JET PROPULSION LABORATORY

INTEROFFICE MEMORANDUM
521-ARH-90-01

February 27, 1990

TO: MMII Project Staff and Project Representatives

FROM: A. R. Hoffman A.R. Hoffman

SUBJECT: Galileo Environmental Program Lessons Learned

REFERENCE: 1) Galileo Document 1625-455, "Galileo Environmental Test and Analysis Program Summary" (Draft dated December 15, 1989).

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The attached excerpt from the referenced summary document is being distributed to MMII personnel to provide a resource for planning and implementing the environmental programs for the CRAF and Cassini spacecraft. The information is provided in two forms: Attachment A is simply a listing of the topics and the relevant recommendations; Attachment B gives the entire text of Section 7 of the report, provides a description of the concern, and repeats the recommendation.

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Attachments

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(2/8/90)

ATTACHMENT A

# 7.0 LESSONS LEARNED

## 7.1 Dynamics Lessons Learned

### 7.1.1 General Comments

**7.1.1.a System Level Test Documentation**

Recommendation: System Level dynamic tests should be thoroughly documented, including a complete set of response data and sketches or photographs of all instrumentation.

**7.1.1.b Incompatibilities in Design and Test Documents**

Recommendation: Future projects should 1) develop environmental requirements and structural design criteria documents which are compatible, and 2) develop more realistic vibration test methods, specifically dual force and acceleration control vibration testing and alternatives to sine vibration which better simulate the characteristics of flight transient vibration environments.

**7.1.1.c Vibroacoustic Prediction Model**

Recommendation: Future projects should develop vibroacoustic models early in the program and update them as necessary.

### 7.1.2 Assembly Level

**7.1.2.a Assembly Level Pyroshock Qualification Testing**

Recommendation: New assembly level shock test methods need to be implemented and methods of performing system or subsytem shock environmental qualification with margin would be highly desirable.

**7.1.2.b Transient Vibration Test Alternatives**

Recommendation: Future projects should further develop and utilize transient vibration test alternatives to the swept sine.

### 7.1.3 System Level

**7.1.3.a Precursor Sine Vibration Test**

Recommendation: Future projects should perform a precursor test on a DTM or, as a minimum, on a mockup structure.

### 7.1.4 S/C Transporter

### 7.1.4.a Transporter Dynamic Requirements

Recommendation: Future projects should 1) establish van acceptance criteria early in the program based on spacecraft capabilities and 2) subject the van certification process to the same level of management control as the development of flight hardware.

## 7.2 Galileo Thermal Environmental Lessons Learned

### 7.2.1 General Comments

#### 7.2.1.a Material Optical Property Characterizations

Recommendations: Outer surface materials (especially thermal control surfaces) should be fully characterized before acceptance for design. In particular, the synergistic effects of time at temperature, long solar UV and possibly solar wind should be simulated. The transformation of ITO should always be considered.

JPL should invest in better materials characterization equipment. In particular, the portable optical property measurement devices (which are acceptable to measure trends, but not absolute values) should be supplemented with more state-of-the-art equipment. We should not have to depend on our colleagues at TRW to provide reliable absolute values of absorptance and emittance.

#### 7.2.1.b Solder Joint/Solithane Fatigue (Thermal Cycle Testing)

Recommendations: Electronic assembly packaging must be designed and qualified for the combined ground test/mission thermal cycle environment. Qualification must be on non-flight hardware and should be taken to failure. The expected ground test cycle estimates must include plausible retesting scenarios for fixes and modifications.

Flight electronic assemblies should not be thermal cycle tested. The risk of using up available solder joint fatigue life is significant if the cycle approach is used. The standard JPL single cycle dwell approach is proper. It provides workmanship verification of mechanical stress failure physics (without significant loss of fatigue capability), as well as an Arrhenius time-at-temperature reliability demonstration.

Environmental requirement groups (especially Thermal Environments) should receive more information about the total thermal exposure of all assembly elements. PWBs, for example, are sometimes thermal cycle tested as a workmanship screen prior to part laydown. Conformal coating cure processes sometimes involve elevated temperature. Unplanned mission operational cycling scenarios need to be examined early. All of these aspects are needed to understand the total ground test/mission fatigue requirements.

### 7.2.1.c Temperature Agreement Memos

Recommendation: The JPL standard allowable flight levels (+5°C to +50°C for electronics) and protoflight test levels (-20°C to +75°C) and their associated margins (±25°C) should be adhered to as much as possible throughout future projects. This reduces the requirements for requalification as thermal predictions evolve.

