronounced creep and severe charge slump at the end of 120 hours--presumably because of the very low propellant modulus of about 65 psi.

It is hoped that the new Saturethane class of propellants can be substituted later for the JPL 540 in the feasibility demonstration firing because of its inherently lower burning rate (about 0. 1 in. /sec at 100 psi compared to 0. 14 in. /sec for JPL 540). Formulation work has now produced a Saturethane propellant, which cured in 13 days at 190°F, with a maximum tensile strength at 72°F of about 190 psi and an elongation of 83% at maximum stress.

Recent insulation-propellant bond tests have also revealed that the new Saturethane formulation is chemically incompatible with V-52 insulation at the elevated cure temperature required, but fortunately a new and superior insulation, a polyethylene propylene rubber designated GTR 4010, provides excellent adhesion to both the propellant and chamber.

In the forthcoming period two 60-lb Syncom motors, insulated with GTR 4010, will be loaded with the new Saturethane propellant, pressure tested at ambient, 10°F and +140°F, then statically fired to demonstrate feasibility of the case-bonded end-burning concept.

PUBLICATIONS

None

SOLID AUXILIARY PROPULSION SYSTEMS (731-27)

ELECTRO-EXPLOSIVES TECHNOLOGY ADVANCEMENT

NASA Work Unit 731-27-02-01-55

JPL 331-70101-2-3810

J. E. Earnest

OBJECTIVE

The objective of this program is to ensure that technologies are available to allow design, fabrication, and test of any reliable explosive-actuated device which might be needed for a spacecraft application.

STATUS AND ANTICIPATED ACTIVITIES

Work to date on this program has centered mainly on evolution of a non-proprietary electro-explosive cartridge (squib) design which would meet a wide range of requirements (nonmagnetic, dual-bridge, insensitive to electro static discharge and R F, nonventing 30 kpsi seal strength, etc.), and this evolutionary process in turn centered on JPL Contract 951912 (Atlas Chemical Industries) for which the final report was received during November.

In essence, the work done by Atlas was highly successful; drawings compiled by Atlas have been modified to provide several variations which would be less expensive when certain restraints can be relaxed, and these drawings are being used as the base for all Mariner 71 squib procurement RFQ's.

Work on a detonator version of this same squib has been temporarily deferred, as has work on a high-temperature high-radiation-resistant version. (Although the present design is capable of withstanding prolonged exposure to 300°F, inquiries have been received this year as to the practicality of providing a squib capable of indefinite exposure to radioactive exhaust environments and to planetary atmosphere temperatures well in excess of 300°F.)

One of the attractive features of the present squib design is that it lends itself readily to modifications in the hands of competent NASA staff, and thus lends itself to a continuing program of "product improvement"; one such modification which may be made for the Mariner 71 applications is a change from titanium to titanium hydride as the "fuel" in the output charge, and there is room for improvement, when convenient, in the present anti static match-head (boron-based).

It is envisaged that future work in this area will involve:

(1) Minor R&D support for Mariner 71 in "debugging" problems which may arise from the necessary design modifications.

(2) Continuing search for an improved anti static match.

(3) Continuing evaluation of the state of the art as it bears on withstanding unusually severe high temperature and radiation levels.

(4) Investigation of the practicality of direct deposition of a silicon carbide anti static shunt as an alternate to the present use of silicone RTV as a matrix for silicon carbide powder.

(5) Continuing work on basic device designs to provide a starting point for special requirements.

PUBLICATIONS

None

SOLID PROPULSION, TEST METHODS, EQUIPMENT,
SAFETY, AND SUPPORT (731-28)

EXPERIMENTAL ENGINEERING CONTRACT MANAGEMENT

NASA Work Unit 731-28-06-09-55

JPL 331-80101-2-3810

W. Gin

OBJECTIVE

The objective of this program is to provide technical management of contracts that are under the program management of NASA Office of Advanced Research and Technology, Solid Propulsion Experimental Engineering, Code RPM.

STATUS

Under this task, the following contracts were technically managed for RPM during this report period:

(1) "Solid Propulsion System Reliability," NAS 7-459, TRW Systems.

(2) "Nozzle Reuse Program, III," NAS 7-540, TRW Structures Division.

(3) "Auxiliary Propulsion for Spacecraft," NAS 7-656, LMSC.

(4) "Pyrostrand Restartable Nozzle Materials," NAS 7-700, Atlantic Research.

(5) "Fluid Controlled Motor for Space," NAS 7-701, Lockheed Propulsion Co.

(6) "Carbitex Nozzles," NAS 7-695, Carborundum Company.

(7) "HEUS Rocket Motor," NAS 7-688, Hercules.

(8) "Lockseal TVC for 260-inch Motor," NAS 7-707, Lockheed Propulsion Co.

(9) "Flexible TVC for 260-inch Motor," NAS 7-709, Thiokol-Wasatch.

An oral semiannual report was made on all contracts being managed by JPL to NASA headquarters RP personnel and NASA Center representatives on November 21, 1968, at JPL.

PROJECTED ACTION

During the next report period, it is anticipated that two new contracts will be transferred from headquarters technical management to JPL technical management. These are NAS 7-7-3, "Advanced Upper Stage Propulsion Systems," being performed by McDonnell-Douglas at Huntington Beach, and NAS 7-309, "Economics of Solid Propulsion Systems," being performed by Stanford Research Institute. Contract amendments are being made to both these contracts in conjunction with the transfer of technical management.

PUBLICATIONS

None

RESEARCH PROGRAM SRT (129)

FLUID PHYSICS RESEARCH (129-01)

BOUNDARY LAYER TRANSISTION STUDIES

NASA Work Unit 129-01-04-03-55

JPL 329-10901-1-3270

J. M. Kendall, Jr.
L. M. Mack

OBJECTIVE

The objective of this work unit is to explore the relationship between stability and transition; to identify the source of boundary layer disturbances present in supersonic tunnels.

PROGRESS

Experimental — J. M. Kendall, Jr.

An experimental study of the energy transfer from a traveling pressure field to a laminar boundary layer has begun in order to understand the origin and characteristics of the fluctuations appearing in supersonic wind tunnel boundary layers. These oscillations subsequently are amplified to turbulence. The pressure disturbances in a supersonic tunnel, which are generated by the turbulent wall boundary layers, travel at about half the stream speed. Thus there exists in the irradiated laminar layer one lamina whose speed equals that of the pressure pattern. The fluid there experiences a persistent pressure gradient. The energy so transferred appears as perturbation energy growth and as increased dissipation. This energy augments the Tollmien-Schlichting amplification and may help explain why at certain Mach numbers transition occurs at relatively low values of overall Tollmien-Schlichting amplification.

Circumstances limit the present investigation to subsonic speeds. The first goal was to demonstrate beyond reasonable doubt the importance of matching the pressure field propagation speed to the stream speed. This was done by moving a bluff object, a cylinder, in proximity to a flat plate boundary layer at various speeds. When the object was moved downwind at about three-tenths stream speed, transition occurred on the plate. At slightly higher or lower speeds than the critical range, large amplitude laminar waves were produced.

At greater variance from the critical speed, including upstream motion at the critical speed, virtually no disturbance was created in the test layer.

A more realistic experiment is in progress. A wavy wall set near and parallel to a flat plate imposes a traveling pressure disturbance of variable speed upon the plate boundary layer. Tollmien-Schlichting waves of the principal length are not amplified for the present range of Reynolds numbers, so that the energy growth which is observed in the laminar layer is due to forcing. X-phase measurements show that the boundary layer oscillations propagate in the same direction and with the same speed as the pressure disturbance. Preliminary results show that the growth and the amplitude and phase through the layer depend upon the propagation direction. The experiment is continuing with emphasis upon improvement of experimental techniques, whereupon the energy transfer can be determined quantitatively.

Application of Linear Stability Theory to the Transition from Laminar to Turbulent Flow — L. M. Mack

The extensive work of the last few years on the laminar stability theory has advanced our understanding to the point where it is now feasible to consider the direct application of the theory to the transition problem. The previous work was directed toward the study of the amplification rate, which is the best criterion for characterizing the relative stability of various boundary layers. However, for the transition problem, the important quantity is the growth of a constant-frequency disturbance as it travels through the boundary layer. Accordingly, a large number of computations have been made to obtain the amplitude ratio (with respect to initial amplitude) as a function of Reynolds number. In particular, the amplitude ratio of the most unstable frequency has been computed as a function of Mach number at a fixed Reynolds number for a 60° wave, which is close to the most unstable wave at all Mach numbers above 1.5. In contrast to a two-dimensional wave, which is almost stable between $M_1 = 2$ and 4, the 60° wave has large amplitude ratios in this Mach number range.

One of the most puzzling transition observations is the increase of transition Reynolds number with unit Reynolds number. If an attempt is made to correlate transition Reynolds numbers with the amplitude ratio of the most unstable frequency, as was successfully done by A. M. O. Smith for low-speed flow, no unit Reynolds number effect can be obtained because this ratio is independent of unit Reynolds number. However, if the boundary-layer response is considered along with a spectrum of input disturbances, then there is a unit Reynolds number effect. The reason is that the nondimensional frequency parameter of stability theory, but not of the input disturbances, is $\beta\nu/U^2$ (β is the circular frequency, U/ν the unit Reynolds number). Consequently, as U/ν changes, so does the relation of the boundary-layer response to the input spectrum, and consequently the disturbance amplitude at a given x-Reynolds number will be a function of unit Reynolds number.

Unfortunately, not enough is known of the input disturbance spectrum to make a definitive calculation of this effect. However, a calculation has been carried out at $M_1 = 4.5$ based on the assumption that the input spectrum has the same shape as the far-field power spectrum of the sound radiated from the turbulent side-wall boundary layers of a supersonic wind tunnel. A second assumption is that the disturbance energy is distributed uniformly through all wave angles. With the response to a uniform input computed from stability theory for several wave angles and Reynolds number, the disturbance spectrum can be computed as a function of x-Reynolds number for a fixed unit Reynolds number. The integral of the disturbance spectrum gives the amplitude. The results of the calculation show that there is a marked effect of unit Reynolds number which reduces the disturbance amplitude at a fixed Reynolds number as the unit Reynolds number increases.

PUBLICATIONS

Meetings and Symposia Papers

1. Mack, L. M., "Amplitudes of Two-and Three-Dimensional Linear Disturbances in the Laminar Boundary Layer up to $M_1 = 10$," Annual Meeting of the Division of Fluid Dynamics, American Physical Society, Seattle, Washington, November 25-27, 1968.

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HEAT TRANSFER FROM ACCELERATING AND DECELERATING IONIZED GAS FLOWS

NASA Work Unit 129-01-05-10-55

JPL 329-10701-0-3830

P. F. Massier

OBJECTIVE

The general objective of this task is to experimentally and theoretically investigate fundamental heat transfer and fluid dynamics phenomena of high-temperature gas and plasma flows. Included is the evaluation of the influence of ionization, large property variations, swirl, acceleration and deceleration on convective heat transfer, and fluid dynamics. The motivation for this investigation resulted from the high heat transfer rates that can occur to some of the elements of electrical propulsion devices. The fraction of the total energy of the gas that is transferred to the coolant in such devices can be significantly higher than that encountered in chemical propulsion thrust chambers.

The first objective for FY 69 is to complete the computer programming of a theoretical investigation of heat transfer from nonadiabatic core flows — not including ionization, radial gradients, or swirl — and to compare the results with experimental data.

A second objective of FY 69 is to continue the experimental investigation which was initiated previously of heat transfer from high-temperature weakly ionized swirling flows. Swirl has commonly been introduced into arc-heated flows to help stabilize the arcs. Sufficient experimental evidence exists that indicates convective heat transfer from such flows is generally higher than from nonswirling flows.

NONADIABATIC CORE FLOW ANALYSIS

A method for predicting convective heat transfer from an internal laminar flow that has a nonadiabatic core has been formulated. The analysis also includes the effects of flow acceleration, radial pressure gradients, swirl, and ionization.

This is applicable to variable area, axisymmetric channels. Other features of the analysis were discussed in a previous Progress Report, TM-33-322, Vol. II.

The conservation equations have been approximated numerically and are programmed on a digital computer. Numerical solutions have been obtained for high-temperature gas flow through a highly cooled tube to investigate the flow structure and heat transfer to the tube wall. The thermal boundary layer that grows along the cooled tube was found to extend to the centerline at a location about 7-tube radii downstream of the inlet of the tube whose length was 14-tube radii. Predicted velocity and enthalpy distributions across the flow were in good agreement with measurements at a calorimetric probe station about 3-tube radii downstream of the inlet. At the tube exit, the predicted enthalpy at the centerline was about 5% less than at the tube inlet. Consequently, the core of the flow leaving the tube and entering the supersonic nozzle is believed to be nonadiabatic. The predicted heat flux to the tube wall was somewhat less than measured in the inlet region of the tube. However, there was good agreement in the latter portion of the tube, especially near the tube exit.

Programming of this analysis is being continued to take into account the effect of a changing cross-sectional area such as exists in a nozzle.

SWIRLING FLOWS

A few experiments have been conducted to evaluate the heat transfer from swirling arc-heated argon to the cooled walls of a constant-diameter tube and a convergent-divergent nozzle. Tangential velocity distributions in the tube located upstream of the nozzle are determined from radial distributions of the pressure measured along the end wall, and radial distributions of enthalpy are determined by means of a calorimetric probe. A symmetrical radial distribution of the enthalpy was found to exist in the tube and it was possible to establish the edge of the thermal boundary layer. Extending radially inward from the edge of the boundary layer, the enthalpy remained constant to a location about 0.4 of the tube radius measured from the centerline. Then at 0.2 of the tube radius a maximum in the enthalpy occurred from where the enthalpy decreased to the centerline. Similar distributions of the temperature had been found in previous experiments using ambient temperature gas. A more detailed discussion appears in Ref. 2.

The high-temperature experiments have been suspended until FY 70 when additional funding is anticipated.

DIAGNOSTICS

Radial distributions of temperature and/or electron density in an axisymmetric plasma are obtained commonly from edge-on spectroscopic observations that have been transformed to yield radial distributions of emission. It is sometimes difficult or inconvenient to make edge-on or transverse observations across the whole plasma and only one observation (for example, along a single diameter of the plasma) must suffice. The question then arises as to how the weighted temperature determined from observations at a single location should be interpreted. It has been shown (SPS 37-52, Vol. III) that temperature determined spectroscopically from off-axis or edge-on views tend to agree closely with the maximum temperature in the path of view. The agreement is poorest at the center of the duct, and also tends to decrease with an overall increase in temperature level. It is concluded that Abel inversion of off-axis intensity data to obtain radial intensity distributions is not necessary when the conditions of the present treatment are met. Thus, the transverse temperature distribution obtained from scanning may be taken as the true radial distribution of temperature with very little error. These results are not general, however, and do not necessarily apply when the center temperature greatly exceeds 10^4 K or when the ionization fraction α begins to approach 0.1 or more.

REFERENCES

1. Back, L. H., "Flow and Heat Transfer in Laminar Boundary Layers with Swirl," submitted to the AIAA Journal.

2. Massier, P. F., "Radial Distribution of Enthalpy in a High-Temperature Swirling Flow," SPS 37-51, Vol. III, June 30, 1968, pp. 128-130.

PUBLICATIONS

Meetings and Symposia Papers

1. Massier, P. F., Back, L. H., and Roschke, E. J., "Heat Transfer and Laminar Boundary Layer Distributions in an Internal Subsonic Gas Stream at Temperatures up to 13,900°R," presented at the AiChE-ASME Heat Transfer Conference and Exhibit, Philadelphia, Pa., August 11-14, 1968, ASME Paper 68-HT-16.

2. Back, L. H., "Effects of Severe Surface Cooling and Heating on the Structure of Low-Speed, Laminar Boundary Layer Gas Flows with Constant Free-Stream Velocity," presented at the AiChE-ASME Heat Transfer Conference and Exhibit, Philadelphia, Pa., August 11-14, 1968, ASME Paper 68-H-23.

SPS Contributions

1. Roschke, E. J., "Special Applications For Spectroscopic Scanning of Internal Plasma Flows," SPS 37-52, Vol. III, pp. 106-109, August 31, 1968.

LASMA HEAT TRANSFER WITH APPLIED MAGNETIC AND ELECTRIC FIELDS

NASA Work Unit 129-01-05-11-55

JPL 329-10601-0-3830

P. F. Massier

OBJECTIVE

The general objective of this task is to investigate the effects of applied electric and magnetic fields on the heat transfer and fluid dynamics of partially ionized gas flows. The regions of investigation include subsonic and supersonic internal laminar flows. Experimental information of this nature is not readily available, but is important in the prediction of electrode heat transfer in electrical propulsion devices and power generators. In such devices, anode heat transfer may be very high and can easily cause failure by burnout.

STATUS

Experimental measurements have been completed on the effects of an applied, transverse magnetic field upon heat transfer from partially ionized argon in a square channel. These results are being reduced and analyzed. In addition, a nonequilibrium analysis of electrode heat transfer has been initiated, and a series of experiments have been planned on the blowing effect and electrode heat transfer for cross flow between segmented parallel-plate electrodes.

Experiments on Channel Flow with a Transverse Magnetic Field

The apparatus and method of acquiring data for heat transfer experiments in a 2 x 2-in.-square channel have been described in SPS 37-51, Vol. III, pp. 130-135. Argon gas is preionized by means of a conventional electric-arc heater discharging into a square duct. Steady-state heat transfer is measured at several downstream stations by calorimetry for various flow conditions and for applied magnetic field strengths of from zero to approximately 10,000 gauss. Data have been acquired for two directions of the transverse magnetic field and for flow with and without a swirl component. The flows were laminar and, in most cases, subsonic. Only the magnetic field strength is varied during a particular series of tests; the argon mass rate of flow, pressure in the test section, and the electric power applied to the gas in the arc-heater tend to remain approximately constant. Observations have indicated that Lorentz forces are produced in the gas by the applied magnetic field in both the axial and transverse directions, and these effects seem to become more pronounced the higher the initial Mach number.

Heat transfer was determined individually for each of the four walls and effects with changing magnetic field strength were observed. Theoretically, changes in heat transfer brought about by a magnetic field alone should be accounted for by joule heating. Experimental heat flux values were expressed in terms of an appropriate nondimensional heat flux and correlated with calculated values of the joule heating parameter. To date, three tests have been examined in detail. For a subsonic case, the maximum observed increase in nondimensional heat flux was 80% over the result with zero applied field. One case in which the flow was initially supersonic indicated an increase in nondimensional heat flux by a factor of six compared to the zero field result. Trends and magnitudes established by experiment show approximate agreement with the simplified theoretical prediction.

Plans are to complete this work during the second half of FY 69.

