A STUDY TO IDENTIFY HYDROGEN MASER FAILURE MODES*

A. E. Popa, H. T. M. Wang, W. B. Bridges, A. N. Chester, J. E. Etter, and B. L. Walsh**
Hughes Research Laboratories
Malibu Canyon Road
Malibu, California 90265

Summary

Technical problem areas are presented that may adversely affect the reliability of extended spaceborne operation of a hydrogen maser frequency standard in the Navstar Global Positioning System. Included are failures that have occurred in past maser designs even though such failures are now understood and could be circumvented in future designs. It is concluded that all the failure mechanisms are amenable to space qualification engineering. The greatest potential problem areas are dissociator stability and atom production, storage bulb lifetime in a space radiation environment, and radiation damage to the electronics subsystem, particularly sensors.

Introduction

This study was undertaken to identify technical problem areas that may adversely affect the reliability of spaceborne operation of a hydrogen maser frequency standard in the Navstar Global Positioning System (GPS). From this analysis of existing maser designs, areas for design improvement can be identified.

In this paper we attempt to list all possible failure mechanisms that may occur in both spaceborne and ground-based hydrogen masers. Included are failures that have occurred in past maser designs, even though such failures are now understood and could be circumvented in future designs.

Physics Unit Failure Modes

Tables 1 and 2 list the various components that comprise the physics unit of a hydrogen maser. Associated with each component or element are one or more modes of failure that have been observed in past maser designs or that we project as possibilities for a spaceborne maser design. For each failure mode several possible causes are listed; the asterisks indicate known chronic cases.

Hydrogen supply and regulation components are low risk items because of the past experience with similar space-qualified gas supply systems. Careful engineering of the final hardware design is all that is required here.

Difficulties with the rf discharge plasma hydrogen dissociator have been common in the past, but recent experience has improved typical operating life to three or more years. Figure 1 is a schematic representation of a typical spherical glass bulk dissociator plasma with capacitively coupled electrodes. The power is fed into the bulb by displacement current through the glass walls to the conducting hydrogen plasma within.

Table 1. Principal Failure Modes — Physics Unit (1)

4416-19

COMPONENT	FAILURE MODE	POSSIBLE MECHANISM
H_2 SUPPLY	LOSS OF H_2 FLOW CONTROL	VALVE HEATER BURN-OUT PRESSURE SENSOR MALFUNCTION CONTROL SYSTEM FAULT GAS LEAK POWER LOSS
DISSOCIATOR	DISCHARGE CEASES	*IMPEDANCE CHANGE THRU CONTAMINATION *WALL EROSION RF DRIVER FAILS CONTROL CIRCUIT FAILS POWER LOSS
	H ATOM PRODUCTION DECLINES ("WHITES OUT")	*WALL RECOMBINATION GAS CONTAMINATION *WALL SPUTTERING SERVO CONTROL FAILURE
COLLIMATOR	DECREASED THROUGHPUT OF COLLIMATED ATOMS	MECHANICAL CRACKING WALL EROSION WALL CONTAMINATION CAUSING RECOMBINATION *MISALIGNMENT
STATE SELECTOR	DECREASED THROUGHPUT OF FOCUSSED ATOMS	LOSS OF POLE STRENGTH MISALIGNMENT

*HIGHEST RISK ITEMS

Table 2. Principal Failure Modes — Physics Unit (2)

4416-20

COMPONENT	FAILURE MODE	POSSIBLE MECHANISM
STORAGE BULB	LOSS OF SIGNAL AND/OR STABILITY	*DECREASED STORAGE TIME BY TEFLON IRRADIATION DAMAGE *CHANGE IN WALL SHIFT BY RADIATION DAMAGE *MECHANICAL FRACTURE MIS-ALIGNMENT DURING LAUNCH MICROWAVE LOSSES DUE TO BULB IRRADIATION
MICROWAVE CAVITY	LOSS OF SIGNAL AND/OR STABILITY	LOSS OF CAVITY Q THRU COATING SEPARATION STRESSES ON CAVITY
ION PUMP	LOSS OF VACUUM	*MECHANICAL STRESS (Ti HYDRIDE) *HIGH VOLTAGE SHORTS (ZERO G)
VACUUM SYSTEM	LOSS OF VACUUM	OUTGASSING VIRTUAL LEAKS DISCHARGE SPUTTERING
MAGNETIC SHIELDING	LOSS OF STABILITY	EXCESSIVE EXTERNAL MAGNETIC INTERFERENCE
THERMAL SUBSYSTEM	LOSS OF TEMPERATURE UNIFORMITY OR STABILITY*	POWER LOSS *AGING OF THERMAL SENSORS CONTROL CIRCUIT FAILURE STRESS-INDUCED MECHANICAL FRACTURE
MAGNETIC FIELD AND DEGAUSSING COILS	LOSS OF STABILITY	COIL BURN-OUT CONTROL CIRCUIT FAILURE POWER LOSS