Some form of the agreement memo process should be continued on future projects, especially for instrument sensors. One option might be to attach these forms as an appendix to the General Assembly Level Test specification.

## 7.2.2 Assembly Level Design/Test

### 7.2.2.a Appendage Instrument Temperature Margins

Recommendation: Design and test temperature levels/margin should be maximized for appendage mounted equipment (especially instruments). A different philosophy for margin may be appropriate when the predicted temperatures are extreme in either direction. The concept of margining energy (i.e. $T^4$) rather than simple temperature may be better. Most elements that operate relatively near room temperature (i.e. +5 to +50°C) and are tested at -20°C to 75°C have an energy margin of about 1.4, similar to structural margins. This concept would result in a lower actual temperature margin for very cold items; similarly, hot assemblies would require a greater margin than the current philosophy of +25°C.

### 7.2.2.b Vacuum versus Atmospheric Testing of Electronic Assemblies

Recommendation: Electronic assemblies should be Protoflight thermal tested under vacuum conditions (where vacuum is a flight environment).

A well thought out conservative thermal analysis of the assembly to the piece-part level should be performed for design purposes. An addition of convective terms to such an analysis should be performed if atmospheric testing is proposed in lieu of vacuum. If the predicted reduction in piece-part case temperatures under atmospheric conditions is less than 5°C (for <u>all</u> parts), then an atmospheric test may be acceptable.

**7.2.2.c Thermal Analysis of Electronic Assemblies to the Piece-Part Level**

Recommendation: Perform a thermal analysis of each new or modified electronic assembly to the piece-part level. Power dissipation should be based on realistic worst-case levels expected in the circuit (not maximum part specification values).

Parts Stress Analyses are based on the Protoflight shearplate temperature (usually 75°C). This is the recommended thermal analysis boundary condition.

Worst-Case Analysis for performance are based typically on an 85°C shearplate. The thermal model can be rerun for this condition, or a 10°C delta can be added to the part temperature predicted for the Parts Stress Analysis.

**7.2.2.d Electronic Assembly Thermal Retest Approach**

Recommendation: The GLL Category D refurbishment thermal retest requirements are generally applicable to future JPL projects.

**7.2.3 System Level Test**

**7.2.3.a System Level Thermal Margin Demonstration**

Recommendation: System Thermal Vacuum tests should continue to include Protoflight test phases that demonstrate thermal margin. This can be accomplished with added internal test heaters, or where infrared simulation (instead of solar) is used, the total external energy levels can be raised. Judicious elevation of the chamber sink temperature is one possibility. A goal of about a 5°C margin (i.e. traditional JPL Flight Acceptance levels) is recommended.

**7.2.4 Spacecraft Transporter**

**7.2.4.a GLL Transporter Qualification**

Recommendation: Failure of a spacecraft transporter system during qualification should require the same process as a flight hardware failure. Find the problem, fix it, and perform the necessary requalifications.

**7.2.4.b GLL Transporter Humidity/Seal Issues**

Recommendations: Obtain design, test, and use data on the KSC PETS transporter. Develop a better seal system for future transporters, perhaps a double seal with a $GN_2$

purge inbetween them. Avoid leaving transporters unattended with A/C units operating if the storage environment is different than the internal transporter conditions. Provide redundant, continuous readout, recordable measurements of both temperature and humidity with audible alarm levels.

### 7.2.5 Other Issues (Facility Environmental Control)

#### 7.2.5.a KSC Environmental Control

Recommendation: Future projects should be aware of these recent KSC problems. It is hoped that KSC will improve its redundancy and procedures to preclude such incidents in the future.

#### 7.2.5.b Storage of Spacecraft Assemblies

Recommendation: The Environmental Exposure Guidelines developed for GLL should be implemented for all JPL projects.

## 7.3 Electromagnetic Compatibility

### 7.3.1 General Comment

#### 7.3.1.a MIL STD vs Tailored EMC Testing Program

Recommendation: A conventional military standard EMC program should be implemented and should be coupled with a tailored approach for addressing specific needs (for example, science instruments with special EMC requirements).

#### 7.3.1.b Radiated Emissions

Recommendation: An assessment of the Radiated Emissions requirements and margins being imposed on the spacecraft design should be evaluated early among the affected organizations.

#### 7.3.1.c Interference Between STS and Galileo

Recommendation: Future programs would benefit from early co-ordination between Telecommunications Engineering, Systems Engineering and the EMC Group relative to frequency assignment.

#### 7.3.1.d Unexpected Occurrences During Final Spacecraft Assembly

Recommendation: Both areas noted above should receive further analysis and test prior to the next assembly of a spacecraft.