Electrode Heat Transfer Experiments

Two parallel flat-plate electrodes, each containing sixteen 0.25 x 0.25-in. segments that are electrically insulated from each other have been installed in a transparent vacuum chamber for testing. Each segment is individually cooled with water so that heat transfer measurements can be made. The anodes are copper and the cathodes are tungsten. All segments can be connected to a common terminal or any pair of electrodes can be connected to a single power supply. Thus it will be possible to determine:

(1) Current, voltage, and heat transfer distributions for an electric field applied from a single source.

(2) The influence of upstream discharges on the heat transfer to downstream electrodes.

(3) Heat transfer and the influence of gas motion on discharges between electrodes that are offset in the transverse and longitudinal directions.

Testing of various flow conditions, power settings, and power connection arrangements will be initiated during the second half of FY 69.

Electrode Boundary Layer Analysis

A theoretical investigation has been initiated to determine heat transfer rates to electrodes in the presence of an electric field for a laminar boundary-layer flow of a two temperature plasma at an elevated electron temperature. The differential equations needed for the analysis were formulated for a quasi-neutral plasma with a small Hall parameter neglecting the blowing effect. The nondimensionalization of these equations established the importance of six different dimensionless parameters on heat flux. The present activity is concentrated on investigating different methods of solution and making necessary changes in the computation program. Debugging and obtaining solutions will occupy most of the effort available for this problem during the second half of FY 69.

PUBLICATIONS

Open Literature

1. Gardner, J. A., "Effects of a Dynamic Gas on Breakdown Potential," AIAA Journal, Vol. 6, No. 7, pp. 1414-1415, July 7, 1968.

SPS Contributions

1. Roschke, E. J., "Hall and Ion-Slip Effects in Channel Flows," SPS No. 37-52, Vol. III, pp. 109-113, August 31, 1968.

2. Roschke, E. J., "Further Heat Transfer Results with an Applied, Transverse Magnetic Field in a Square Channel," SPS No. 37-54, Vol. III, December 31, 1968.

Gardner, J. A., "Dynamic Gas Effects on the Breakdown Potential of Helium," SPS No. 37-52, Vol. III, pp. 119-121, Jet Propulsion Laboratory, Pasadena, Calif., August 31, 1968.

Gardner, J. A., and Noel, M. B., "Potential Distribution Associated with a Glow Discharge Influenced by a Transverse Gas Flow," SPS No. 37-53, Vol. III, October 31, 1968.

HEAT TRANSFER AND FLUID DYNAMICS IN ACCELERATING AND DECELERATING FLOWS

NASA Work Unit 129-01-05-12-55

JPL 329-10401-0-3830

P. F. Massier

OBJECTIVE

The general objective of this task is to investigate experimentally the structure of supersonic and subsonic, accelerating and decelerating, internal flows and the convective heat transfer from these flows. During FY 69, emphasis is placed on three supersonic flow regimes:

(1) Flow between an oblique shock wave and a surface.

(2) Single shock boundary layer interaction.

(3) Compression by multiple shock waves, referred to as pseudo shocks.

Both boundary layer and heat transfer measurements are being made in some of these flow regimes which will provide information related to hypersonic inlet research for air-breathing propulsion engines. These heated air studies with turbulent boundary layers are being conducted within the range of Reynolds numbers and stagnation temperatures found in hypersonic inlets at a Mach number of 3.5, which is at the low end of the range of interest. With the available funding, measurements will be obtained at one stagnation temperature, but boundary layer measurements originally planned in the pseudo shock region will not be made.

APPROACH

Compressed air flows through an upstream duct, a nozzle, and then through the diffuser where the measurements are made. The flow undergoes a six-degree compressive turning at the diffuser inlet where an oblique shock is generated. Reflections occur farther downstream. The flow then passes through the pseudo-shock structure and discharges into the atmosphere. Heat transfer to the cooled walls is determined by calorimetry for heated air flow.

Temperature and velocity distributions in the boundary layer and internal flows are determined from probe measurements. Static pressures are measured along the wall. Gas stagnation pressure ranges from 80 to 150 psia, and the stagnation temperature of the heated air is 1500°R.

BOUNDARY LAYER MEASUREMENTS

Miniature boundary layer probes with flattened tips have been developed, and they are now being used. The pitot probe is 0.005 in. high and the shielded, aspirating thermocouple probe is 0.010 in. high. Probe measurements will be made at two locations upstream, and two locations downstream of a shock boundary layer interaction. From these measurements the change in size and structure of the boundary layer as well as the shock orientation will be determined. Boundary layer measurements have been made at one location; however, because of the large thickness of the boundary layer, some upstream sections of the test apparatus will be removed to thin the layer before proceeding with the tests.

HEAT TRANSFER AND COLD FLOW TESTS

Several tests have been conducted in which heat transfer measurements have been made to determine the heat flux distribution along the entire system.

Wall static pressure distributions have been obtained for cold flow. These do not have sufficient resolution, however, to establish that the wall static pressure rise is continuously increasing and that the flow does not separate. Therefore, additional measurements will be made using a new duct segment to obtain greater detail in the static pressure distribution.

Two papers, relating to the general objectives have been written; they pertain to experimental work completed during the previous fiscal year. One is on the effect of cooling on a turbulent boundary layer (Ref. 1). The other is a technical note (Ref. 2) on the transonic flow in a nozzle with a small radius of curvature relative to the throat radius.

REFERENCES

1. Back, L. H., Cuffel, R. F., and Massier, P. F., "Effect of Cooling on the Structure of a Low-Speed, Turbulent Boundary Layer," paper in editorial and approval process.

2. Cuffel, R. F., Back, L. H., and Massier, P. F., "The Transonic Flow Field in a Supersonic Nozzle With Small Throat Radius of Curvature," accepted for publication in the AIAA Journal.

PUBLICATIONS

None

ELECTRO PHYSICS RESEARCH (129-02)

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PHOTOCHEMISTRY

NASA Work Unit 129-02-01-04-55

JPL 329-21001-1-3280

W. B. DeMore

OBJECTIVE

The objective of this work unit is to contribute fundamental information on the chemical behavior of photo-excited atoms, molecules, and free radicals. Particular emphasis is placed on problems relevant to planetary atmospheres and photochemical air pollution.

PROGRESS

Photochemistry of Carbon Dioxide

In recent years there has been considerable interest in the possible existence of a new oxide of carbon, the CO_3 molecule. Several workers have postulated that this species is formed by the reaction $O(^1D) + CO_2 \rightarrow CO_3$, but definite information has been lacking. We have studied this problem by the photolysis of O_3 - CO_2 mixtures in liquid CO_2 or liquid SF_6 at -50°C. The advantages of this method are that the liquid solutions offer a favorable environment for stabilization of the initially vibrationally excited CO_3, and at the same time the formation of a stable CO_3 can be detected unambiguously through its influence on the quantum yield of O_3 photolysis. The results which have been obtained prove that CO_3 is formed in the $O(^1D)$ - CO_2 reaction, and also show that it is formed with high collisional efficiency.

The following overall mechanism for CO_3 formation has been proposed:

$$O(^1D) + CO_2 \rightleftarrows CO_3^* \qquad (1,2)$$

$$CO_3^* \rightarrow CO_2 + O(^3P) \qquad (3)$$

$$CO_3^* + M \rightarrow CO_3 + M \qquad (4)$$

In addition to proving the existence of the CO_3 molecule, these experiments have provided the first insights into its chemical behavior. It has been found that CO_3 does not react rapidly with either O_2 or O_3, but does attack hydrocarbons. The manner of reaction with hydrocarbons is similar to that previously found for $O(^1D)$ (Ref. 1), with the exception that CO_3 shows preferential reaction with the weaker C-H bonds in the molecule. These properties have suggested a possible role of CO_3 in the photochemistry of air pollution.

Reactions of Atomic Oxygen

The reaction $O(^3P) + O_3 \rightarrow 2O_2$ plays a dominant role in determining atmospheric O_3 concentrations. However, despite many attempts the rate and temperature coefficient of this reaction have not been established with the accuracy needed for aeronometric calculations. By application of our technique of O_3 photolysis in liquid SF_6, we have succeeded in making rate measurements of this reaction relative to other known reactions of atmoic oxygen. The results indicate that the activation energy is considerably lower than previously indicated.

Similar experiments have been used to study the reactions of $O(^3P)$ with hydrocarbons, which are not well understood despite their importance in combustion and air pollution. The reason for the difficulty is that primary processes cannot be distinguished from secondary processes under the usual gas phase reaction conditions. Our own methods involving photolysis in inert solvents avoid problems of this type, and we have been able to obtain definitive information on the initial reaction mechanisms. It has been found, for example, that unlike $O(^1D)$ (Ref. 1), $O(^3P)$ does not react with hydrocarbons by removal or displacement of two hydrogen atoms.

REFERENCE

1. DeMore, W. B., and Raper, O. F., "Reaction of Singlet-D Atomic Oxygen with Alkanes at 87°K," JPL SPS 37-43, Vol. IV, p. 287, February 1967.

PUBLICATIONS

Meetings and Symposia Papers

1. DeMore, W. B., "Kinetics of the Gas Phase Ozonation of Ethylene and Acetylene," 156th National Meeting Am. Chem. Soc., Atlantic City, New Jersey, September 8-13, 1968.

Open Literature

1. DeMore, W. B., "Arrhenius Constants for the Reactions of Ozone with Ethylene and Acetylene," International J. of Chem. Kinetics, in press.

2. DeMore, W. B., "Reactions of $O(^1D)$ with Hydrocarbons in Liquid Argon," J. Phys. Chem., in press.

THERMIONICS RESEARCH

NASA Work Unit 129-02-01-07-55
JPL 329-21101-1-3450

K. Shimada
S. Luebbers

OBJECTIVES

The long-range objective of this work is to better understand the physics involved in thermionic energy conversion. With this understanding, possible methods for improving converter performance will become apparent. The current work is concerned with ionization phenomena in cesium gases (preignition characteristics), guard-ring converter experiments, and geometry and impurity effects upon electron emission.

PREIGNITION CHARACTERISTICS

During this report period, further analyses of data obtained from a fixed-gap cesium diode were completed, and additional data were obtained from a variable-gap diode that was acquired from the Marine Engineering Laboratory, Annapolis, Md., as surplus equipment. A guard ring and sapphire viewport on the new diode as well as the variable-gap mechanisms allowed us to eliminate a number of uncertainties that existed in our past results.

We confirmed that the diode current increases at two different rates in the preignition region of the volt-ampere curve depending on the diode voltage; Schottky-like and avalanche-type increases occurred for smaller and larger voltages, respectively. It was also found that the current avalanche was accompanied by an "anode glow" of the cesium discharge and that the rate of current increase in this avalanche region was related to the product of cesium pressure p, and interelectrode distance d (p x d). Phenomenologically, an increase of current in the preignition region is explained by how the potential barrier, which limits current flow, varies with applied voltage. In the Schottky-like region, appearing at smaller applied voltages, the barrier height varies linearly with applied voltage. Here cesium ions are produced at the emitter by surface ionization. In the avalanche region appearing at larger voltages, ions produced in the interelectrode gap by collisional processes, especially near the collector, also contribute toward lowering of the barrier.

Guard-Ring Converter

A guard-ring converter with a fixed interelectrode gap, having a geometry similar to that of a practical thermionic energy converter, has been purchased. The guard ring of this converter is unique in that it is bonded to the collector by an extremely thin alumina layer. This diode will be used to perform controlled experiments on sidewall currents that have existed in diodes with cavity emitters and in other diodes with practical geometries.

A diode teststand and a vacuum chamber which houses the teststand have been completed. Electronic circuitry which automatically equalizes the guard-ring potential with the collector potential is nearly completed.

Geometry and Impurity Effects

The plasma-immersion-probe technique has been used to study impurity effects upon the electron emission from tantalum emitters and will be applied to the study of emission-modifying effects caused by probe geometry. In this technique, the emitter material under investigation is mounted on a probe which extends into a cesium discharge. The probe is directly heated by a half-wave current and the emission area is established by electrically isolating the support structure with ceramic insulators. The probe volt-ampere characteristics are then measured to determine the temperature-saturated emission.

The results of experiments with tantalum-wire probes immersed in a cesium vapor have shown that an oxygen impurity level of 0.14 atomic percent increases the electron emission of the probe by more than an order of magnitude above that expected from "clean" tantalum. The effect of high-temperature flashing (2470°K) is to reduce the electron emission at high probe temperatures, while the electron emission at lower probe temperatures still remains an order of magnitude above the clean tantalum value. (Flashing merely reduced the oxygen-impurity level to 0.12 atomic percent.) The observed high-emission behavior was directly attributed to oxygen dissolved interstitially in the tantalum lattice.

A third plasma-immersion-probe tube containing planar and cavity probes is nearing completion. These probes will be used differentially to ascertain probe-geometry effects upon the electron emission from rhenium surfaces.

FUTURE PLANS

Experiments as well as analyses will be continued to arrive at a plausible model that describes the preignition characteristics of cesium thermionic diodes. Particular emphasis will be placed on the effect of electron-impact ionization occurring in the avalanche region of volt-ampere curves.

Differential probe experiments, using the plasma-immersion-probe technique, will be performed on two planar probes, one with and one without a cavity. This experiment will be carried out in order to identify the true geometry effects on electron emission.

Experiments will be carried out on the guard-ring converter to refine data and eliminate uncertainties, such as sidewall currents, which existed in our past data.

Feasibility of fabricating a plasma-immersion-probe tube in a metal-ceramic envelope will be explored. This tube will have a larger range of operating temperatures and will be equipped with demountable probes.

Increased understanding of impact ionization and electron emission in a diode with a cavity emitter will be utilized to determine suitable geometries for thermionic energy converters which operate with reduced plasma losses.

PUBLICATIONS

Meetings and Symposia Papers

1. Shimada, K., "Side-Wall Currents in Unignited Hardware-Type Thermionic Energy Converters," presented at the Thermionic Conversion Specialist Conference, Boston, Mass., Oct. 14-16, 1968.

2. Stapfer, G., and Shimada, K., "Electrical Testing of a 6-Converter Generator," presented at the Thermionic Conversion Specialist Conference, Boston, Mass., Oct. 14-16, 1968.

3. Luebbers, S., and DeSteese, J., "Oxygen Effects in Tantalum Thermionic Emitters," presented at the Thermionic Conversion Specialist Conference, Boston, Mass., Oct. 14-16, 1968.

Open Literature

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RADIATIVE TRANSPORT AND INELASTIC RATE PROCESSES IN PARTIALLY IONIZED GASES

NASA Work Unit 129-02-01-08-55

JPL 329-21901-0-3830

G. R. Russell

OBJECTIVE

The overall objective is to study, both theoretically and experimentally, radiative transport and inelastic rate processes in partially ionized gases. A prerequisite and associated primary objective is the development of plasma diagnostic techniques. Particular attention is focused on the interaction of radiation and rate processes such as ionization, recombination, and the population of excited states in nonequilibrium plasmas. This research is fundamentally related to the basic problems associated with electrical propulsion devices, MHD generators, and gaseous lasers which operate almost entirely in a region where the working fluids are not in equilibrium. Determination of rate processes in static CO_2 and argon lasers, and the study of instabilities in magnetogasdynamic lasers are emphasized in FY 69.

STATUS

Rate Processes in Magnetogasdynamic Lasers

In the latter part of FY 68, a theoretical study was initiated to determine the feasibility of using a cross-field accelerator to produce atomic population inversions in inert gases. This study indicated that inversions could be produced in the exhaust of a cross-field device and that, for argon, the inversions are to be expected in the energy range $13 < E < 15$ eV. To more completely determine what particular lines are likely to be inverted, the kinetic model has been extended to include ten excited atomic states instead of four. Solutions obtained with the expanded kinetic model show that, as the electron temperature is rapidly reduced at the exit of the channel, inversions appear at several different energy levels at various points downstream of the channel exit. When the electron temperature decays to an asymptotic value approaching the heavy particle temperature, both the 3d-4p and 5p-5s transition arrays remain inverted for about a meter downstream of the channel exit. Certain lines within these arrays are expected to lase in the infrared at wavelengths from about one to two microns.

In the latter half of FY 69, solutions will be obtained for krypton and xenon. It is expected that population inversions for these gases will also be in the infrared in the same wavelength range (1-2 microns).

A paper summarizing the current work dealing with cross-field lasers is being completed, and will be submitted for publication in the third quarter of FY 69.

Instabilities in Nonequilibrium Plasmas

Because it was expected that instabilities might play a role in the performance of magnetogasdynamic lasers, a theoretical study was initiated in FY 69 to study this problem. Specifically, the amplification factor for dispersive waves in a slightly ionized monatomic plasma is to be investigated.

In the study, viscous effects are neglected (the Reynold's number is large) and only a moderately large magnetic field is considered (the ion Hall parameter is small). The conditions of the analysis make it germane to MHD generator and laser channels. The basic fluid equations are those resulting from 13-moment solutions to Boltzmann's equations for the plasma components. The radiative loss is calculated, using the first three terms in the Taylor series expansion of the radiation source function in optical depth (Ref. 1). The radiation transport is found to consist of an optically thin loss, which includes the continuum radiation, line radiation from transitions between upper energy levels, and photon escape in the wings of optically thick lines (such as resonance lines), plus a diffusion loss for the thick line cores. Formulation of model equations for the excited state kinetics is presently being completed. Inelastic collision rates are obtained by integration of the classical Gryzinski excitation and ionization cross sections. A preliminary calculation of the forzen and equilibrium limits has been made. One result of this calculation (for electro-thermal waves) is that the inclusion of electron thermal diffusion changes the character of the interaction of the electron heat flux with the plasma waves. At equilibrium, thermal diffusion may counteract the damping action of electron heat conduction to produce a disturbance amplification.

Electron Recombination Rates

The experimental and theoretical work dealing with electron collisional-radiative recombination rates has been completed and a paper summarizing the work has been accepted for publication in the Journal of Chemical Physics (Ref. 2).

The measurement of dissociative recombination and molecular ion production rates and their temperature dependence has been finished and the results will be published in the Physical Review. The most important result of the work is that the dissociative recombination rate is shown to depend on the atomic temperature as well as on the electron temperature. It is shown that the previous controversial experimental results published in the literature can be reconciled if the atomic temperature is taken into account.

Rate Processes in Static CO_2 and Argon Ion Lasers

In the first half of FY 69, experimental work has been started to study rate processes in static CO_2 lasers. A steady-state and pulsed CO_2 laser has been constructed. Langmuir probes, a spectroscope, and a fast rise infrared detector have been used to determine the laser plasma properties. Hopefully, the possible mechanisms responsible for the population inversions (associative excitation, resonance intermolecular collisonal excitation, and cascading) can be understood. Some interesting preliminary results on the time delay of laser output relative to the discharge current have been obtained.