*HIGHEST RISK ITEMS

Figure 2 illustrates the potential distribution near the glass walls, showing the potential fall or "wall sheath" necessary to satisfy boundary conditions on wall current. The wall sheath has the effect of increasing the energy with which positive ions strike the wall; this, in turn, greatly increases the yield of wall material sputtered by the incident ions. Figure 3 shows the typical steep dependence of sputtering yield

*This work was supported by the Naval Research Laboratories under Contract N00014-75-C-1149, Robert B. Moore, Scientific Officer.

**Hughes Aircraft Company, Space and Communications Group, P.O. Box 92919, Los Angeles, CA 90009.

on ion energy for the low energies typical of the wall sheath. Only a one or two volt change in wall sheath can cause an order of magnitude change in the sputtered material yield.

The improvements in dissociator bulb life observed empirically in recent years can probably be attributed to

- Increase in bulb size
- Better coupling into the plasma
- Lower drive power.

These three factors serve to decrease the displacement current density through the walls and decrease the energies of the ions incident on the bulb walls. Further improvement may be possible by further changes in configuration and choice of wall materials.

While the multitube glass collimators themselves have exhibited little difficulty, mechanical strains in the region adjacent to the collimator often produce problems in conventional designs. Careful attention to mechanical design and vacuum interlocks that prevent large transient pressure differentials across the collimator bundle during startup should eliminate this potential failure point.

No areas of high risk are associated with the maser state selector magnet.

The principal potential cause of failure resulting from the hydrogen storage bulb is degradation of the Teflon© coatings from the space radiation environment. Increased recombination rates will occur if the fluorine bonds are broken to produce more chemically active sites. Microcracks in the coating which expose the underlying SiO_2 will also increase the probability of recombination. Changes in the wall shift may be produced by radiation, although this has not been documented experimentally. We have performed dose calculations on a typical maser design in the Navstar GPS orbit and have obtained values of 7000 rads (Tf) for seven years in the natural background and 18,000 rads (Tf) if a nuclear event is added. These values are known experimentally not to cause any gross degradation of Teflon. ©

A spaceborne maser development program will require accelerated radiation testing to determine if any wall shift and linewidth changes occur for the radiation dose encountered in the Navstar orbit. We have found x-ray diffraction measurements can detect slight changes in Teflon© below the threshold of gross radiation damage. For example, thin Teflon© solar cell covers exposed to doses several times greater than that encountered by Navstar show a development of crystallinity as illustrated in Fig. 4. Whether changes observed by x-ray diffraction will correlate with degradation in maser performance remains to be determined.

The microwave cavity structure offers small failure risk. Substantial weight savings through the use of advanced composite materials technology will indirectly contribute to the reliability of the entire maser by reducing structural stresses.

The ion vacuum pump is a well-developed component. However, a zero-g environment offers the potential hazard of free-floating particles which can short the high voltage elements. Special attention to mechanical design will be required to keep stresses caused by conversion of titanium to titanium hydride from creating distortions that would short out internal electrodes.

Of the remaining components in Table 1, only the thermal sensors are likely to be a problem in the spaceborne maser design. Calibration drift with radiation dose or thermal cycling will have to be investigated carefully.

Electronics Unit Failure Modes

All electronic subsystems are subject to failure mechanisms that are generally well known. Thermal fatigue, chemical diffusion, and electromigration are particular hazards for devices dissipating high power, while contamination and corrosion, shorts (from loose metallic particles) and bond failures are encountered by all electronic components.

In Table 3 the principal failure modes for the hydrogen maser electronics unit are listed. The highest risk is associated with space-radiation damage and inadequate thermal sinking of the higher power solid state devices. In the past, point contact devices, such as Schottky mixers, have been subject to contact failure in vibration; however, recent work at Hughes and other laboratories has produced techniques to greatly reduce the occurrence of this potentially serious problem. Many electronic problems can be eliminated by careful inspection as shown in the Scanning Electron Microscope (SEM) pictures, Figs. 5, 6, and 7. Figure 5 is a mechanically stable Schottky diode whisker contacting a gold electrode imbedded in the semiconductor surface. Figure 6 shows a blunted whisker that has mechanically moved off the gold electrode causing a failure. The SEM picture shown in Fig. 7 graphically illustrates the result of electromigration. In this case potassium contamination left from wafer processing has migrated to the whisker causing diode failure.