### 7.3.2 Assembly Level Testing

### 7.3.3 System Level Testing

Recommendations:

## 7.4 Magnetics

Recommendations:

Future projects should avoid using Invar and Kovar, if possible, to minimize magnetic uncertainty and improve magnetic cleanliness if flying a magnetometer.

A larger Helmholtz coil system should be obtained for the JPL magnetics laboratory.

Magnetic "tattletales" during spacecraft shipment should become a normal part of the instrumentation complement for spacecraft with a magnetics cleanliness requirement.

## 7.5 Natural Space Environment

### 7.5.1 Radiation Shielding Analyses

Recommendations: Have a younger engineer work with the older experienced person before the expert leaves, not after. This should probably be extended to any area and not just to someone nearing retirement - in critical areas, have a capable back-up; this is just common sense but we don't always do it.

Before someone like a senior analyst leaves, make sure all the important computer models of the spacecraft (used with the radiation transport code) are archived and, if at all possible, are somehow or other transferred or translated to a new code; the calculations for the new hardware and new environment on GLL were made using the code NOVICE whereas prior calculations were done using SIGMA.

If possible, don't change key people and codes at the same time. This adds to problems when comparing previous SIGMA calculations (and SIGMA calculations for new hardware) with NOVICE calculations for same. Much of this difficulty was because of differences in geometry (details) but sometimes the problem was just in trying to make sure we were comparing apples with apples.
Make absolutely sure that all assumptions, details, etc., are included in the memos. A prime example is the environment - it is absolutely pointless to supply shielded dose values; without the external environment they are meaningless.

### 7.5.2 Solar Proton Events Model

Recommendations: Do not underestimate the sun - many people questioned the conservatism of the new proton model. They argued there had been no major proton events since the August 1972 event; this was an anomalously large event and so there probably wouldn't be any more big events this cycle. On the contrary, there have been 3 or 4 major proton events since March of this year, with the last one in October being equal in size (peak flux and total fluence, >10 MeV) to the 1972 event within the error of the measurements. However, we still have not exceeded the 95% confidence level predicted by the model for the fluences (@ the >10, >30, >60 and >100 MeV levels).

Keep models for the solar proton events updated on a regular basis -- don't wait until there's a problem. Funding should be provided to update the model either institutionally or spread among the major projects. If this is done then an accurate model will be available when needed. For example we now have data from cycle 22 which should be used to update the existing model and there are no models for peak flux nor for the electrons. These updates should be started now!

### 7.5.3 Micrometeoroid Model

Recommendations: The model being used for the environment in question should be documented in one place.

Additionally, the model needs to be updated on a reasonably frequent basis. The NASA standard model dates back to circa 1970 and is badly in need of revision.

## 7.6 Single Event Upsets

Recommendation: The application of new technology into spacecraft hardware should be assessed from an environmental interactions perspective.

Figure 7-1? Linear Energy Transfer ...

## 7.7 Electrostatic Discharge

### 7.7.1 External Electrostatic Discharge

Recommendation: Aging and handling effects on surface properties should be addressed on future programs.

### 7.7.2 Internal Electrostatic Discharges (IESD)

Recommendation: IESD requirements should be imposed on all future JPL projects.

## 7.8 Programmatic

### 7.8.1 General Comments

#### 7.8.1.a Basis of Environmental Program

Recommendation: The Voyager/Galileo environmental test programs and documentation should serve as models for major in-house flight projects.

#### 7.8.1.b Hardware Test and Analysis Configuration

Recommendation: The process for developing the test and analysis configuration list and matrix should be performed early and be a cooperative effort among hardware cognizant engineers and environmental requirements personnel as it was done for Galileo. The comments and suggestions noted in the discussion above and in paragraph 7.7.2.b should be addressed.

#### 7.8.1.c Test and Analysis Matrix

Recommendation: The test and analysis matrix on future programs should use the format that includes distinguishing between sine and random vibration testing and includes explicit requirements for performing contamination analysis.

#### 7.8.1.d Radiation Analyses

Recommendations: If a Radiation Analysis Review Committee is formed, the duties and responsibilities of the committee should be clearly delineated in the Radiation Control Document. For example, explicit requirements that the committee is the review board for the RACS and can reject the RACS when it is evident that it is incomplete or not in compliance with requirements should be established.

The Radiation Analysis Completion Statement form should be reviewed and revised to make it easier to understand and to prepare.

For new projects with a radiation design requirement, neither the Worst Case Analysis nor the Radiation Analysis should be waived for any engineering or instrument subsystems. These analyses are necessary for determination and verification of the Radiation Design Margin.