A steady-state argon ion laser has also been constructed. This laser will be used to study the effect of instabilities and certain kinds of buffer gases and impurities on the performance of the laser. Preliminary results indicate that the plasma in the laser becomes turbulent when the lasing action is occurring. This turbulence will be studied in detail in the latter half of FY 69, and will be correlated if possible with the theoretical work dealing with acoustic and electrothermal instabilities.

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PUBLICATIONS

Meetings and Symposia Papers

1. Chen, C. J., "Temperature Dependence of Dissociative Recombination and Molecular-Ion Formation in He, Ne, and Ar Plasmas," presented at the annual meeting of the Division of Plasma Physics (APS), November 1968, Miami Beach, Fla.

Open Literature

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1. Harstad, K., "Transport Equations for Gases and Plasmas Obtained by the 13-Moment Method: a Summary," JPL Technical Report 32-1318, October 1, 1968.

PHYSICS OF MOLECULAR INTERACTIONS

NASA Work Unit 129-02-01-09-55

JPL 329-20301-1-3280

J. King, Jr.
M. Geller
L. Lane

OBJECTIVE

The long-range objective of this program is to investigate the reactions and interactions of ions and excited species in the gas phase. A study of ion-molecule reactions is undertaken for the purpose of selecting those reactions with potential laser applications and relevance to planetary atmospheres. The excited states produced in the ion-molecule reactions will be studied both for their light emission characteristics and their subsequent reactions with neutrals to form other excited species.

PROGRESS

The feasibility study of the utilization of the Ion Cyclotron Resonance (ICR) technique to produce ion-molecule lasers is continuing. During the report period the energy dependence of the He^+ - N_2 reactions has been investigated. The two reactions occurring in the system are

$$He^+(^2S) + N_2\left(^1\Sigma_g^+\right) \rightarrow He(^1S) + N_2^+\left(C\ ^2\Sigma_\mu^+,\ v = 3, 4\right)$$

followed by predissociation

$$\rightarrow He(^1S) + N(^4S) + N^+(^3P) \qquad (1)$$

and the charge exchange between He^+ and N_2

$$He^+(^2S) + N_2\left(^1\Sigma_g^+\right) \rightarrow He(^1S) + N_2^+\left(X\ ^2\Sigma_g^+\right) \qquad (2)$$

A study of the energy dependence of reactions (1) and (2) indicated that the two reactions obey different energetics. This difference was exemplified in the ICR double resonance spectra (see JPL SPS 37-46, Vol. IV p. 205). A large dip occurred in the center of the double resonance spectrum of N^+ but was absent in the spectrum of N_2^+. The occurrence of the dip indicates that the rate constant for N^+ production, unlike that for N_2^+, goes through a maximum as the kinetic energy of He^+ increases. This peculiar line shape has previously been observed with reactions where it had been definitely established that a maximum occurred in the rate constant vs. energy curve (see JPL SPS 37-50, Vol. III p. 231).

Also, during the report period a significant discovery was made in the investigation of ion-molecule reactions occurring in CO_2. When CO_2 is bombarded with 50 eV electrons, large quantities of O^+ are formed.

$$CO_2 + e^- \rightarrow CO + O^+ + 2e^- \tag{3}$$

Through double resonance experiments it was discovered that the product O^+ ion reacts with CO_2 to form O_2^+.

$$O^+ + CO_2 \rightarrow O_2^+ + CO \tag{4}$$

The thermal rate constant for reaction (4) was measured to be $2.0(\pm 0.2) \times 10^{-9}$ cm^3/sec. This is a very fast reaction where essentially each collision leads to reaction. It was also discovered by utilizing double resonance techniques that O_2^+ is produced by another reaction in pure CO_2.

$$CO_2^+ + CO_2 \rightarrow O_2^+ + CO \tag{5}$$

The energy dependence of this reaction is currently being investigated.

The study of the ion-molecule reactions occurring in rare gas-methane mixtures is continuing. It has been found that both CH_2^+ and CH_3^+ are produced when methane is bombarded by He^+ ions. The energetics of the reactions are being studied using the newly developed techniques.

The monochromator, to be used in the photoionization experiments, has arrived and is being put into operative condition. The photoionization ICR spectrometer will allow more precise energy measurements to be made.

In the theoretical investigations, calculations have been completed on the molecules BeH_2, BH_2^- and NF_2^+ using the program MOSES — Molecular Orbital Self-Consistent Field Energy System. Work at present is being concluded on the systems CF_2, O_3 and $BeLi_2$.

The molecule, BeH_2, has been determined to be linear with a total energy (believed to be within 0.001 a.u. of the Hartree-Fock limit) of -15.773 a.u. (1 a.u. = 27.21 eV). The Be-H distance is 1.32 Å, the dissociation energy into atoms is 7.47 eV and the correlation energy is 0.168 a.u. The largest basis set used was Be - $11^s7^p1^d$ and H - $7^s5^p1^d$. Force constants, vibrational frequencies and zero point energy have also been calculated.

The results for NF_2^+ show a total energy of -252.68 a.u. (expected to be within 0.3 a.u. of the Hartree-Fock limit). The geometry is an N-F distance of 1.281 Å and an F-N-F angle of 108°. The geometry should be correct to within 2%. Other properties have been calculated and the complete results have been submitted for publication.

PUBLICATIONS

Meetings and Symposia Papers

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DETERMINATION OF ELECTRONIC POPULATION INVERSIONS IN MAGNETOGASDYNAMIC DEVICES

NASA Work Unit 129-02-01-10-55

JPL 329-22301-0-3830

G. R. Russell

OBJECTIVE

A primary objective of this work unit is to determine the feasibility of producing electronic population inversions in magnetogasdynamic devices. A secondary objective is to study, both theoretically and experimentally, the detailed mechanisms responsible for the population inversions, and relationships that exist between device size and magnitude of the coherent radiation and device efficiency.

STATUS

Faraday Cross-Field Laser

Because of the positive results obtained from a theoretical study dealing with the production of population inversions in Faraday cross-field devices, an experiment has been started in the first half of FY 69 to detect population inversions in the exhaust of a cross-field accelerator. The experimental equipment has been designed and construction is approximately two-thirds complete. This experiment requires a Mach 3 jet of argon plasma with the following properties: atom stagnation temperature 3000°K, atom density 3.5×10^{16} cm^{-3}, electron temperature 2700°K, and electron density 1.5×10^{13} cm^{-3}. The equipment required to produce this jet is in operation and has been tested completely. The electromagnet required to provide the specified magnetic field distribution in the supersonic jet has been set up and calibrated. The accelerator duct, required to produce the atomic population inversions, has been completed, and is now being instrumented with an array of potential probes in the insulator walls. The accelerator utilizes 21 pairs of electrodes and provision is required to vary the current density and potential along the accelerator axis. Specifically, the required current density is near zero at the entrance and exit of the duct, and rises to a maximum of 5.5 A/cm^2 approximately one-third of the distance from the duct entrance. Also, the centerline potential must decrease monatomically from zero at the entrance to -67 volts at the exit. A power distribution system for the 21 electrode pairs has been designed to produce the required current and potential distributions, and is currently being constructed. The optical cavity, which will be located downstream of the accelerator duct, has been designed and its construction is nearing completion.

The entire experimental setup will be completed during the third quarter of FY 69. It is anticipated that initial experiments will be conducted during the fourth quarter of FY 69. The goal of these initial experiments will be to produce a continuous laser beam in the 1 to 2 μ region of the infrared spectrum.

MPD Arc

During the first half of FY 69, additional evidence concerning the degree of nonequilibrium in the MPD exhaust flume was obtained from Langmuir probe measurements that were compared with observations of both the atomic and ionic spectral lines of argon. Attempts to obtain direct evidence of population inversions in the MPD exhaust have been started.

It was reported earlier that the results obtained from spectroscopic observations of a large number of argon ion lines revealed that the upper energy levels do not exhibit a Boltzmann distribution. The data were evaluated with the aid of calculated values of the transition probabilities and included upper states with energies from 19.2 to 24.8 eV. Confirming experimental values of some of these transition probabilities for lines with high upper energy levels have now been obtained. A paper summarizing the measurements of these transition probabilities is currently being prepared.

An indication of the degree of nonequilibrium may be obtained by comparing the electron temperature, measured with a Langmuir probe, with the value obtained from the spectroscopic measurements. At a position on the plume centerline 32 cm downstream, the electron temperature was found to be 6000°K, the temperature obtained from the 4p levels only was 10,000°K and the temperature derived when the higher energy states were included was 25,000°K. At the same position, the temperature determined from four atomic lines was 6800°K. The average equilibrium stagnation temperature, calculated from the total gas enthalpy at the arc exhaust, was 8600°K. These results show that the relative intensities of ion lines in the plasma produced by the MPD arc used here yield incorrect results for the electron temperature. In addition, the results reveal that an apparent Boltzmann distribution of levels that include a limited energy range is insufficient evidence to justify a conclusion that the excitation and electron temperature are equal.

A comparison of the spectroscopic data with data obtained in a static argon ion laser (Ref. 1) revealed striking similarities, and suggested that inversions may exist in the plumes of MPD arcs. Therefore, evidence of enhancement of selected ion lines by stimulated emission was sought. Initial attempts, using an optical arrangement that permitted multiple passes of the laser beam through the plasma, showed definite amplification of the laser beam, although small vibrations of the experimental equipment proved to be bothersome. Solutions of the remaining technical difficulties are nearing completion, and it is expected that definitive results will be obtained in the third quarter of FY 69.

Study of Population Inversions in Alkali Metal Plasmas

An experiment using a flowing alkali metal plasma has been initiated in the first half of FY 69. The experimental arrangement consists of ionizing in an RF discharge the vapor generated in a molecular beam oven. The plasma is then allowed to expand freely through a small nozzle into a vacuum chamber cooled with liquid nitrogen. The expansion region is shielded from the excitation region to allow a very rapid recombination of the highly nonequilibrium plasma. It is expected that population inversions can be attained in the recombining jet. Potassium is currently being studied. The detailed spectroscopic measurements of the jet that are necessary for determining the existence of population inversions are in the initial stages.

Radiative and collisional transition rates are being calculated to estimate which excited states are likely to be inverted. Collisional rates calculated using the Gryzinski theory have been submitted for publication in the Journal of Chemical Physics (Ref. 2).

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PUBLICATIONS

Meetings and Symposium Papers

1. Russell, G. R., and Harstad, K. G., "Feasibility of Magnetogas-dynamic Lasers Utilizing Faraday Generators and Accelerators," Research Summary in Gas Lasers, NASA Headquarters Conference on Gas Laser Research, Washington, D. C., July 1968.

OPTICAL PHYSICS RESEARCH

NASA Work Unit 129-02-05-01-55

JPL 329-20101-1-3450

A. R. Johnston
R. J. Stirn

OBJECTIVE

The objective of the work on the electro-optic (E-O) effect has been to experimentally characterize the effect in certain materials. The apparatus at the Laboratory is capable of determining both the clamped and unclamped E-O response with the same sample. A comprehensive study has been made of $BaTiO_3$, including observation of the clamped and unclamped response as a function of light wavelength.

The objective of the work on the photoelectric response of barriers is to develop a photo detector, sensitive over a selected range of wavelengths, which can generate a modulated signal without the use of mechanical parts. In order to exploit the thin-film insulator sandwich or semiconductor Schottky barrier for this purpose, phenomena associated with these systems, such as the effects of the metal interface, amorphous structure of the thin films, and hot-carrier transport in thin-film metals and insulators, needs to be investigated.

The objective in the area of metal-photoconductor contacts is to study the barrier heights of blocking contacts on CdS with respect to their apparent dependence on the amount of photocurrent flowing through them, and their effect on photoconductive gain factors.

PROGRESS

Electro-Optic Effect

A detailed paper for submission to Applied Optics on the experimental technique and apparatus has just recently been completed. A paper, authored jointly with T. Nakamura, which treats the results of the E-O effect in $NaNO_2$, is in nearly final form. Preparation of another paper detailing the dispersion of the E-O effect in $BaTiO_3$ has begun.

Recently, a theoretical model for the E-O and second-harmonic generation (SHG) effects was reported at the Montreal meeting of the Electrochemical Society, October 1968, by Di Domenico and Wemple of Bell Labs, who will publish three papers treating it. They calculate, in their second paper, a number of characteristics of E-O modulators, light deflectors, as well as SHG devices. Fundamental design limitations and optimum material properties were discussed. This is the first attempt to discuss the implications of the material properties on device applications founded on basic principles instead of empiricism.

The measurements on $BaTiO_3$ are important in testing this model. For example, a single oscillator frequency can be chosen to fit the refractive index well, but the observed wavelength dependence of the E-O response cannot be explained. Introducing a second oscillator frequency results in an improved model which may predict the correct dispersion. The data obtained will be compared in more detail with the two-frequency model as a part of preparing the paper on the dispersion of the E-O effect in $BaTiO_3$.

The theory treats the strain-free condition, and therefore the capability of measuring both clamped and unclamped response on the same sample is important.

In view of the success of this model in describing the properties of the oxygen-octahedra ferroelectrics, the result that the linear electro-optic effect in $NaNO_2$ changes sign is quite interesting because it suggests that the nonlinear interaction in $NaNO_2$ may be quite different. The independent oscillator model does not agree with this observation in the case of $NaNO_2$.

Additional work in two specific areas is planned which will contribute to defining the accuracy and limitations of the model. First, a phenomenological analysis of the difference between clamped and unclamped E-O responses in $BaTiO_3$ will be attempted. The data already obtained should be sufficient to determine the necessary constants. Second, exploratory conversations with Dr. Philip Klein at the Electronics Research Center have suggested the possibility of investigating the effect of MgO, used in the growth of $LiNbO_3$ on the E-O response, and correlating these observations with the dielectric properties determined by him. The possibility of cooperation involving crystals in the tungsten-bronze family, which includes $Ba_2NaNb_5O_{15}$, will also be explored.

A new application of E-O modulators, that of using the anisotropy of the refractive index tensor of a crystal, together with a modulator to make a direction sensor, will be investigated. An initial effort to clarify the characteristics and limitations of such a device is planned. The advantage obtained is that the image dissector, a complex and expensive component, is replaced by an appropriate simple detector, and the direction-sensing function is taken over by a passive optical element containing the crystal and an E-O modulator.

The possibility of investigating the potential of long rod-like organic molecules for an optical modulation will also be examined. A solution of such molecules has been reported in the literature to be orientable by a reasonable electric field, producing a useful optical anisotropy. The resulting device behaves like a Kerr cell. The fundamental relationship between the molecular size, the voltage sensitivity, and the speed of response is the key research problem, and will determine the feasibility of device applications.

Photo-response of Barriers

An excellent photo-response optical apparatus has been completed which focuses the output of a quartz prism monochromator to a spot size of 6 to 7 mils by means of an ellipsoidal mirror. Part of the output beam is deflected toward a thermopile, which, when used with a separate lock-in amplifier channel, monitors the photon flux density for the particular wavelength being used. This arrangement is a very useful feature when using light sources which are rich in spectral emission lines such as the Xenon arc lamp. Good photo-response has been observed in Au-CdS barrier contacts with photons having energies as low as 0.6 eV (2000 nm). Because of a damaged thermopile, which is now being repaired, the monochromator output cannot be calibrated, and hence the photo-response data collected to date have not been analyzed to obtain barrier-height information. Schottky barriers formed on other semiconductors will be investigated and their relative efficiencies compared. It is now possible to commence fabrication of thin-film $A\ell$-$A\ell N$-metal diodes again, and study their photo-response as a function of metal counterelectrode and insulator formation. The photo-response data for CdS will be used in support of the metal-photoconductor work.

Metal-Photoconductor Contacts

An investigation of the barrier heights of blocking contacts on high-resistivity photoconducting CdS, using a stationary high-field domain analysis, has been essentially completed for metal electrodes deposited on vacuum-cleaved crystals. This work is being done in collaboration with Dr. K. W. Boer at the University of Delaware. The results of the analysis to date will be published in the open literature. These results have been presented at the November APS meeting in Miami, and are discussed in SPS 37-53 and 37-54, Vol. III. Values of barrier heights of around 0.50 eV at room temperature, and photocurrent densities of about 10^{-3} amp/cm^2 were found. Little dependence on metal work function was found, contrary to the situation found for semiconducting CdS with no current flow through the contact. The results, which are presented in figures in SPS 37-54, Vol. III (p. XXX), also showed that the values depend strongly on temperature and photocurrent (light intensity). Previously published values of barrier heights on low-resistivity CdS, which are generally higher, will be checked by photoresponse and differential capacitance measurements on guarded electrodes of different metals. Attempts will be made to extend these types of measurements to the higher resistivity material for independent checks on the barrier heights. The existing equipment will also be used to study the photovoltaic effect in CdS, particularly with copper as an electrode (Schottky barrier), and with a copper-reacted interface (Cu_2S). Parameters affecting the efficiency of the photo-voltaic process will be determined, particularly in recrystallized thin-film CdS, if a suitable supply of samples can be maintained.

PUBLICATIONS

Meetings and Symposia Papers

1. Stirn, R. J., and Boer, K. W., "Effective Work Function of Metal Contacts to Vacuum-Cleaved Photoconducting CdS for High

Photocurrents," presented at the American Physical Society Meeting, Miami Beach, Fla., November 25-27, 1968.

Open Literature

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SPS Contributions

1. Stirn, R. J., "Effective Work Function of Metal Contacts to Vacuum-Cleaved Photoconducting CdS," SPS 37-53, Vol. III, XXX, October 1968.

2. Stirn, R. J., "Barrier Heights of Blocking Contacts to Vacuum-Cleaved Photoconducting CdS in the Conducting State," SPS 37-54, Vol. III, XXX, December 1968.

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CRYOGENICS RESEARCH

NASA Work Unit 129-02-05-02-55

JPL 329-20201-1-3450

P. V. Mason

OBJECTIVE

The goal of the Cryogenics Research Group is to study low-temperature phenomena from a fundamental point of view with the intention of developing knowledge that will lead to improved methods of spacecraft guidance control, and power generation and conditioning.

The studies are in three areas:

(1) Josephson-effect devices, with particular interest in their use as very-high-speed high-density memories.

(2) Thin-film superconducting transmission lines, for use as pulse storage and handling devices.

(3) The problems of providing a low-temperature environment aboard a small spacecraft.

PROGRESS

Josephson Junctions

As described in an article in SPS 37-51, Vol. III (p. 72), the Josephson effect offers a possible solution to the problem of producing large-volume, high-speed, random-access memory at a reasonable cost per bit. It is intended to study the effect itself, and the processes necessary to fabricate memories by methods suitable for mass-production techniques. The ultimate aim is to fabricate small-scale arrays of devices in sizes large enough to prove the feasibility of large-scale arrays.

One immediate goal is to examine current methods of fabrication in order to determine if they are suited to production with high yield and tight tolerances.