Table 3. Principal Failure Modes — Electronics Unit (3)

4416-7

COMPONENT	FAILURE MODE	POSSIBLE MECHANISM
CRYSTAL OSCILLATOR	EXCESSIVE FREQUENCY AGING	*RADIATION DAMAGE TO QUARTZ
	LOSS OF SIGNAL	VIBRATION INDUCED FRACTURES
SYNTHESIZER	DEGRADED STABILITY	RADIATION DAMAGE TO JUNCTIONS
VARACTOR	DEGRADED OUTPUT SIGNAL LEVEL	RADIATION DAMAGE INCREASES REVERSE LEAKAGE CURRENT
MIXERS	DEGRADED NOISE FIGURE	*RADIATION DAMAGE INCREASES SERIES RESISTANCE
	LOSS OF SIGNAL	POINT CONTACT FAILURE IN VIBRATION
DISSOCIATOR DRIVER AND POWER OSCILLATORS	OUTPUT POWER DEGRADATION	*THERMAL AGING

*HIGHEST RISK ITEMS

Conclusions

Although there are many difficult problem areas that may adversely affect the reliability of a long lived spaceborne hydrogen maser frequency standard, all are amenable to space qualification engineering. We feel the greatest potential problem areas at present are

©is DuPont trademark.

- Dissociator stability and atom production
- Storage bulb lifetime in a space radiation environment
- Radiation damage to the electronics subsystem components, particularly sensors.

Acknowledgments

We began our hydrogen maser studies by visiting a number of organizations active in the maser field and related activities. Specifically, we would like to acknowledge contributions from the following groups: H. E. Peters (NASA, retired) and V. S. Reinhardt at the NASA Goddard Space Flight Center; N. F. Ramsey and D. Larson at Harvard University; our own divisions at Hughes Aircraft Company working in related areas of technology; R. Sydnor and P. Dachel at the Jet Propulsion Laboratory of California Institute of Technology; R. L. Easton, V. Folen, and R. B. Moore at the Naval Research Laboratories; H. Hellwig and F. Walls of the Boulder Laboratories of NBS; R. F. C. Vessot and M. W. Levine at Smithsonian Astrophysical Observatory; and S. B. Crampton and H. T. M. Wang (now with Hughes Research Laboratories) at Williams College.

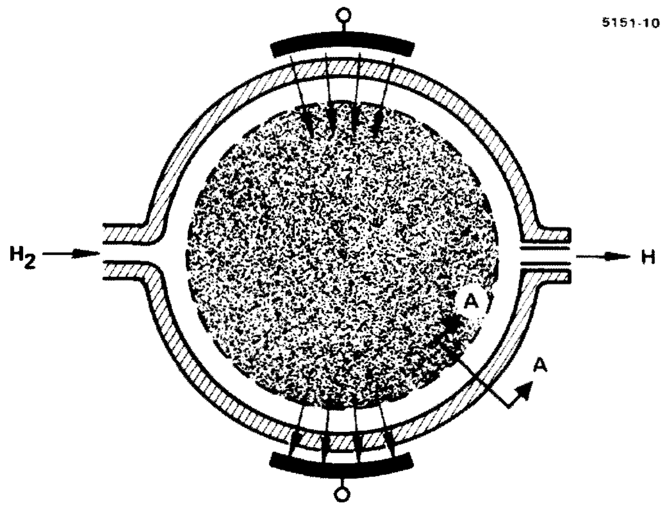

Fig. 1.
Schematic representation of the plasma within an rf excited dissociator showing displacement current through the walls under the electrodes.

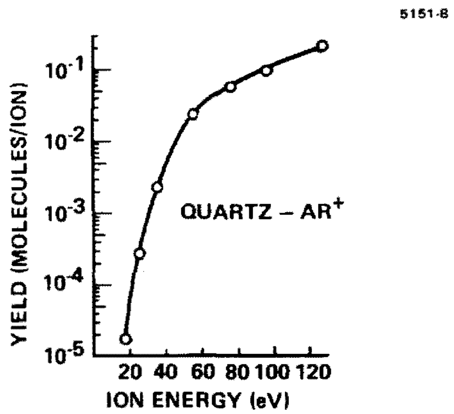

Fig. 3.
Sputtering yield of SiO_2 molecules from a SiO_2 surface under bombardment of low energy argon ions.