### 7.8.2 Assembly Level

#### 7.8.2.a Test Reporting-Assembly Level

Recommendation: In establishing the testing and analysis grouping in 625-260, consider grouping the hardware by the following heirarchy: 1) set of subassemblies normally environmentally tested as complete assembly, delivered and stored in Quality Assurance Bonded Stores and subsequently integrated on to the spacecraft as a unit, 2) set of subassemblies of a given subsystem that must be functionally or physically grouped together to perform meaningful environmental testing or analyses, and 3) hardware supplying organization. A tier numbering scheme may prove useful, eg 63A, 63B, in identifying the equipment grouping in 625-260.

**7.8.2.b Approved ETSS Before Performing Environmental Testing**

Recommendation: Remind new cognizant engineering personnel of the requirement. Enlist QA and test facility personnel's help in implementing the requirement.

**7.8.3 Systems Level**

See comments in technical discipline lessons learned.

**7.8.4 Spacecraft Transporter**

See comments in technical discipline lessons learned.

**7.8.5 Other**

**7.8.5.a Problem Failure Reporting Process**

Recommendation: As with the lesson learned for preparing environment test and analysis forms (7.7.2.d) an education process is clearly indicated. Future project/ tasks need to make sure that everyone knows how to properly enter information onto the P/FR form. It would also be very helpful if the Reliability Section, who has oversight of the PFAC to modify the P/FR to clearly distinguish between a formal environmental test environment and a bench-fabrication/assembly-systems environment test. It should be distinct on the form that they are not the same. Each individual who is in the P/FR review process should be asked to verify that the header information is correct. If errors are found, the corrections should be noted, the originator should concur in any change, and the PFAC should correct their data base.

It should again be noted that the non-adherence to the breakdown of subsystems/assemblies in PD625-260 was also in evidence on P/FRs. this non-adherence meant that some "digging" had to be performed to determine to what piece of hardware the P/FR belonged.

### 7.8.5.c Environmental Files

Recommendation: Future projects should continue to have the ERE as the focal point of the environmental test and analysis program documentation. Cognizant personnel should be encouraged to provide the necessary documentation as requested on each test and analysis form.

## 7.9 Early In-Flight Experiences

### 7.9.1 Spacecraft Charging/ESD

### 7.9.2 Solar Flare Event - 19-22 October 1989

Recommendation: First, prior to the 1989 solar flares, the solar proton fluence models were believed to be overly conservative. The current extreme increase in activity has gone far toward validating them and verifies the Galileo project decision in adopting them. Secondly, it is proposed that solar activity be continuously monitored prior to, during, and following launch. If the flare had occurred a few days earlier, it might have affected the mission success. A forecast of impending activity might have allowed contingencies to have been taken; luck ruled this time. Thirdly, the heavy ion model of solar flares will need to be continuously reviewed and updated during the course of the mission given the importance of SEU survivability to Galileo and the data now becoming available.

### 7.9.3 EMC

Recommendation: The lesson learned is that, although a test verification program is required, an especially intensive and carefully implemented design program in both spacecraft ESD immunity and for shielding for the plasma experiment quietness seems to have bene successful when comprehensive testing was not considered possible or appropriate.

### 7.9.4 Temperature

### 7.9.5 Dynamics

ATTACHMENT

B

## 7.0 LESSONS LEARNED

In this section, the lessons learned are described and recommendations are presented. The Galileo environmental program extended throughout the spacecraft development phase, 11 years, and represents 99 workyears of effort. During this period, there were some things that were done that definitely should be continued on future programs. There are other facets of the program that should be improved for future flight projects. Many of the lessons, even though resulting from an in-house project, can also be applied to a system contractor developing hardware for JPL.

In the following, the lessons learned are presented by discipline, including: dynamics, thermal, electromagnetic compatibility, magnetics, natural space environments, electrostatic discharge, and programmatic. In the last paragraph (7.9) entitled Early In-Flight Experiences, comments and lessons learned during the first two months of flying the Galileo spacecraft having environmental program implications are discussed.

## 7.1 Dynamics Lessons Learned

### 7.1.1 General Comments

#### 7.1.1.a System Level Test Documentation

Utilization of Voyager system level dynamics (acoustics, sine vibration, pyrofiring) test data for development of Galileo assembly level requirements was severely hampered by the lack of well documented test reports. This resulted in considerable efforts to assess the data and the necessity of special developmental tests. As a result, considerable uncertainty regarding the adequacy of the Galileo requirements existed in the early stages of the project. In contrast, Galileo system dynamic tests were thoroughly documented.