It is also necessary that the resulting devices be stable with time and cycling to low temperatures.

During the past year, experiments have been conducted primarily with thermal oxidation of vacuum-deposited lead films. Process parameters such as temperature and relative humidity have been varied in an attempt to find a satisfactory process. The conclusion has been reached that thermal oxidation is not satisfactory. In particular, the stability of the films under room-temperature storage is very poor. This appears partly due to the process, and partly due to the diffusion of lead into the oxide.

Experiments are now being conducted with oxidation in a glow discharge. Results are better, but still not satisfactory. Work will continue to attempt to improve the process.

It is planned to work in three other areas of fabrication. First, the insulating film will be formed by reactive sputtering of aluminum nitride. This process has been used successfully by G. Lewicki of JPL in the study of normal tunneling. It lends itself to the production of a series of films of evenly graded insulation thickness. It is therefore planned to study the effect of thickness on Josephson current, a topic of considerable theoretical and practical interest.

Secondly, it is planned to study a promising technique, that of forming an oxide during exposure to ultraviolet light. Preliminary results show higher Josephson currents than any other technique.

Thirdly, a study is being conducted on other metals for suitability in forming junctions since lead, in spite of its high critical temperature, presents a number of problems. One promising possible material is niobium which has a high critical temperature, thus yielding a higher output voltage and reducing the amount of refrigeration required. Furthermore, the oxides of niobium are known to be very tenacious and stable. Recent work has shown that niobium can be fabricated in superconducting films by sputtering, and that fairly satisfactory oxides can be grown. It is planned to investigate various methods of fabrication.

The most interesting characteristic of Josephson-junction memory elements is their very rapid switching time from one state to another. Previous measurements, which were limited by external circuitry rather than fundamental physical processes, have shown times less than 1 nanosecond. A device has been designed which places the Josephson junction at the center of a thin-film transmission line, thus avoiding the circuit limitations. There are some difficulties in the fabrication, but methods have been developed to overcome them, and it is planned to proceed with the measurement during the next few months.

Superconducting Thin-Film Transmission Lines

In earlier studies of superconducting thin-film transmission lines, it was shown that the propagation velocity of electromagnetic waves on such lines is greatly reduced as the film thickness and interfilm spacing are made small. It has been recently shown that, theoretically, it is also influenced by the purity of the superconductors. Since the velocity is easily measured, it is a convenient tool for the study of such effects. Measurements for the study of thickness effects have already been made, and apparatus has been assembled to fabricate films with controlled amounts of impurities. Studies of these effects will be made.

Some studies to determine the capacity of such structures to store fast rise pulses have also been conducted. Since the propagation velocity is greatly reduced, a very high density of storage should be possible. Furthermore, attenuation and distortion are greatly reduced over that found in normal metal lines.

It has already been shown experimentally that two-nanosecond-rise-time pulses can be delayed up to one microsecond without serious distortion, and it is estimated from measurements that at least 1000 pulses could be stored. It is intended to construct lines long enough to explore the limits of the technique.

Low Temperature Environment

During the past year, contact has been maintained with those companies and government agencies active in the development of spacecraft-compatible refrigerators. No major developments have taken place. The situation is now being reviewed, as time permits, and it is hoped to prepare a report on the present state of affairs.

PUBLICATIONS

Meetings and Symposia Papers

1. Mason, P. V., "Slow-Wave Structures Utilizing Thin-Film Transmission Lines," presented at Applied Superconductivity Conference, Gatlinburg, Tenn., October 28-30, 1968.

SPS Contributions

1. Mason, P. V., "Josephson-Junction Memory Elements," SPS 37-51, Vol. III, pp. 72-75, June 1968.

LOW TEMPERATURE PHYSICS

NASA Work Unit 129-02-05-04-55

JPL 329-20401-1-3280

D. D. Elleman

OBJECTIVE

The objective of this task is to measure and study a variety of fundamental low-temperature phenomena and conduct magnetic resonance studies. Current emphasis is on (1) the study of the Fermi surface of selected metals using the de Haas-van Alphen effect, (2) ion cyclotron resonance spectroscopy studies of various ion-molecule reactions, and (3) investigation of a wide-line nuclear magnetic resonance (NMR) spectrometer to be used for measurement of lunar and planetary rock and soil samples.

PROGRESS

de Haas-van Alphen Effect Studies

Experimental studies of the Fermi surface in a number of metallic systems are currently being conducted using the de Haas-van Alphen effect. The experimental method uses radio-frequency modulation techniques to measure a small component of the magnetic susceptibility which oscillates as the magnetic field changes. The amplitude and frequency of these susceptibility oscillations furnish direct measurements of the Fermi surface. By collecting data as a function of crystal orientation, temperature and magnetic field it is possible to determine not only the size and shape of the Fermi surface, but also to see fine details of the surface structure such as small energy gaps at critical points. This knowledge is necessary for a qualitative and quantitative description of the electronic structure of the metal and for predicting transport properties.

Digital data handling techniques have been developed for processing and performing numerical Fourier analysis of the experimental data to yield accurate values for the frequencies and amplitudes of the oscillations. This is the first such application of numerical Fourier techniques to de Haas-van Alphen studies.

Figure 1 shows the de Haas-van Alphen data taken on white, or metallic, tin and the Fourier transformation of the data. The height of each signal spike is directly proportional to the intensity of the corresponding oscillation, and the ordinate gives the frequency of the oscillation. The frequency is directly proportional to an external cross sectional area of the Fermi surface perpendicular to the magnetic field direction. The numerical technique is able to resolve and determine the amplitude of a number of very weak oscillations, even in cases where they lie close in frequency to much more intense oscillations. The ability to resolve complex DHVA data in this fashion has become particularly important with the application of recently developed experimental techniques which are furnishing much more complex and detailed information on the band structure in metals.

Additionally, the numerical technique allows elimination of a large fraction of the electronic noise encountered in this type of measurement, and thus effectively increases the sensitivity of the experimental apparatus. The numerical Fourier techniques described here are directly applicable to the analysis of data in many other experimental situations and a paper describing this application has been submitted for publication.

Knowledge of the change in the intensity of the oscillations as a function of temperature allows a determination of the effective mass of those electrons on the various sections of the Fermi surface. Although white tin is probably the material most extensively investigated by the DHVA effect, previous experimenters using analog signal processing of the data obtained in sensitive radio frequency modulation experiments have not been able to yield values of the amplitude of the oscillations with sufficient accuracy to determine such effective mass values. We have recently submitted for publication such results on white tin which are easily obtained with the numerical data reduction techniques. In addition we are further investigating the striking and unexpected behavior of a large number of higher harmonic frequencies seen for the first time in this investigation.

DHVA investigations of other materials are also in progress. These include attempting to see the DHVA effect in niobium for the first time, examing unknown segments of the Fermi surface in indium and aluminum, and examination of magnetic breakdown effects in the hexagonal close packed metals.

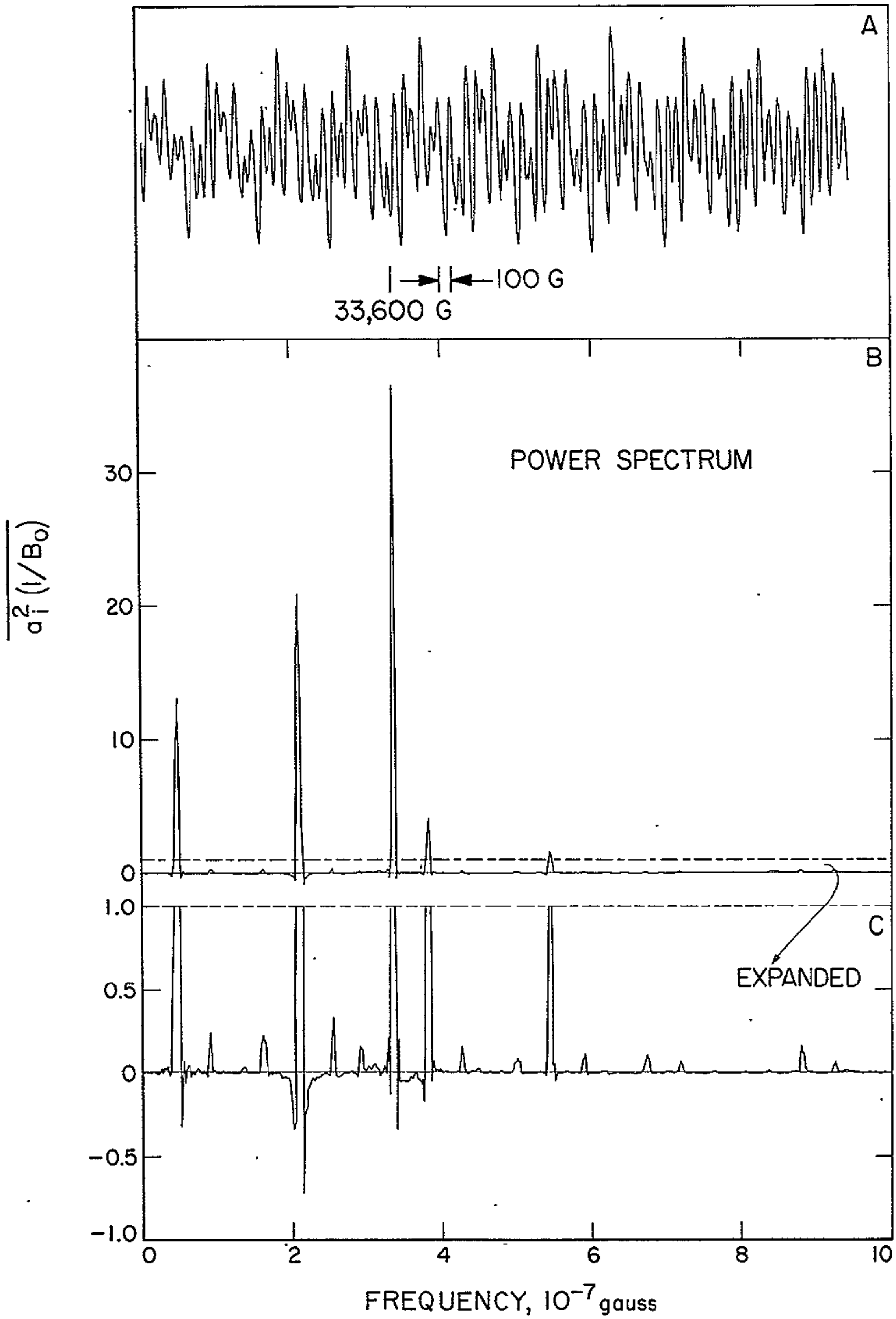

Figure 1. De Haus - Van Alphen Data Fourier Transformation

Ion Cyclotron Resonance Studies

Extensive studies of ion-molecule reactions and charge-exchange reactions have been undertaken in collaboration with Dr. J. King, Jr. of JPL. In addition, Dr. M. T. Bowers of the University of California at Santa Barbara has participated in a number of the experiments as well as W. T. Huntress, Jr., a recent NASA Resident Research Associate assigned to the task. The work performed in this area of research is reported by J. King, Jr., under Physics of Molecular Interactions, NASA Work Unit 129-02-01-09-55.

NMR Studies

A wide-line NMR system including a time-average computer has been constructed and tested. This system offers increased sensitivity for the NMR method of measuring moisture (as protons, ^1H) in soils and rocks. Thus far, it has been possible to achieve better than a factor of 30 increase in sensitivity for such samples.

PUBLICATIONS

Open Literature

1. Vaughan, R. W., and Elleman, D. D., "Fourier Analysis of Complex DHVA Data; Effective Mass Determination in White Tin," abstract appearing in Bull. Am. Phys. Soc., 13 (1968).

2. Bowers, M. T., Elleman, D. D., and Beauchamp, J. L., "Ion Cyclotron Resonance of Olefins I. A Study of the Ion-Molecule Reactions in Electron Impacted Ethylene," J. Phys. Chem. 72, 3599 (1968).

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2. Cohen, E. A., and Manatt, S. L., "Observation of Fluorine-19 Isotopic NMR Chemical Shift Due to Chlorine-35 and Chlorine-37 Isotopes," JPL SPS 37-53, Vol. III, p. 151, October 31, 1968.

3. Manatt, S. L., Bowers, M. T., and Chapman, T. I., "Energy Level Iterative NMR Method for Sets of Magnetically Nonequivalent, Chemical Shift Equivalent Nuclei," JPL SPS 37-53, October 1968.

MAGNETICS RESEARCH

NASA Work Unit 129-02-05-06-55

JPL 329-21401-1-3450

G. Lewicki

OBJECTIVE

The long-range objective of this unit is to study the feasibility of magneto-optic information storage on manganese bismuthide films. The immediate objective is to gain an understanding of laser Curie-point switching in manganese bismuthide films so that the limitations of this storage technique relevant to mass memory and recording applications can be defined.

PROGRESS

Growth of Manganese Bismuthide Films

Within the past year, some understanding of the growth of thin ferromagnetic films of manganese bismuthide has been achieved. As a result, films suitable for experimental work are being prepared on a reproducible basis. Ferromagnetic manganese bismuthide films are grown by annealing bismuth and manganese films, lying on top of each other, on a mica substrate. An understanding of the film-growth process was reached by visual observation of the film during growth. The process was found to be quite intricate, inasmuch as reaching the ferromagnetic phase of manganese bismuthide, with its c axis perpendicular to the plane of the film, meant taking the layered structure through a maze of intermediate phases by using a proper sequence of annealing temperatures. Each phase was identifiable by its different optical characteristics. As yet, there exists no structural identification of these various phases. The word maze is used, inasmuch as it was found that the layered structure could be taken to phases from which the desired ferromagnetic manganese bismuthide could not be obtained. A paper describing this growth process is in preparation.

Laser Curie-Point Switching

Some preliminary Curie-point-switching experiments have led to an interesting development. In switching one micron spots on a magnetically saturated film, it was found that the spots could be switched to any shade of gray as viewed through a polarizing crystal under polarized light. The controlling factor was the magnetic field applied during switching. The range of the magnetic field required to cover the shades of grey was on the order of 150 Oersteds. Once switched, the spots were insensitive to magnetic fields within this range.

These results imply that manganese bismuthide films, in the thickness range investigated, have information-storage densities approaching those of photographic film. They also suggest a novel recording technique wherein a laser beam, moving with respect to the film, would Curie-point-switch a one-micron track; the optical density along this track, as viewed under polarized light through a polarizer, was determined by the value of field applied at the time of switching.

Such a recording technique would lead to recording densities many orders of magnitude greater than those presently available in conventional magnetic-tape recording systems.

FUTURE WORK

The sensitivity of the electronic equipment used to read out the magneto-optic density of Curie-point-switched areas has not been sufficiently high to adequately characterize the gray scale encountered in Curie-point switching. The problem has been fluctuations in the output of the laser used for electronically reading the films. A control loop to remedy this problem has been designed and will be implemented.

Continuous films most probably will be inadequate for memory applications where binary Curie-point switching with small fields is required, rather than analog switching with relatively large fields. Theoretical considerations lead us to believe that small discrete areas of much thicker manganese bismuthide films will have Curie-point-switching characteristics more compatible for memory requirements. During the coming year, considerable effort will be devoted to prepare and characterize such films.

All Curie-point-switching experiments to date have been carried out with a fixed laser beam, with respect to the film. The dynamics of switching will certainly be different with a roving beam, with respect to the film. A beam scanner is being assembled, and in the near future, some simple recording experiments will be carried out.

PUBLICATIONS

Open Literature

1. Lewicki, G. W. and Mead, C. A., "Currents through Thin Films of Aluminum Nitride," J. Phys. Chem. Solids 29, No. 7, 1955 (1968).
2. Tchernev, D. I., "Temperature Dependence of the Linewidth of Garnets Containing Fe^{4+} Ions," J. Appl. Phys. 39, No. 2, 826 (1968); Phys. Abstracts 71, No. 848, 2457 (1968).

SPS Contributions

1. Lewicki, G. W. and Guisinger, J. E., "Preliminary Results from Switching Experiments on Manganese Bismuthide Films," SPS 37-53, Vol. III, XXX, October 1968.

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SEMICONDUCTOR RESEARCH

NASA Work Unit 129-02-05-09-55

JPL 329-21801-1-3450

J. Maserjian
A. Shumka

OBJECTIVES

The long-range objective of this work is to exploit various semiconductor and related phenomena in search of new active electronic devices for eventual applications in space missions. Two specific areas being investigated are (1) the control and modulation of space-charge-limited (SCL) current in semiconductors directed toward the realization of a solid-state triode, and (2) the properties of very thin insulating and semiconducting films and their application to new devices.

STATUS

Control of Space-Charge-Limited (SCL) Current in Solids

There is a lack of clear understanding of the fluctuation phenomena in solid-state diodes. The existence of several theoretical models for the limiting noise in solid-state diodes emphasizes this fact. In particular, if these various theories were related to $\langle e^2 \rangle = 4\ kT\ R_n \Delta f$ where $\langle e^2 \rangle$ is the mean-square noise voltage, and R_n the equivalent noise resistance, then different expressions are obtained for R_n which are $kT/2qI_a$, V_a/I_a, and dV_a/dI_a where V_a is the applied voltage and I_a the applied current. Measurements on the limiting noise in various solid-state diodes have been of marginal value in discriminating among the theories largely because of an appreciable LF component of noise which predominates at frequencies as high as 40 MHz. A program was set up, in collaboration with Prof. M. A. Nicolet at Caltech, for investigating noise in germanium solid-stage diodes. It was anticipated that an experimental approach may succeed in considerably lowering the L F component of noise. A major part of the total effort was directed toward accomplishing this task. Small area $p^+\pi p^+$ solid-state diodes were designed and fabricated for this purpose (SPS 37-51, Vol. III). The LF component of noise did not extend beyond 2 MHz, which is more than an order of magnitude less than that reported for other solid-state diodes. Consequently, the limiting noise in these structures could be accurately measured. The noise measurements were made over a wide range of temperatures of three solid-state diodes. Preliminary evaluations of the data indicate that no existing theory was able to predict the observed results. A model is being constructed which may account for the results. This phase of the research effort is nearing completion and a publication is in preparation.

The feasibility of controlling and modulating SCL current in germanium has been demonstrated (SPS 37-49, Vol. III). The results of this effort have been submitted for publication. Solid-state triodes with various geometrical parameters are being prepared for a more intensive investigation. Characterization of the electrical parameters for these solid-state triodes, under dynamic operating conditions, will make it possible to describe, in greater detail, the electronic processes involved in the modulation of SCL current. An investigation of the fluctuation phenomena in these structures is being contemplated. Exploratory efforts have been directed toward making solid-state triodes from silicon, in order to extend the range of operation to higher temperatures. A survey will be made of the existing wide-band-gap semiconductors to form a basis for selecting materials appropriate for studying SCL currents at very high temperatures.