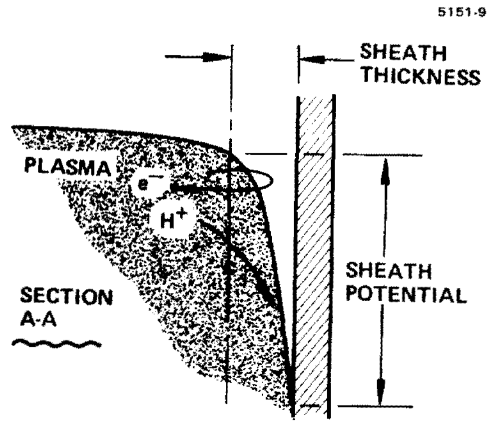

Fig. 2.
Plot of potential versus radius in a section through the plasma sheath near the glass wall.

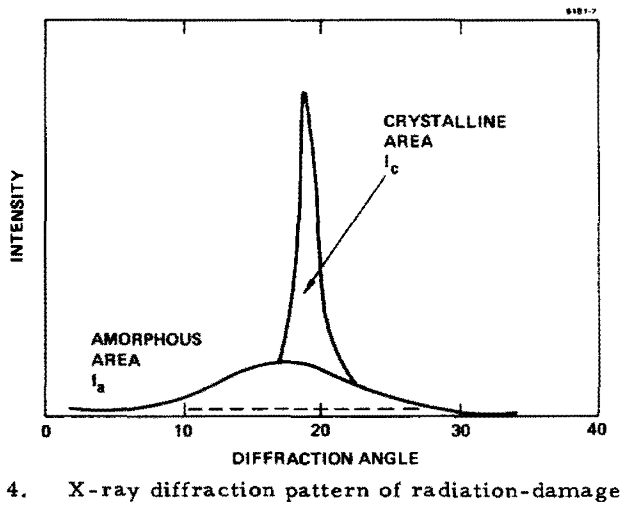

Fig. 4. X-ray diffraction pattern of radiation-damage Teflon solar cell covers.

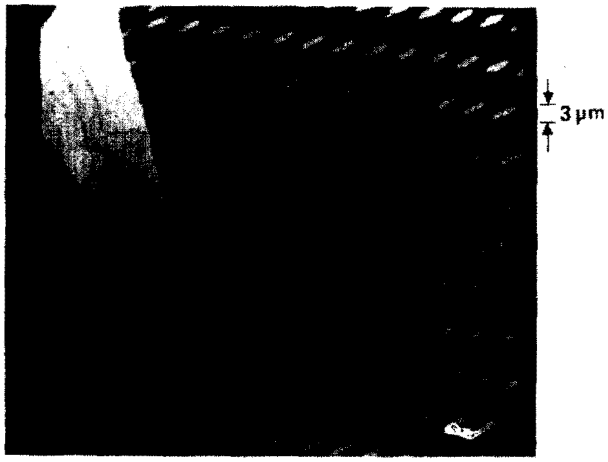

Fig. 5. SEM of a mechanically stable Schottky point contact.

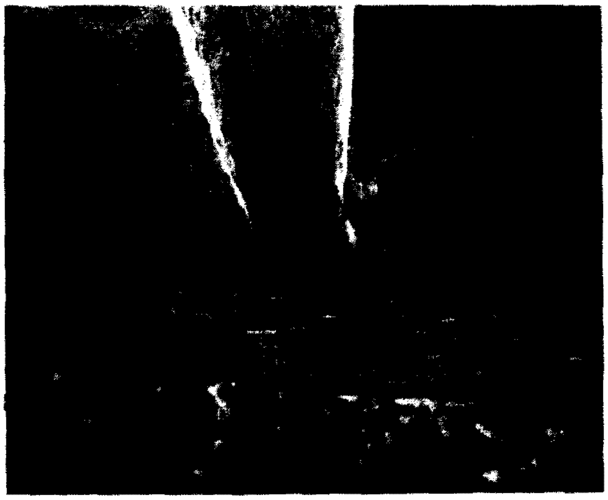

Fig. 6. SEM of a blunted Schottky diode point contact that has mechanically failed.

Fig. 7. SCM of a potassium contaminated Schottky diode illustrating the electromigration process.