Semiconducting and Insulating Thin Films

The feasibility study of a new thin-film thermal detector (or capacitive bolometer) was essentially completed during the period. A final report has been drafted and will be submitted for publication after some final editing. Some general results and conclusions drawn from this study are (1) thin-film capacitive bolometers showing good performance were fabricated using two different laboratory approaches, (2) the underlying principle for the device was related to a large ionic space charge in the dielectric film of the capacitor, (3) there remain definite opportunities for improved detector performance and applications in imaging arrays with a continued development effort.

To increase the likelihood that the detector will be developed by at least one of several interested manufacturers, further study is needed for establishing a more precise relationship between the optimum characteristics of the thin-film capacitor, and the properties of the dielectric barrier. It is hoped to satisfy this need through continued study of the ac impedance of such barriers. A more complete formulation of the ac theory, which directly relates to the distribution of traps within the barrier region, has recently been undertaken. Experimental results obtained from some of the Nb_2O_5 capacitors support the preliminary predictions, and are consistent with the previous contention of a nearly uniform trap distribution.

Following the decreasing emphasis of the work on the thin-film detector, a new device objective for motivating the continued studies of thin insulator barriers was needed. Among several possibilities are those which require extremely thin barriers, but which are relatively impermeable to electrons. Such barriers are possible in principle and, it is now believed, also in practice. The new, exciting MNOSFET storage devices are an excellent example of what can be accomplished with extremely thin films of amorphous SiO_2, in combination with the other layers (metal, SiN, Si) of the device. It is conceivable that thin-film devices with such barriers may offer advantages for both electrical storage and switching, and are directly applicable to high-density memory systems.

In connection with this goal, other methods for forming thin insulator films including gaseous anodization, evaporation in ozone, and oxide growth under intense ultraviolet illumination have been studied. The latter method has shown particular promise for thin barriers, but appears limited to only certain compounds (e. g. , $A\ell_2O_3$ but not SiO_2). The fabrication and electrical evaluation of such barriers also relate to another effort in support of the solar-cell program at JPL. This effort, carried out in collaboration with the Optical Physics Group, will attempt to determine whether internal photoelectric emission over thin barriers can be effectively used for solar energy conversion. The photo-response data obtained from these studies also provided independent determinations of the barrier heights.

This work unit has also been assisting the solar-cell program on more immediate problems. This assistance has included consultations regarding current contracts on radiation damage, and lithium doping in silicon solar cells. Also, a short-range experiment is being undertaken to test some ideas for improving electrical contacts to solar cells. The investigations on magnetic semiconductors have been postponed after some preliminary measurements because of the need for specialized test equipment which cannot be justified with the present resources.

PUBLICATIONS

<u>SPS Contributions</u>

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2. Lee, D. H., Nicolet, M-A., and Bilger, H. R., "Noise Measurements on a Double Injection Silicon Diode," SPS 37-52, Vol. III, pp. 70-73, August 1968.

3. Shumka, A., "Fabrication of Small-Area $p^+ \pi p^+$ Solid-State Diodes for Noise Measurements," SPS 37-53, Vol. III, pp. XXX, October 1968.

MOLECULAR SPECTROSCOPY

NASA Work Unit 129-02-06-01-55

JPL-329-22001-1-3280

R. L. Poynter
S. Trajmar

OBJECTIVE

Microwave spectroscopy will be used to study molecules and free radicals present in planetary atmospheres or space. The molecular rotational, spin reorientation and Λ-doubling energy levels and transitions will be elucidated. Electron-scattering from atoms and molecules will be studied using high-energy resolution to obtain both relative and absolute cross sections for different inelastic processes. Photons will be used to ionize molecules and a study will be made of the energy dependence and angular distribution of the ejected electrons.

PROGRESS

Microwave Spectroscopy

The microwave spectrometer detection system was modified to improve the overall system sensitivity. A 7-9 GHz microwave oscillator was used to complete the remaining OH frequency measurements. A complete set of lambda doubling and nuclear hyperfine coupling constants has been derived from the observed transitions. This set of constants has been used to predict all of the OH microwave transitions to an accuracy which is within our experimental error limits.

The OD molecule was also studied, and all of its $\Delta F = 0$ transitions in the frequency range between 7 to 40 GHz have been measured. Numerous new transitions belonging to OD have been observed for the first time. The OD spectral analysis has been successfully employed to generate a very good set of lambda doubling constants, and one nuclear hyperfine constant. These constants accurately reproduce all of the observed OD transitions.

A complete report on both the OH and OD molecules is in preparation. A preliminary account of the OH work has been published (Publications 1). A brief account of the OD radical will be published (see JPL SPS 37-54, Vol. III).

Future Activities

The microwave spectrometer is being modified so that it can be used either for normal spectroscopy or for the study of maser and laser effects in free radicals. Experimental work has been initiated on free radical lasers, and will be continued during the next FY. Other suitable free radicals will also be sought.

Electron Scattering

The experiments on the electronic excitation of H_2O by low-energy electron impact are completed and the results are being evaluated. The main emphasis during this report period has been on the vibrational excitation of H_2 and N_2 by low-energy electron impact. Detailed descriptions of these investigations and theoretical calculations have been published or are being prepared for publications.

The low-energy, high-resolution electron-impact spectrometer has been producing data with high efficiency. The semi-automatic manner of operation makes it possible to collect data seven days a week, twenty-four hours a day with relatively little interruption and attention to the instrument. Most of the time is spent on transferring information from the memory of the multi-channel scalar to the computer and on evaluating the data. Several auxiliary computer programs have been written for curve-fitting the experimental data. The results are used to calculate the "effective scattering pathlengths" of the electrons as a function of scattering angle and for the determination of the true scattering angle.

The entire electron optics of the high-resolution machine have been redesigned using computer programs loaned by the Electron Physics Section of NBS. The gun, scattering chamber entrance and exit optics, and the detector optics are now all energy independent. The new optics will improve the angular and energy resolution thereby increasing the efficiency of the system.

A simplified electron scattering apparatus was designed and built (~75%) with special features. These features make it possible to measure elastic differential cross sections at 40° and 80° on the absolute scale. From these measurements and from the ratios of the intensities of the inelastic to elastic features obtained by the high-resolution apparatus one can put <u>all</u> differential cross sections on the <u>absolute scale</u>. This apparatus and its performance will be described during the next year.

A photon impact spectrometer was designed and built in cooperation with Caltech's Chemistry Department. This instrument is being assembled at Caltech and will be used to obtain data complementary to electron impact spectroscopy.

A computer program previously written in the rigid rotor approximation for calculating and curve fitting the $(\nu_1 + \nu_3)$ combination band of ozone is being extended and improved to take into account the interaction of vibration and rotation. This is being done in cooperation with Mr. Alex Castelli of Army Advanced Projects Division, Point Mugu, California. The program will be utilized for analyzing the infrared spectrum of O_3, H_2O and HDO.

PUBLICATIONS

Meetings and Symposia Papers

1. Polynter, R. L., and Beaudet, R. A., "Predictions of Several OH Λ Doubling Transitions Suitable for Radio Astronomy, "Phys. Rev. Letters, 21, 305 (1968).

2. Poynter, R. L., and Beaudet, R. A., "OH Free Radical Transitions of Radio Astronomical Interest, " Molecular Spectroscopy Symposium, Ohio State University, Columbus, Ohio, September, 1968.

Electron Scattering

Meetings and Symposia Papers

1. Kuppermann, A., Rice, J. K., and Trajmar, S., "Low-Energy High-Angle Electron-Impact Spectrometry Symposium on Photochemistry and Radiation Chemistry," U.S. Army Natick Laboratories, Natick, Mass., April 22-24, 1968.

2. Trajmar, S., Rice, J. K., Truhlar, D. G., and Brinkmann, R. T., "Angular Dependence of the Vibrational Excitation of N_2 by 20 eV Electrons," Twenty-First Gaseous Electronics Conference, Boulder, Colorado, October 16-18, 1968.

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2. Trajmar, S., Cartwright, D. C., Rice, J. K., Brinkman, R. T., and Kuppermann, A., "Angular Dependence of Low-Energy Electron-Impact Excitation Cross Section of the Lowest Triplet States of H_2," J. Chem. Phys., December 15, 1968 issue.

3. Kuppermann, A., Rice, J. K., and Trajmar, S., "Low-Energy High-Angle Electron-Impact Spectrometry," J. Phys. Chem. 72, 3894 (1968).

JPL Technical Memoranda

1. Trajmar, S., Rice, J. K., and Kuppermann, A., "A Low-Energy High-Resolution Electron Impact Spectrometer," JPL TM 33-373, March 1, 1968.

THEORETICAL PHYSICS

NASA Work Unit 129-02-07-02-55

JPL 329-20901-1-3280

M. M. Saffren

OBJECTIVE

The objective of this work unit is to define and solve specific problems which define the frontier of modern theoretical physics and are relevant to the long-range goals of NASA. The current work is in quantum theory. The recent work in plasma theory and in relatively theory is now being continued in other tasks.*

PROGRESS

Quantum Theory — M. Geller, M. M. Saffren, J. S. Zmuidzinas

The present work in quantum theory now centers about the attempt to understand the electronic behavior of molecules and solids. The quantum states of polyatomic molecules as given by the Hartree-Fock method continues to be studied by Geller. Saffren has shown that in the electronic band structure of crystals there is a portion of the band structure that is determined by the space group of the lattice alone independent of the crystal potential. He has also shown how the band structure of one crystalline phase is related to that of another crystalline phase of the same chemical element. Zmuidzinas (with Saffren) is engaged in a definitive study of the longstanding and very important problem of the electron gas at metallic density.

The program MOSES (Molecular Orbital Self-Consistent-Field Energy System) — previously described — has been applied to the molecules NF_2^+, BeH_2, BH_2^-, CF_2, O_3 and $BeLi_2$. The results of the computations are reported by Geller in the Physics of Molecular Interactions Task. Described here is work

*Though work both in plasma theory and in relativity theory will no longer be carried out in this task, progress of the work previously initiated in the task is reported here, and, of course, publication of that work will be noted in the future reports of this task.

done to make the program applicable to larger molecules, and to excited states of molecules. The work involves not only improvement of the program but new theoretical investigations as well. The theoretical investigations stem from an attempt to use as basis functions Slater-type orbitals rather than the presently used Gaussian orbitals. With Slater-type orbitals the basis sets would be smaller which would result in computation times being considerably shortened. The difficulty in using such orbitals is — as has long been known — the calculation of the three and four center coulomb and exchange integrals. Geller, in collaboration with Professor Harris Silverstone of Johns Hopkins University, hopes to eliminate this difficulty by using a combination of the Fourier convolution transform and Barnett-Coulson expansion techniques to evaluate the integrals. The other work — work done in improving the program itself — involves the following additions and modifications: (1) a property package which evaluates population analysis, dipole moment, quadrupole moment, force constants and electric field gradient; (2) elimination of integrals already known to be zero because of symmetry; (3) use of "contracted" functions (which greatly shortens the diagonalization and iterative process); (4) a speeded-up integral package for "d" orbitals in preparation. (The first three were done in collaboration with Dunning, Winter and McCoy of Caltech.) Awaiting completion is the important open-shell package. The package will be checked by calculating properties of the H_3O^+ molecule. Once checked the package will be used to determine the possible existence, stability, geometry and properties of N_2C^+ and C_2N^+, molecules of interest to chemists studying the process of abiogenesis. With the open-shell package working, the calculations of ground and excited state properties of other molecules so difficult to observe — the free radicals — will be made. These molecules have biological as well as space physics interest. The calculation of excited states of ordinary molecules will also be possible, and these calculations should be of extreme value to experimenters in the new field of the chemistry of the excited state.

Saffren continues his investigation of the extent to which the order of levels of a symmetric system is predetermined by the symmetry of the system alone. The methods already developed to demonstrate the existence of such an order for systems having the symmmetry of the cubic and tetrahedral point groups have been extended and modified to investigate the structure of electronic energy bands in crystals. The investigation has led to the discovery of an "invariant" band structure — a portion of the band structure predetermined by the symmetry of the crystal alone. It is, therefore, a portion of the band structure that can be predicted without any knowledge of the crystal potential. An important application of the invariant band structure is its use in deciding whether or not a crystal pseudopotential exists for a particular crystal. It has now been shown that for the transition metals, and for the rare earth metals, no pseudopotential exists that will duplicate merely the conduction bands alone; but that a pseudopotential may exist if, along with the conduction bands, the pseudopotential is allowed to duplicate one or two of the core bands immediately below the conduction band. Studied so far have been the invariant band structure of the body- and face-centered lattices. A study of the hexagonal close-packed lattice will complete the work on the common metallic lattices, and then work will begin on the common insulator and semiconductor lattices — the diamond, the wurtzite and the zincblende lattices. Another interesting aspect of the band structure of crystals has come to light as a result of a new way of deriving the invariant band structure. Not only are the new methods easier to apply, but more importantly, as it turns out, they allow the band structure of two different lattices such as the body-centered and face-centered lattices to be related to one another rigorously and exactly. For the first time this allows the band structure of dissimilar lattices to be compared in a precise fashion. This is of great interest in the study of the band structure of those metals that exist in two or more crystalline phases (almost all metals do). Subsequent work may yield insight into the difficult problem of determining the relative stability of the different phases of a metal.

Zmuidzinas is engaged in a far-reaching study of the quantum many-body problem. The main mathematical tool he is using is the so-called equation of motion method. Zmuidzinas is applying this method to two self-interacting systems — one relativistic, the other non-relativistic. The non-relativistic system is the electron field interacting with itself electrostatically in a neutralizing background of uniform positive charge — the so-called electron gas (being studied with Saffren); the relativistic system is the Dirac field interacting with itself through a completely local interaction. For the Dirac field the first part of the work — the general formalism — has already been completed and is contained in a paper to be submitted for publication, "Theory of a Self-Interacting

Field. I." The second part of the work dealing with the actual dynamics has been simplified considerably by the investigation of the self-interacting Weyl field (two-component spinor field). Using this example it has been possible to reduce the dynamics to simple equations of motion, the fermion obeying Dirac equations and the bosons obeying Klein-Gordon equations. The fields are coupled by inhomogeneous terms in these equations, quadratic in the fields. The remaining problem is to solve these equations by a self-consistent version of the equation of motion method mentioned above.

The non-relativistic system to be studied, the electron gas, is a system of great interest to solid state physicists. It is generally assumed that the behavior of the electrons in this system is essentially the behavior of electrons in actual metals; one can, in fact, marshal semi-quantitative arguments that show this to be so. Aside from the obvious value such a study would have as the basis of a rigorous and modern theory of metals, it would also be of value in understanding the extremely interesting but poorly understood phase transition that takes place in the electron gas. In going through this transition — presumably taking place at metallic density — the electron gas becomes an electron lattice and in so doing goes from a conducting to an insulating state. A true understanding of this transition would be valuable in understanding the transition from the insulating to the conducting state that takes place in actual materials. But despite the interest attached to the electron gas problem, it has so far resisted solution for densities of the gas that approximate electron densities of actual metals. The difficulty is that the system at these densities is not a weakly coupled system. At high densities the interelectron repulsion energy is a perturbation on the kinetic energy and at low densities it is the kinetic energy that is a perturbation on the interelectron repulsion energy. However, at intermediate densities both energies are comparable and the perturbation approach is inappropriate. In most previous attempts to understand the gas at intermediate densities, quantities calculated for the high density gas have been extended into the range of metallic density and even lower density with no real justification. Part of the present program is to test the validity of this extrapolation. The test is to calculate the dielectric constant of the low density gas and to compare it with the dielectric constant of the high density gas. To make this comparison more meaningful, an improved Hartree-Fock ground state for the low density gas is being calculated. If the methods proposed prove successful for the electron gas, they will be applied to other many-body problems. Among these problems are: (1) a rigorous theory of phonons; (2) a theory of metallic hydrogen, with particular emphasis on determining whether or not metallic hydrogen displays nuclear ferromagnetism; and (3) the theory of the various phases of helium.

PUBLICATIONS

Meetings and Symposia Papers

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1. Wahlquist, H. D., "Interior Solution for a Finite Rotating Body of Perfect Fluid," Phys. Rev. 172, 1291 (1968).
2. Wu, C. -S., "Kinetic Theory in the Klimontovich Formalism," Lectures in Theoretical Physics, Vol. 9c, Gordon and Breach Publishers, New York, 1967.
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3. Unti, T. W. J., "Compressional Waves in the Solar Wind," JPL SPS 37-54, Vol. III, December 1968.
4. Zmuidzinas, J. S., "Dielectric Function of a Low-Density Electron Gas," JPL SPS 37-54, Vol. III, December 1968.

JPL Technical Reports

1. Zmuidzinas, J. S., "Quark Model of Leptons," JPL TR 32-1082, May 1967.

PLASMA SOURCES, GENERATORS, AND ACCELERATORS

NASA Work Unit 129-02-08-03-55

JPL 329-21201-0-3830

G. R. Russell

OBJECTIVE

This work unit was discontinued in the first half of FY 69 because of reductions in funding and a partial re-direction of the research program. The MPD arc diagnostics study is now included in NASA work unit 129-02-01-10-55 (JPL 329-22301-0-3830), and the MPD arc is currently being studied as a possible magnetogasdynamic laser device.

Experimental work in the simulation of fission fragment ionization in a nonequilibrium MHD generator has been discontinued. Limited theoretical work is being continued in NASA work unit 129-03-01-08-55 (JPL 329-21901-0-3830).

PUBLICATIONS

None

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INTERPLANETARY AND SOLAR FLUID PHYSICS

NASA Work Unit 129-02-08-04-55

JPL 329-22101-1-3270

A. Bratenahl
C. Yeates

OBJECTIVE

The objective of this task is to seek solutions, through laboratory experiments and theory, to certain basic problems prerequisite to understanding plasma dynamics in the sun's atmosphere and the earth's magnetosphere. Special emphasis is on dynamics of the magnetic x-type neutral point and the process of reconnection of magnetic field lines. Motivation is based on the need to know more about the physics of solar flares, not simply for its general scientific interest alone but especially because such knowledge can be used in a practical way to improve flare forecasting technology. Further motivation stems from the likelihood that the neutral-point process is the most common and therefore one of the most important sources of particle and plasma acceleration, including plasma injection into the earth's magnetosphere.

PROGRESS AND PRESENT STATUS

The previous Review, January-June 1968 (Document 701-15), provided a good qualitative statement of the process as a "conspiracy" of flow dynamics tending to convert a volume current into a surface current at a hyperbolic pinch, together with an "antagonistic conspiracy" related to the mechanism of current conduction, which strictly forbids the attainment of surface currents in real plasmas. In a real plasma the conductivity is not only noninfinite, but it also is limited to supporting current densities less than a critical maximum, $j_{crit} = N_e e\sqrt{KT/2m_e}$. At such large current densities, the conduction mechanism fails and the current carriers, no longer controlled by "collisional friction," gain large amounts of energy from the electric field and "run away." The electric field at the neutral point is a measure of the rate of reconnection of lines of force. As long as the conduction mechanism is ohmic, the field is short-circuit-limited to the value of j/σ. If, however, $j \rightarrow j_{crit}$, this limitation is lifted. Although this certainly could happen, given the appropriate conditions on T and N_e, recent analysis of our data are beginning to suggest a purely thermal effect. The pinch compression and the ohmic power j^2/σ heats the plasma and increases N_e. But the radiative cooling rate due to free-bound transitions, proportional to N_e^2 may exceed this heating rate, lowering T and therefore σ sufficiently to effect the impulsive flux reconnection. This interesting possibility is yet another mechanism in the "conspiracy" antagonistic to formation of surface currents. Whether we are dealing here with an arc starvation instability or thermal instability, we hope to settle the problem shortly by (1) search for possible run-away electrons, and (2) direct determination of the current density at the neutral point. Despite the present uncertainty as to which instability is effective, one thing remains sharply clear: the flow leads inexorably to a situation where a "resistive instability" of some kind becomes inevitable. We see the instability operate and we see its consequences.

Preliminary schlieren pictures show high density in the pinch region, but some difficulties have been encountered in the schlieren optics that need to be resolved for satisfactory pictures.

The greatest present effort is concentrated on preparation of a publication on the results to date.

FUTURE PLANS

The results obtained to date, which we hope shortly to submit for publication, appear to us to have great value in application to the solar flare, an opinion shared by a number of experts who have heard our oral presentation at meetings. We are accordingly actively planning two things: (1) a three-dimensional extension of our experiment which can utilize much of the existing equipment; (2) a program to apply these results directly to improve flare forecasting technology. Item (1) was briefly discussed in the previous Semiannual Review (Document 701-15). Item (2) will be the subject of a formal proposal.

PUBLICATIONS

Meetings and Symposia Papers

1. Bratenahl, A., and Yeates, C. M., "Flux Reconnections at the Magnetic Neutral Point: Some Laboratory Observations," International Conference on Plasma Instabilities in Astrophysics, Asilomar Conference Grounds, Pacific Grove, California, October 14-17, 1968.

SPS Contributions

1. Bratenahl, A., and Yeates, C. M., "Magnetic Topology and Flux Reconnection," SPS 37-52, Vol. III, p. 176, August 31, 1968.*

JPL Technical Memorandum

1. Bratenahl, A., and Yeates, C. M., "Interplanetary and Solar Fluid Physics," Semiannual Review of Research and Advanced Development, Vol. II, January 1 — June 30, 1968, R&AD Program Document 701-15, p. 681, October 15, 1968.

*This paper was also presented at the NASA Subcommittee Meeting on Solar Physics at the Jet Propulsion Laboratory, June 5, 1968, Pasadena, California.

LIQUID METAL FLUID DYNAMICS

NASA Work Unit 129-02-08-05-55

JPL 329-22401-1-3270

A. L. Kistler
T. Maxworthy

OBJECTIVE

To study the astrophysically and technologically important subject of magneto-turbulence. In particular, there is considerable interest in trying to understand the role of the magnetic Reynolds number (Rm) in changing the structure and evolution of turbulence in a conducting fluid in the presence of a magnetic field. The liquid sodium tunnel at JPL is uniquely suited to such a study and a program to measure the properties of turbulent jets at high Rm has been initiated.

PROGRESS

The "unipolar generator," used as a power source for the solenoid, has been repaired, following destruction of the internal insulation, and its performance actually improved by the modifications necessary to effect replacement of the insulation.

A new test section has been designed and manufactured. It awaits the availability of the responsible technician before it can be installed in the liquid sodium loop.

While waiting for the tunnel to be brought into operation, a series of exploratory tests on turbulent air jets have been performed. These tests will develop an understanding for the effect of placing the jet in a surrounding tube, i.e., tunnel test section. This geometrical configuration has not been studied before in detail, and the flow in it must be understood before the liquid metal experiments begin. The basic idea is to determine under what circumstances the enclosed jet can be made to behave like a jet in an infinite fluid. When the ratio of jet diameter (d) to container diameter (D) is relatively large, the jet spreads more rapidly than the "free" jet. It is necessary to surround it by a secondary stream with a velocity about 1/10th the jet velocity to "correct" its behavior. When d/D is made much smaller, the jet, with no secondary flow, spreads at a slower rate than the previous case but still faster than the "free" jet. A more complete parametric study is under way.

ANTICIPATED PUBLICATIONS

Open Literature

1. Maxworthy, T., "Experimental Studies in Magneto-Fluid Dynamics: Flow Around a Sphere with a Cylindrical Afterbody," J. Fluid Mech. (in press).

PUBLICATIONS

None

MATERIALS RESEARCH (129-03)

ELECTRIC PROPERTIES OF POLYMERS

NASA Work Unit 129-03-11-03-55

JPL 329-30401-1-3820

A. Rembaum

OBJECTIVE

The immediate objective of this unit is to determine the effect of ionic bonds on the mechanical, optical, and electrical properties of covalently bonded polymers. The ultimate goal is the synthesis of an organic or polymeric superconductor.

APPROACH

The synthesis of a well-defined and characterized system was found to be a necessary preliminary step. It was established that ionene polymers satisfy this condition. An additional advantage of this system is that the distance between ionic bonds can be varied and the effect of increasing distance on the properties of the polymers can be investigated.

PROGRESS

Formation of Linear and Cyclic Molecules

Ionene polymers are synthesized by means of the following reaction:

$$\underset{\text{I}}{(CH_3)_2N(CH_2)_xN(CH_3)_2} + \underset{\text{II}}{Br(CH_2)_yBr} \longrightarrow \underset{\text{III}}{\left[-\overset{CH_3}{\underset{CH_3}{\overset{|}{\underset{|}{N^+}}}}(CH_2)_x\overset{CH_3}{\underset{CH_3}{\overset{|}{\underset{|}{N^+}}}}(CH_2)_y- \right]_n} \quad \text{(with } Br^- \text{ counterions)} \tag{1}$$

However, when x and/or y are small integers, cyclic or linear compounds are formed. In order to find the exact values of x and y which yield polymers exclusively, an extensive study of reaction (Eq. 1) was carried out using all possible combinations of x = 1 to 6 and y = 1 to 6. The summary of results and the structure as well as analysis of the isolated compounds are shown in Figure 1 and Table 1, respectively.

Kinetics

The rates of formation of 6:6 polymers were investigated at various concentrations in a mixture of dimethyl formamide and methanol (1:1 by volume). The rate was followed by titration of unreacted dimethylamino groups. The results are shown in Figure 2. The values of rate constants were confirmed by means of NMR spectroscopy and the activation energy for the polymerization reaction was determined using the NMR technique.

Cationic Crosslinking Agents

The previously reported crosslinking agents obtained by reaction I, but using vinyl monomers instead of Reaction I were studied. It was found that 4-vinylpyridine and 4-dimethylamino styrene polymerize spontaneously at ambient temperature in presence of α, ω-dihalo compounds to yield viscoelastic materials. The effect of ionic charges on the mechanical properties of these materials is being investigated at present. The ion exchange resins obtained by homopolymerization of crosslinking agents were found to be unchanged after CO γ irradiation of 160 megarads.

FUTURE WORK

It is planned (1) to continue the present work on ionene polymers and (2) to initiate an extensive effort towards the synthesis of an organic superconductor.

(1) The examination of x-y reaction will be completed. A study of the effect of positive charges on the mechanical properties of viscoelastic polymers obtained through the intermediate formation of crosslinking agents, as well as the potential use of these materials as solid propellant binders will be explored. The electrical conductivity of ionene TCNQ complexes with even and uneven numbers of CH_2 groups will be compared.

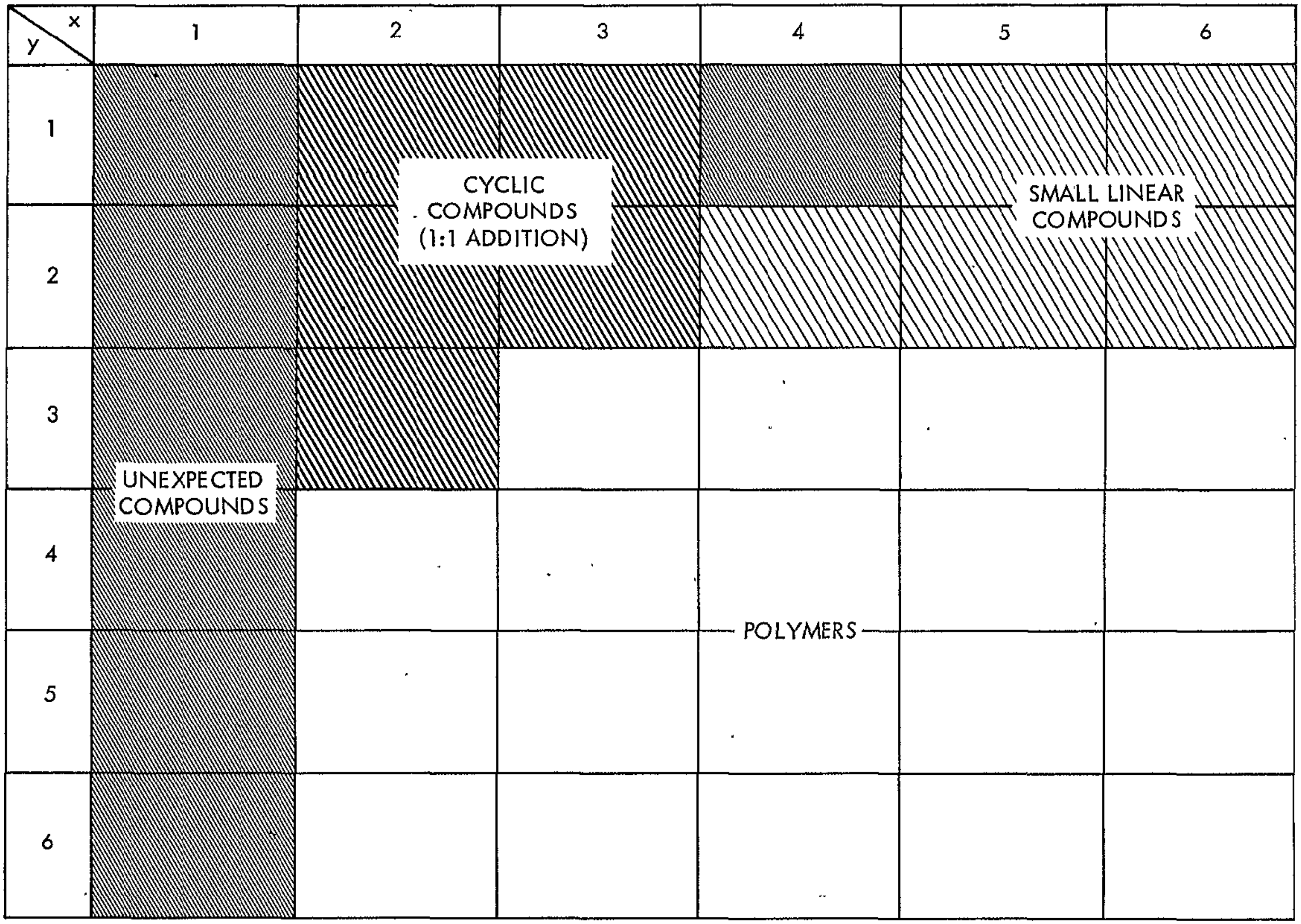


Figure 1. Summary of Results of X-Y Reactions

Table 1. Structure and Elemental Analyses

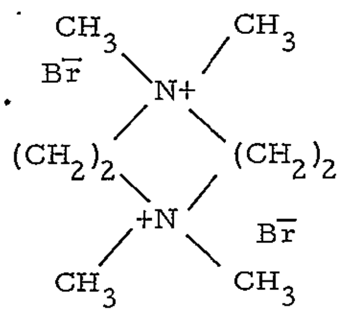
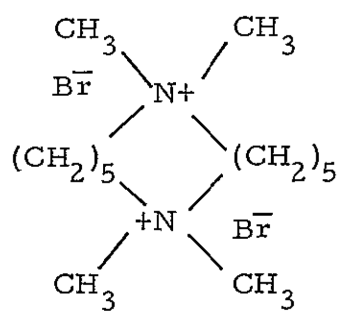
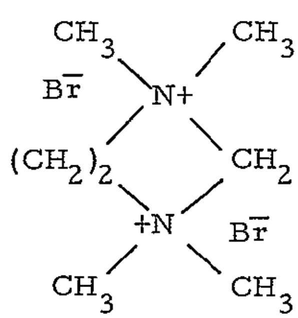
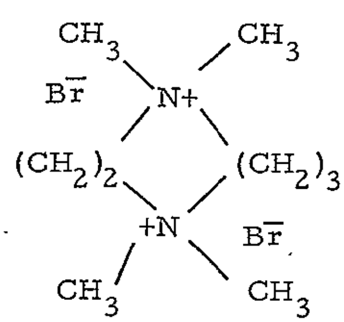
x-y	Formula	Elemental Composition (%)	C	H	N	Br^-
1-2		Calcd	31.60	6.63	9.21	52.56
		Found	31.52	6.60	9.13	52.50
1-5		Calcd	43.31	8.31	7.22	41.16
		Found	43.50	8.28	7.11	41.00
2-1		Calcd	28.99	6.26	9.66	55.10
		Found	28.96	6.20	9.60	55.06
2-2		Calcd	31.60	6.63	9.21	52.56
		Found	31.58	6.64	9.22	52.54

Table I (contd)

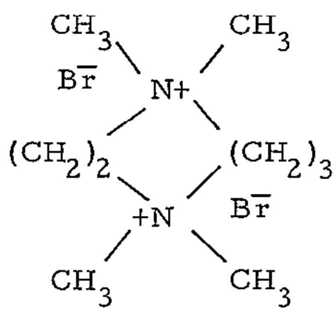
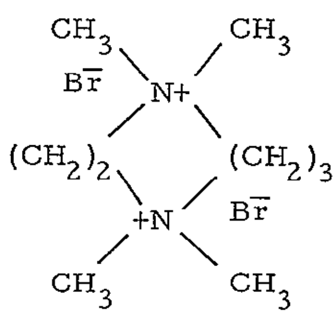
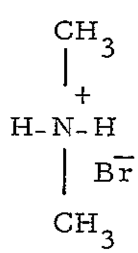
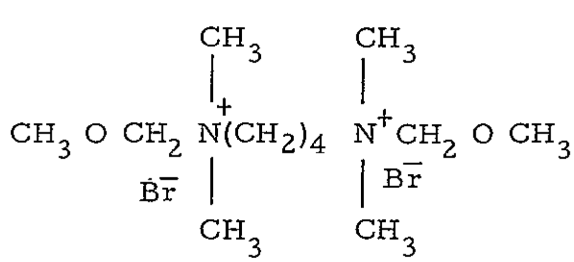
x-y	Formula	Elemental Composition (%)	C	H	N	Br^-
2-3		Calcd	33.98	6.97	8.81	50.24
		Found	34.07	6.98	9.01	50.11
3-2		Calcd	33.98	6.97	8.81	50.24
		Found	34.08	7.07	8.96	50.36
1-1		Calcd	19.06	6.40	11.12	63.42
		Found	19.09	6.26	11.00	63.48
1-4		Calcd	36.56	7.67	7.11	40.54
		Found	36.57	7.66	7.04	40.52

Table 1 (contd)

x-y	Formula	Elemental Composition (%)	C	H	N	Br^-	Total Br
4-1	$H\text{-}\overset{+}{N}(CH_3)_2(CH_2)_4\overset{+}{N}(CH_3)_2\text{-}H$ Br^- Br^-	Calcd	31.39	7.25	9.15	52.22	—
		Found	31.28	7.18	9.13	52.19	—
4-2	$Br(CH_2)_2\overset{+}{N}(CH_3)_2(CH_2)_4\overset{+}{N}(CH_3)_2(CH_2)_2Br$ Br^- Br^-	Calcd	27.72	5.43	5.39	30.73	61.46
		Found	27.84	5.50	5.46	30.71	61.38
6-1	$Br\ CH_2\ \overset{+}{N}(CH_3)_2(CH_2)_6\overset{+}{N}(CH_3)_2(CH_2)_2Br$ Br^- Br^-	Calcd	27.72	5.43	5.39	30.73	61.46
		Found	27.64	5.51	5.36	30.66	61.38
6-2	$Br(CH_2)_2\overset{+}{N}(CH_3)_2(CH_2)_6\overset{+}{N}(CH_3)_2(CH_2)_2Br$ Br^- Br^-	Calcd	30.68	5.89	5.11	29.16	58.32
		Found	30.86	5.96	5.24	29.17	58.23

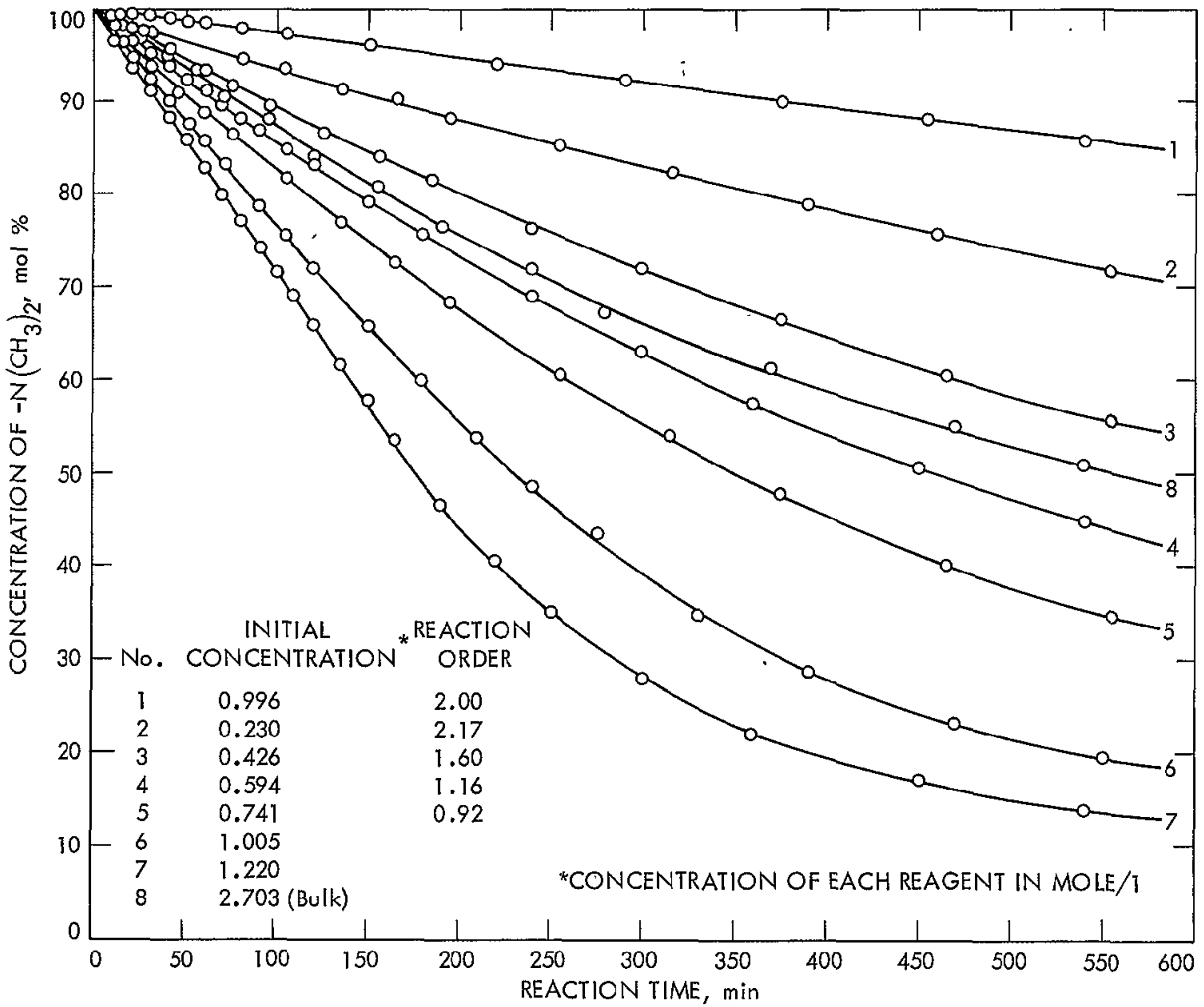


Figure 2. Rates of Formation of a 6-6 Aliphatic Ionene as a Function of Concentration

(2) Preliminary investigations will be carried out on the interaction of conjugated systems with alkali or transition metals in solution or in the solid phase. The diamagnetism of these systems will be measured as a function of temperature.

PATENT APPLICATIONS

1. Rembaum, A., "Dicationic Crosslinking Agents," filed September 1968.

2. Rembaum, A., and Singer, S., "Polymers and Conductive Compositions Thereof," Serial No. 759,220.

3. Rembaum, A., and Hermann, A. M., "Photovoltaic Material," Serial No. 718,752.

PUBLICATIONS

Meetings and Symposia Papers

1. Rembaum, A., "Ionene Polymers," Southern California Polymer Group of the ACS, Los Angeles, Calif., Oct. 22, 1968.

2. Rembaum, A., Singer, S., and Keyser, H., "Cationic Crosslinking Agents," Pacific Conference of the ACS, San Francisco, Calif., Nov. 7, 1968.

Open Literature

1. Rembaum, A., Hermann, A. M., and Haack, R., "Change Transfer Complexes of N-Ethylcarbazole and Poly-N-Vinylcarbazole, J. Polymer Sci., 6, 1955 (1968).

Technology Reports

1. Rembaum, A., "Radiation Polymerization," Case 1376.

2. Rembaum, A., "Method of Heat Detection," Case 1409.

3. Rembaum, A., "Synthesis of Ionic Rubbers," Case 1471.

4. Rembaum, A., and Noguchi, H., "Cyclic and Linear Organic Diammonium Salts.

RHEOLOGICAL PROPERTIES OF POLYMERS

NASA Work Unit 129-03-11-04-55

JPL 329-30501-1-3820

J. Moacanin
S. H. Kalfayan

OBJECTIVE

The objective of this task is to determine the molecular parameters which control the mechanical properties of amorphous, single- and multi-phase polymeric systems.

PROGRESS

Simple Elastomers

The initial work is concerned with the behavior of simple elastomers. The extension of current theories to long-time behavior is not straightforward because: first, the theory in its present form does not account for degradation reactions, which may be too slow to be ascertained from short-time measurements; and second, there exist poorly understood slow relaxation processes whose effects are presently accounted for by an empirical equation due to Plazek (Ref. 1). He studied the creep compliance in shear of natural rubber and styrene-butadiene rubber, but also found that Thirion's (Ref. 2) stress relaxation data on specimens from the same sheets were in complete accord with his creep data. (Both were very careful to exclude chemical degradation.) The good agreement between the results from these two types of experiments and our own constant strain rate data confirm the validity of Plazek's equation but, of course, this does not mean that it will be generally valid for all elastomers.

Plazek showed that a superposed curve for long-time response could be obtained using the apparent molecular weight between crosslinks, M_c, as a reduction variable. Thus, by carrying out measurements at several tempera tures and M_c levels, one can obtain the viscoelastic response for a reference temperature and reference M_c over nine or ten decades of logarithmic time. Plazek's master curve for creep compliance — the starting point for this work — is given by:

$$\log J_x \frac{t}{a_x} = \log J_e(M_c) + \log \left[\frac{J_e(M_{ref})}{J_e(M_c)}\right] + \log \psi_x \frac{t}{a_x} \qquad (1)$$

where $J_e(M_c)$ is the equilibrium compliance corresponding to M_c, the ratio in the second term represents the vertical shift that brings the response for the specimen onto the level of the reference curve, and ψ_x is a terminal retardation function which describes the very slow approach to equilibrium. The factor $\log a_x$, which provides the reduced time scale, represents the horizontal shift necessary to achieve superposition. The shift factor a_x was found to be an exponential function of M_c:

$$a_x = \text{const} \times M_c^m \qquad (2)$$

with $M = 15.4$ for both natural rubber and SBR.

It follows from this development, once the master curve for an elastomer is established, and consequently the a_x - M_c relationship is known, that M_c is the only parameter needed to predict the creep compliance of a given specimen at time t. Also, one can use the compliance curve to calculate other rheological properties via the distribution of retardation times.

The relationship between a_x and M_c suggests a method of incorporating the effects of chemical changes into the same formalism. We merely let M_c, and hence a_x, become a time dependent parameter whose value is determined by the appropriate degradation kinetics.

For the description of a system undergoing degradation, it is appropriate to use the initial material as reference; then the master curve describes the behavior of the undegraded material. As degradation proceeds, a_x departs from unity:

$$a_x(t) = \left[\frac{M_c(t)}{M_c(o)}\right]^m = \left[\frac{\nu_e(o)}{\nu_e(t)}\right]^m \qquad (3)$$

where the relationship for the number of effective chains ν_e is taken as $\nu_e = \rho/M_c$. Considerations of first-order degradation kinetics lead to

$$a_x(t) = \exp\,(mk't)$$

where k' is the rate constant for chain-scission. Extension to more complex kinetics is straightforward. However, the problem is to derive relationships between $\nu_e(t)$ and the reaction kinetics, since the mechanical response is determined by $\nu_e(t)$, whereas chemical analyses will yield the number of bonds broken.

Relaxometer Testing

A stress relaxometer capable of operating at temperatures as high as 350°F in gaseous atmosphere (air, oxygen, inert gas) and vacuum was assembled. It was operated at 200°F for two weeks under a load of 50g. The drift during this period amounted to less than 1.5% (>0.75g). The instrument will be used in studying the effects of chemical aging on stress relaxation.

An extensive literature search was carried out concerning the reactions of rubbers (natural and styrene-butadiene) in air at various temperatures and the contribution of such reactions (aging) to the relaxation of these rubbers.

FUTURE WORK

An analysis of the literature for appropriate degradation studies or systems such as SBR will be carried out. These data will be used to estimate the degradation rate at low temperatures, such as ambient, and then attempt a realistic comparison of the predicted and experimentally determined behavior.

This analysis will help ascertain the range of conditions where chemical effects can be separated from pure mechanical contributions.

REFERENCES

1. Plazek, D. J., J. Poly. Sci., A-2, 4, 745 (1966).
2. Thirion, P., Proceedings of the International Conference Physics of Non-Cryst. Solids, North Holland, Amsterdam, p. 345 (1965).

PUBLICATIONS

None

APPLIED MATHEMATICS (129-04)

APPLIED MATHEMATICS
NASA Work Unit 129-04-01-01-55
JPL 329-40101-1-3110
C. B. Solloway

OBJECTIVE

The objective of this work unit is to conduct research in statistical estimation theory, optimal control theory, applied mathematics, computer science studies, and general relativity.

BAYESIAN ESTIMATION

Bayesian estimation by means of orthogonal expansions has been studied for several different types of loss functions. If a quadratic loss function is used, a numerical method based on the Gram-Charlier expansion is found to be optimum. A JPL technical report describing these techniques and their application to optimal nonlinear estimation is in process of publication. The machine program for the implementation of some of these ideas has been almost completely checked out. Only a small part of it, the determination of the mode of the a posteriori density function, has not yet been completed. A tutorial exposition of these ideas, with applications to orbit determination and other areas of statistics, is being prepared.

GENERAL RELATIVITY

A paper describing the behavior of a clock moving radially in a centrally symmetric gravitational field was published in the SPS. This paper shows that the readings of a moving clock which return to their point of departure may be less than, or may exceed, that of the stationary clock, depending on the forces acting on the moving clock. This result may subsequently yield a test of Einstein's general theory of relativity.

A paper was presented at AIAA/AAS meeting, Jackson, Wyoming, September 3-6, 1968, entitled "On the Comparison of the Newtonian and General

Relativistic Orbits of a Point Mass in an Inverse Square Law Force Field," by H. Lass and C. B. Solloway. This paper is being reviewed for publication in the AIAA Journal.

The problem of testing Einstein's theory of relativity by means of radar observations involving only the proper time for the emission and reception of electromagnetic waves is being studied. Highly nonlinear equations arise in the analysis. It is hoped that the problem can be resolved without the use of a computer. If this can be accomplished, the results would be of importance in the JPL ephemeris work.

PERTURBATION THEORY

A systematic study on the prediction of the position and velocity of a satellite after many revolutions about the central mass is presented in Ref. 1 (presently being published as Ref. 2). It is shown that the methods of general perturbations are ideally suited for the prediction of orbits extending over many periods. Furthermore, it is concluded that the application of the variation of parameters with multivariable asymptotic expansions to the set of ordinary nonlinear differential equations governing the motion of a satellite predicts the position and velocity of the satellite to a sufficiently high accuracy after many revolutions about the central mass. Finally, the bibliography provides one of the largest (1370 citations) lists of references on satellite theory. (It should be noted that the contents of Ref. 1 were originally to be published as several technical reports and memoranda instead of the one document.)

During this reporting period, an investigation into the prediction of the position and velocity of a satellite being perturbed by the oblateness of the central mass, atmospheric lift and drag, and a third body was initiated using the variation of parameters with multivariable asymptotic expansions. This investigation is expected to continue for approximately 1 yr. In addition, a continuing review of the publications presented in Ref. 1, as well as current publications on satellite theory, is being conducted. In this manner, an extensive knowledge of satellite theory is being obtained.

Finally, a development of approximate analytic partial derivatives of the range-rate for a spacecraft during the encounter phase of a planetary flyby mission was initiated. In this development, the planet-centered hyperbola is assumed to be perturbed by the oblateness of the planet.

LITERAL SERIES EXPANSIONS AND APPLICATIONS

The last 6 mo have been spent in two major areas of research: (1) automatic manipulation of series expansions (power series and Fourier series) on a computer, and (2) generation of ephemerides for planets (or eventually satellites) with the use of computerized series expansions.

Computerized Series Expansions

Last July, the design and programming work was started on the "algebra package" for series expansions. The basic set of subroutines has now been terminated and is completely operational on the 7094 computer. Although these programs have been prepared mainly for applications in celestial mechanics, it is also true that their range of applications is much larger. These programs can be of use in any area of applied mathematics where some more or less extensive usage is made of polynomials, asymptotic expansions, Fourier series, or Taylor series.

The programs have been prepared in two different versions, according to some of the programming peculiarities of the 7094 computer. The smaller version is called the 3 + 3 version because of the three polynomial variables and three angles that can be manipulated, while in the larger version (6 + 6 system) the number of these variables is limited to six, instead of three.

Both the 3 + 3 and the 6 + 6 systems have been tested and are working satisfactorily. Much effort has been made to obtain the maximum efficiency and speed, and for this reason some of the basic subroutines have been programmed in machine language after they have been first programmed in FORTRAN IV. However, in order to obtain the maximum flexibility, the structure of the whole system is based on the FORTRAN IV language.

Applications to Planetary and Lunar Perturbations

As an application of this computer technique, a first-order planetary theory has been programmed with the 3 + 3 programs. We have been successful, for instance, in duplicating Clemence's planetary theory of Mars, with reasonable computing time: between 2 and 5 min (on IBM 7094) per perturbing planet (according to the distance of these planets from Mars).

The 6 + 6 programs have been tested by duplicating up to fourth order the perturbing function of Delaunay's lunar theory.

Representation of Planetary Observations by Chebychev Series

Programs have been made to investigate the possibility of representing the ephemeris of a planet by Chebychev series and also to improve or modify this ephemeris with an iterative general perturbation technique. It has been found, for instance, that 15 revolutions of a planet can be accurately represented by a Chebychev series with order 500. Work is now in progress to compare a Chebychev series for Venus with the radar observations of Venus.

Investigation of Mean Elements and Secular Terms of the Planets

Work has been started to determine more accurate mean elements of the planets, both with the use of observations (with Newcomb theories) and by double integration of the perturbing effects with Hill's method. The mean elements of the planets have to be accurately known in order to be able to compute accurate perturbations with a general perturbation theory.

Study on New Variation of Parameters and Numerical Integration Techniques

Different new variation of parameters techniques have been found and are now being tested by numerical integration of a Mars satellite model, (for eventual use on Mariner 71).

Life-Time Study for Mariner 71

A large number of computer runs have been made to determine life times of Mariner 71 orbits. These runs use the most recent data available on the atmosphere of Mars. It has been found that orbits with a period of 12 hr and a periapsis of 400 km have a life time of about 50 yr.

SEMINARS AND CONSULTING

The Applied Mathematics Seminar has had a series of talks on special and general relativity and electromagnetic theory. Future lectures will include tensor analysis, Riemannian geometry, and more on general relativity.

Consultant activities to Laboratory personnel in the mathematical disciplines continued as usual.

REFERENCES

1. Dallas, S. S., "Prediction of the Position and Velocity of a Satellite After Many Revolutions," Ph. D. dissertation in Engineering, University of California, Los Angeles, Calif., 1968.
2. Dallas, S. S., "Prediction of the Position and Velocity of a Satellite After Many Revolutions," TR 32-1267, Jet Propulsion Laboratory, in preparation.

ATTENDANCE AT SCIENTIFIC MEETINGS

1. Eighth Special Projects Branch Astrodynamics Conference, Goddard Space Flight Center, Greenbelt, Md., Oct. 17-18, 1968.
2. AIAA/AAS Astrodynamic Specialist Conference, Jackson, Wyo., Sept. 3-5, 1968.

PUBLICATIONS

Meetings and Symposia Papers

1. Broucke, R., "Stability of Periodic Orbits in the Elliptic Three-Body Problem," AIAA/AAS Astrodynamics Specialist Conference, Jackson Wyo., Sept. 3-5, 1968.
2. Broucke, R., "Some New Methods for Computing Planetary Perturbations," Eighth Special Projects Branch Astrodynamics Conference, Goddard Space Flight Center, Greenbelt, Md., Oct. 17-18, 1968.

3. Lass, H., and Solloway, C. B., "On the Comparison of the Newtonian and General Relativistic Orbits of a Point Mass in an Inverse Square Law Force Field," Paper 68-098, AIAA/AAS Astrodynamics Specialist Conference, Jackson, Wyo., Sept. 3-5, 1968.

SPS Contributions

1. Broucke, R., "On the Partial Derivatives of the Two-Body Problem," SPS 37-52, Vol. III, July 31, 1968.

2. Broucke, R., "A New Variation of Parameters Method with Universal Variables," SPS 37-53, Vol. III, Sept. 30, 1968.

3. Lass, H., and Gottlieb, P., "Behavior of a Clock Moving Radially in a Centrally Symmetric Gravitational Field," SPS 37-54, Vol. III, Nov. 30, 1968.

LUNAR AND PLANETARY FLIGHT MECHANICS

NASA Work Unit 129-04-01-02-55

JPL 329-40201-1-3110

C. B. Solloway

OBJECTIVE

The objectives of this work unit are to conduct basic research in celestial mechanics, to evaluate astronomical and physical constants from postflight analysis of tracking data, to improve planetary ephemerides from radio tracking data and planetary radar data, and to study advanced techniques for trajectory calculation and the development of orbit determination capabilities that account more realistically for the physical features of the solar system and the spacecraft.

ASTRODYNAMICAL AND PHYSICAL CONSTANTS

Earth-Moon System

A precise value of the mass of the earth-moon system relative to that of the sun was determined from an analysis of the motion of the minor planet (433) Eros. The 8639 observations which were included in the analysis extend in time from the prediscovery positions of 1893 to observations made in 1966. The observations, made at 85 observatories and based upon 106 different star catalogues, were reduced to the system of the Fourth Fundamental Catalogue. The equations of motion of the nine principal planets and Eros are integrated numerically in rectangular coordinates by the Adams-Stormer method with an n-body computer program. Accurate orbits for the nine principal planets were obtained for the period 1800-2000 from a comparison of the numerically integrated coordinates with those derived from classical astronomical ephemerides. The first-order variational equations were integrated numerically along with the n-body equations of motion. The definitive value of the mass of the earth-moon system adopted from the investigation is $S/(E + M) = 328\ 915 \pm 4$ (standard deviation), which corresponds to values of the solar parallax and the astronomical unit given by $\pi_{\odot} = 8''.79402 \pm 0''.00012$ and $A = 149\ 600\ 400 \pm 800$ km.

Icarus and the Mass of Mercury

Radar and optical observations of the minor planet (1566) Icarus have been analyzed in an attempt to verify the predictions of general relativity using both the Schwarzschild nonisotropic and isotropic metrics, and to estimate the dynamical oblateness of the sun, the mass of Mercury, and other parameters. Motivation for the study has been provided in large part by S. Herrick (Astron. J. 58, 156, 1953). The optical data spanned the interval from June 1949 to August 1968. Seven doppler measurements were taken by R. Goldstein at JPL's Goldstone, California station in June 1968 at 0.04 au. These measurements, which had an accuracy of 0.06 m/sec, were useful in indicating a bias in declination of the optical observations, but otherwise had a negligible effect on the solutions. The mass of Mercury was the only astronomical constant for which consistent estimates could be obtained. The solution for the inverse mass was m^{-1} = 5 940 000 ±50 000.

Relativity coefficients λ_I and λ_S were introduced in the problem, in the manner of Shapiro, et al (Phys. Rev. Lett. 20, 1517, 1968), as multipliers of the Schwarzschild isotropic and nonisotropic metrics, respectively. The transformation between these metrics involves a change in the radial coordinate, which implies a change in the semimajor axes of both Icarus and the earth. This was verified experimentally by noting that identical residuals (to 0.''001) and λ values for the two metrics could be obtained only by including both semimajor axes in the solution. Obtaining a solution for λ in an absolute sense is more difficult since λ is not separable from the oblateness of the sun (J_2) and since both are sensitive to other parameters of the problem, such as the earth ephemeris. The earth ephemeris is poorly determined from Icarus data and therefore the solution for λ varies over the range $0.87 \pm 0.08 \leq \lambda \leq 1.25 \pm 0.11$ when corrections to the orbit of the earth are included.

Planetary Precession, Nutation and Obliquity

An examination was made of effects of errors in the constants of precession and nutation on radar observations. If precession errors are not considered, then station longitudes will absorb the effects and drift approximately 1/3 m/yr.

A direct computation was made of rates of planetary precession and obliquity from an analysis of the angular momentum of the earth-moon barycenter about the sun. Positions and velocities obtained from DE 28 were employed over the interval 1765-2000. The result showed that the theoretical rates of change of planetary precession and obliquity are correct insofar as they depend upon the motion of the plane of the ecliptic. The well-known discrepancy between observation and theory in the rate of obliquity $\Delta\dot{\epsilon} = 0''\!.3T$ still remains unexplained, but it may depend perhaps on the internal constitution of the earth.

In the succeeding period an attempt will be made to estimate correction to the adopted value of the general precession in longitude by analyzing optical and radar observations of the planets. The analysis of the theoretical rates of planetary precession and obliquity by analyzing auto-covariance functions and spectral densities of the components of the earth's angular momentum about the sun to determine frequencies of the periodic terms will be completed.

Mass of Venus

The Mariner V encounter doppler radio tracking data has been used with a radar-improved Venus ephemeris to determine the mass of Venus. Currently the best value, from an analysis of 10 days of data centered near the point of closest approach to the planet, is $1/(408522.4 \pm 0.7)$ solar masses. This is in agreement with the value obtained from the Mariner II doppler tracking data when it is also analyzed with the improved Venus ephemeris. The improved Venus ephemeris, in conjunction with the closest approach distance of 10,151 km and probe inclination to the Venusian equator of the more recent flyby, afforded an opportunity to estimate the first order zonal harmonic (J_2) in the gravity potential expansion. The best-fit solution to the 10 days of doppler radio tracking data centered at planetary encounter indicates that any Venus oblateness must be less than one hundredth that of the earth.

SELENODESY

Analysis of some 9000 doppler observations obtained from Lunar Orbiter V spacecraft has revealed a most unique gravity field for the visible lunar face. All circular maria (Imbrium, Serenitatis, Crisium, Nectaris, and Humorum) exhibit large gravity anomalies whereas the irregular seas (Procellarum, Tranquillitatis, Fecunditatis, and Nubium) produce only slight effects. These gravity effects are believed to be excess mass concentrations and hence were named mascons. The gravity variations are about a magnitude larger than any observed on the earth. Extensive analysis is proceeding to obtain a more quantitative description of the size and shape of these mascons. There has been much speculation as to the origin of these mascons by several prominent theoreticians. Attempts are also being made to use the mascons as explanations for the optical observations in determining the dynamical motion of the moon.

PIONEER CELESTIAL MECHANICS EXPERIMENT

Over the past 3 yr there have been four Pioneer spacecraft launched into orbits about the sun. Highly accurate doppler data have been obtained from each spacecraft by means of ground-based antennas in the NASA/JPL Deep Space Net. These data provide measurements of one component of the relative velocity of the Pioneer spacecraft along a line joining the antenna and the spacecraft to an accuracy of better than 1 mm/sec. By observing changes in this accurately determined velocity component it is possible to obtain information on the masses of the earth and moon and on the orbits of the spacecraft and earth about the sun.

Results obtained from Pioneer VI, launched in December 1965, and from Pioneer VII, launched in August 1966, show that the mass of the earth is 1/332945 that of the sun and the mass of the moon is 1/81.301 that of the earth. The combined mass of the earth and moon is 1/328900 that of the sun.

RELATIVITY

The first n-body relativistic integration of planetary ephemerides fit to optical, radar, and spacecraft data was developed. A confirmation was made (utilizing JPL radar bounce data from Venus) of previous radar values of the radius of Venus and the astronomical unit. This value contrasts with the value of the radius obtained by Venera 4. An anomalous feature in the Venus radar bounce residuals led to a determination of the mass of Mercury.

ATTENDANCE AT SCIENTIFIC MEETINGS

1. Annual Meeting, American Geophysical Union, Washington, D. C., Apr. 1968.
2. JPL/BSRL symposium on "Observation, Analysis and Space Research Applications of the Lunar Motion," Seattle, Wash., Aug. 19, 1968.
3. American Astronomical Society (127th meeting) Victoria, B. C., Aug. 20-23, 1968.
4. AAS/AIAA Astrodynamics Specialists Conference, Jackson, Wyo., September 3-5, 1968.
5. Symposium, Division of Planetary Astronomy, American Astronomical Society, Austin, Tex., Dec. 10, 1968.
6. American Astronomical Society (128th meeting), Austin, Tex., Dec. 10-13, 1968.

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2. Sjogren, W. L., "Mascons," JPL/BSRL Symposium on Observation, Analysis and Space Research Applications of the Lunar Motion, Seattle, Wash., Aug. 19, 1968.
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4. Lieske, J. H., "Dynamical Determination of the Solar Parallax from the Motion of (433) Eros," 127th AAS Meeting, Victoria, B. C., Aug. 20-23, 1968.

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2. Lieske, J. H., "Effect of Precession and Nutation Errors on Radar Observations," SPS 37-54, Vol. III, Dec. 31, 1968.

3. Sturms, F. M., Jr., "An Earth-Venus-Mercury Mission Opportunity in 1978," SPS 37-54, Vol. III, Dec. 31, 1968.

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1. Melbourne, W. G., et al., "Constants and Related Information for Astrodynamic Calculations, 1968," TR 32-1306, July 15, 1968.

NUMERICAL ANALYSIS

NASA Work Unit 129-04-04-01-55

JPL 329-40301-1-3140

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C. L. Lawson

OBJECTIVE

The objective of this work is to bring sound principles of numerical analysis and computer algorithm design to bear on scientific computing problems at JPL. This includes research in numerical analysis, improvement of the general computational capability at JPL, and provision of consulting assistance on particular applications.

CURVE REPRESENTATION USING CUBIC SPLINES

A cubic spline is a function constructed by concatenating a number of cubic polynomials, typically subject to certain continuity conditions at the partition points. A spline is said to be of class C^m if continuity of derivatives through order m is maintained.

Splines are very suitable for the general representation of curves (functions) in digital computers. Specifically, splines are extremely flexible as to the variety of shapes that can be attained, while, with appropriate parameterization, splines have good numerical stability. Here numerical stability refers to avoidance of accumulation of roundoff errors in the computations needed to determine values of the parameters, say in curve fitting, and also in the subsequent use of these parameters for evaluation of the spline function.

JPL's work on splines is an outgrowth of previously reported work on improved algorithmic organization of orthogonal methods in linear algebraic computation and the gradient projection algorithm. These algorithms have been used as modules in the development of two distinct approaches to the least-squares fitting of a spline curve to a discrete set of data.

One approach imposes either C^1 or C^2 continuity and processes data sequentially so that there is essentially no storage limitation on the number of data points that can be used. An effective application of this work occurred in the MASCONS investigation which was done under other funding (Muller, P. M., and Sjogren, W. L., MASCONS: Lunar Mass Concentration, Science, 161, August 16, 1968).

The second approach provides a procedure for satisfying special requirements such as interpolation and inequality conditions on the value, first, second, and third derivatives. Such needs arise in applications and in some cases have caused delays in scientific work as ad hoc solution methods were devised and attempted. The procedure developed here has provided satisfaction of such special requirements in a number of applications.

SPECIAL FUNCTIONS

In collaboration with M. Geller, section 328, a systematic collection of formulas has been derived for the reduction of certain integrals of hypergeometric and exponential functions to simpler integrals.

Computationally efficient approximations have been derived for the Fermi-Dirac functions and certain generalized exponential integrals. These functions occur in atomic structure, solid state physics, and astrophysics and are used in physics research at JPL.

A system of computer programs for testing function generation subroutines was developed under this task about 3 yr ago. These programs were improved and modified during the current report period for use in testing function generation subroutines supplied to JPL with the UNIVAC 1108. It has been found that the UNIVAC-supplied single precision subroutines are generally less accurate than the corresponding IBM-supplied subroutines on the IBM 7094 by about one binary bit (both machines carry 27 significant bits) with a few cases in which the UNIVAC accuracy is much worse.

NUMERICAL SOLUTION OF ORDINARY DIFFERENTIAL EQUATIONS

The work reported last period on a variable-order, variable-step algorithm (VODQ) for the numerical solution of systems of ordinary differential equations has continued. The algorithm has been implemented as both single precision and double precision subroutines and has been tested extensively and used in more than 10 different applications.

In many of these applications other subroutines had previously been used and it was possible to obtain direct comparisons between the different methods in nontrivial applications. The new algorithm proved to be more reliable and efficient than the other methods in all cases.

As an example of one of the applications, a study of the temperature of the ionized and unionized components of a plasma mixture led to a need to solve a system of 10 first order ordinary differential equations. Over a period of several years, a number of different subroutines have been tried for the solution of these differential equations including several fourth order Adams type methods, a Runge-Kutta method, and a Romberg-Bulirsch-Stoer method. Of these methods, one of the fourth order Adams methods proved to be clearly superior to the others. In comparison, the integrator VODQ was twice as fast and gave slightly better results. Since runs of 30 min (now 15 min) are frequently made this represents a considerable savings in computer time, and in fact we have been told by Dr. Gary Russell, section 383, the originator of the problem, that this savings may mean the difference between being able to continue the work and not.

Further work on the numerical solution of ordinary differential equations will concentrate on the special case of stiff ordinary differential equations.

CONSULTATION AND EDUCATIONAL SERVICES

Talks were given at JPL on the use of splines in curve fitting and the numerical solution of ordinary differential equations. Consultation was provided in a variety of applications, particularly in the problem areas mentioned previously in this report.

PUBLICATIONS

Meetings and Symposia Papers

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   Keberle, E. M., "The System of Singular Integral and Ordinary Differential Equations for the Combined Radiation Conduction Heat Transfer of a Finned Spacecraft Cylinder," p. 4.

   Hanson, R. J., "Automatic Error Bounds for Real Roots of Polynomials Having Interval Coefficients," p. 15.

   Lawson, C. L., "Extensions and Applications of the Householder Algorithm for Solving Linear Least-Squares Problems," p. 23.

   Ng, E. W., "Truncation Errors on the Computation of Elliptic Integrals of the First and Second Kinds by Gauss and Landen Transformations," p. 25.

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CELESTIAL MECHANICS

NASA Work Unit 129-04-04-02-55

JPL 329-40401-1-3110

C. B. Solloway

OBJECTIVE

The objective of this task is to develop, analyze, and implement methods for the prediction of the motion of natural and artificial bodies in the solar system. This work is particularly oriented toward increasing the accuracy of the JPL planetary and lunar ephemerides. Increased accuracy is necessary to support planned space flight projects. Improved ephemerides will be made available to other NASA Centers and contractors.

LUNAR EPHEMERIS

The major work activity during the reporting period has been a continuation of the lunar ephemeris activity discussed in Ref. 1. The differential correction problem has been overcome, and numerical integrations have been fit to LE 6 over a 20-year interval. A satisfactory representation of LE 6 could not be achieved, however, because of the impossibility of accurately modeling certain empirical effects contained in the theory. This problem was solved by removing the empirical effects from the theory and fitting the "stripped down" theory. This has been done, and the fit seems reasonably satisfactory. Before this integration can be used, the empirical parts must be grafted onto it, because these parts do exist in the observations. This should be accomplished within the next reporting period.

One scientific result that seems to be emerging from this work is the following conjecture: Further attempts to improve the analytic theory of the lunar motion will be of little practical utility until better planetary theories exist upon which to base the perturbations.

Corrections to the lunar elements and to the equinox have been supplied by USNO and have been applied to the "stripped" LE 6. Numerical integrations have been fitted to it. By the end of this reporting period, the resulting ephemeris will be provided to NAG for reanalysis of station locations, in support of Mariner 69. This analysis will determine if the inconsistency between the results of lunar and planetary missions is due to the equinox.

The results of the integrations have firmly demonstrated that we must begin processing lunar observations at the earliest possible date. Accordingly, work has begun on the modifications to SSDPS that will enable the analysis of observations of the moon to be performed. A new capability is being added to the SSDPS. The Surveyor tracking data are to be used in a new computer least squares adjustment of the following parameters: selenocentric, moon-fixed coordinates of Surveyor (3), coefficients of the physical libration of the longitude of the mean ascending node of the lunar orbit on the ecliptic (5), coefficients of the physical libration of the inclination of the lunar equator relative to the ecliptic (5), coefficients of the physical libration of the mean lunar longitude (7), Brouwer and Clemence set III elements (6), deep space station (DSS) longitude (1903.0 pole, for three DSS), DSS latitude (1903.0 pole, for three DSS), and DSS spin axis (1903.0 pole, for three DSS).

Once completed, this model will be used to check out the Surveyor option of the DPODP, provide one consistent set of Surveyor selenocentric locations (all five Surveyors reduced simultaneously), provide DSS locations, refine the lunar physical libration model (beyond the present accuracy of the DPODP), generate a new lunar initial state to be integrated out into a new observational ephemeris (Holdridge and Mulholland), and, for what it is worth, utilize the finite difference partials and a mean lunar state to provide a new lunar ephemeris without resorting to a new integration (to be checked against the resulting integrated ephemeris).

The research toward an improved lunar ephemeris will continue. It is expected that the discussion of observations will be undertaken and that the concept of a "source theory" will be abandoned. Derivation of a perturbing function for the tidal bulge will be attempted as a means of modeling the effect of tidal friction on the lunar motion. The figure of the moon will be included in the computation of the accelerations. The observable computations will be extended to all data types pertinent to lunar applications. The analysis and computer algorithm is being expanded to include other data types, e.g., laser, radar bounce, Lunar Orbiter, and optical data.

JPL provided one of two organizers of a specialists' meeting on the subject "Observation, Analysis, and Space Research Applications of the Lunar Motion," held in Seattle last August.

PLANETARY EPHEMERIDES

In the past 6 months all projected goals of the previous R/AD report, Ref. 1, have been met or exceeded. During this period the Solar System Data Processing System (SSDPS) has become an operational programming system used in research.

The initial research activity was an investigation of an anomaly in the Venus radar range residuals for 1966. The anomaly was shown to be directly proportional to the unmodeled parameters, i.e., the masses of Mercury, Venus, and Mars. A further study led to a determination of the mass of Mercury. The preliminary results were reported in SPS 37-53. Further research with respect to the masses of Mercury, Venus, and Mars is anticipated in the next 6 months.

The research on the radius of Venus was continued. The inclusion of Mariner V spacecraft range data in the study gave a value of 6052 km. This result was presented in a paper given at the American Astronomical Society meeting in Victoria, B. C., in August. The results confirmed the radar-determined value and led to the conclusion that Venera 4 results do not give a valid radius for Venus.

The long-term effort at compiling the optical observations of all the planets has been completed. Eighteen-thousand observations made with the Six-Inch Transit Circle and Nine-Inch Transit Circle over the period 1911-1967 were placed in a common card format. These observations were compared to Development Ephemeris (DE) 28. This initial comparison allowed 700 observations to be corrected.

The radar data set was expanded through the addition of 1968 range data for Mercury and Venus. The data now extends from 1964 to October 1968. Additional information obtained at the October meeting of the ad hoc ephemeris group in Dahlgren, Virginia, resulted in the removal of the radar observations from Arecibo Ionospheric Observatory where observations were available from other radar sites.

This total data set of radar and optical observations has been utilized in the construction of the planetary ephemeris for the Mariner 69 mission.

A thorough study was made of the system of planetary masses used in ephemeris development. As a result the masses of Mercury, Mars, Neptune, and Pluto were altered.

This total effort was brought to bear on the production of the ephemerides for the Mariner 69. These ephemerides represent the first consistent ephemerides of all the major planets fit to optical, radar, and Mariner V spacecraft data. The inclusion of Mariner V data represents a new and unique use of spacecraft range data. The ephemeris was integrated over the period of 1910-1970.

After careful examination, this new ephemeris will be exported to NASA users. It will replace DE 19 issued early in 1967. This ephemeris will be suitable for Mariner 69 and the planning phases of Mariner 71 and Mariner 73. The "Grand Tour" mission studies will have a greatly improved ephemeris in their studies as a result of this new integration.

During the past six months, the following various versions of PLINT of the SSDPS have been generated to accomplish various ends.

For Icarus integrations, the solar oblateness perturbation was added and runs made to form partials from finite difference quotients. Production runs were also made to supply predictions up to the year 2000.

For the current version of PLINT used in the SSDPS, not only the solar oblateness perturbation on all the bodies but also the isotropic form of the Relativity perturbation was introduced.

An offspring of the above coding effort was also used in the special Mariner V deck. Many runs were made both forward and backwards for the computations including solar radiation pressure.

Finally a version of PLINT called LINT was formed to handle the lunar integration. This is still under development and appears to be giving good results even with the new form of the Relativity perturbation.

Production runs of RADAR10 were made for Earl Jackson on demand for Venus radar predictions and will continue to be made in the future.

During the period, some effort was directed at providing planetary ephemerides for remote time periods (pre-1850) to Dr. R. Head, NASA Electronics Research Center, in connection with astronaut radiation hazard studies.

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ATTENDANCE AT SCIENTIFIC MEETINGS

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1. 127th meeting, American Astronomical Society, Victoria, B. C., August 20-23, 1968.

Informal Meetings

1. Seminar on "Observation, Analysis and Space Research Applications of the Lunar Motion," Boeing Scientific Research Laboratories, Seattle, Washington, August 19, 1968.

2. Ad hoc ephemeris group, U. S. Naval Weapons Laboratory, Dahlgren, Virginia, October 16, 1968.

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Papers Presented at Meetings

1. Melbourne, W. G., and O'Handley, D. A., "The Radius of Venus as Determined by Planetary Radar and Mariner V Radio Tracking Data," American Astronomical Society, Victoria, B. C., August 20-23, 1968.

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