Recommendation: System Level dynamic tests should be thoroughly documented, including a complete set of response data and sketches or photographs of all instrumentation.

#### 7.1.1.b Incompatibilities in Design and Test Documents

Incompatibilities between dynamics environments design and test requirements documents (Section 521) and structural design criteria documents (Section 354) resulted in a number of conflicts during assembly level vibration testing. These conflicts were due to: 1) structural design criteria which did not consider all environmental loads, and 2) conventional sine and random vibration test methods which were overly conservative.

Recommendation: Future projects should 1) develop environmental requirements and structural design criteria documents which are compatible, and 2) develop more realistic vibration test methods, specifically dual force and acceleration control vibration testing and alternatives to sine vibration which better simulate the characteristics of flight transient vibration environments.

#### 7.1.1.c Vibroacoustic Prediction Model

A vibroacoustic prediction model (VAPEPS) was developed for Galileo late in the program - after the first PF acoustic test. Nonetheless, the model proved extremely useful for quickly and efficiently evaluating the impact of spacecraft modifications and of spacecraft configuration acoustic retest differences from flight.

Recommendation: Future projects should develop vibroacoustic models early in the program and update them as necessary.

### 7.1.2 Assembly Level

### 7.1.2.a Assembly Level Pyroshock Qualification Testing

Assembly level pyroshock qualification using vibration shakers was found to be totally inadequate in that specification levels could not be achieved above about 2500Hz. New assembly level shock test methods are needed for future projects. System level pyrofirings for shock qualification were also unsatisfactory. Multiple firings are expensive and time consuming and do not ensure test margin above the flight environment. In some cases (Superzip) multiple firings were not practical.

Recommendation: New assembly level shock test methods need to be implemented and methods of performing system or subsytem shock environmental qualification with margin would be highly desirable.

### 7.1.2.b Transient Vibration Test Alternatives

A special low frequency modulated sine wave pulse vibration test was developed and implemented for select Galileo assemblies as an alternative to the swept sine vibration test. Although the conventional swept sine test has many advantages, it can result in a significant overtest for some sensitive hardware when compared to the flight transient events it is intended to simulate. The special modulated sine wave pulse test was highly effective in reducing the inherent overtest of the swept sine for select assemblies, in particular the RTGs and the RPM 400 N Engine.

Recommendation: Future projects should further develop and utilize transient vibration test alternatives to the swept sine.

### 7.1.3 System Level

### 7.1.3.a Precursor Sine Vibration Test

The sine vibration test on the Development Test Model (DTM) spacecraft was deleted as a cost savings. Therefore, the Galileo sine test performed on the flight spacecraft was the first spacecraft vibration test performed at JPL in about 10 years, and it was performed primarily by personnel who had not participated in earlier spacecraft sine vibration tests at JPL. Partly as a result, the spacecraft sine test was plagued by delays and technical difficulties. In retrospect, it would have been more cost effective, resulted in fewer project delays, and been safer to have performed a precursor test on the DTM or, as a minimum, on a mockup structure.

Recommendation: Future projects should perform a precursor test on a DTM or, as a minimum, on a mockup structure.

**7.1.4 S/C Transporter**

**7.1.4.a Transporter Dynamic Requirements**

Inadequate attention was paid to GLL spacecraft transportation dynamics requirements and van certification. This resulted in a last minute effort, the evening before the trip to KSC, to verify that the flight spacecraft would not be damaged in transit. It also resulted in a number of "false alarms" during the trip that had to be assessed real time.

Recommendation: Future projects should 1) establish van acceptance criteria early in the program based on spacecraft capabilities and 2) subject the van certification process to the same level of management control as the development of flight hardware.

## 7.2 Galileo Thermal Environmental Lessons Learned

### 7.2.1 General Comments

#### 7.2.1.a Material Optical Property Characterizations

Two types of external thermal blanket materials were introduced for the GLL VEEGA Thermal Control modifications. One was Indium-Tin Oxide (ITO) coated black Kapton; the other was ITO coated aluminized Kapton (ITO/Kapton surface outboard). Both materials were characterized in terms of solar absorptance and infrared emittance with existing JPL portable measurement devices. No data at temperatures equalling or exceeding expected flight conditions was initially obtained.

During the 1988 GLL System Thermal Vacuum (STV) test, both materials reached temperatures well beyond expected levels. Clearly, the optical properties were different than expected. Post STV tests were performed at TRW but not at expected flight temperature levels.

The JPL materials group developed a theory that the primary cause was a change in the Indium Oxide/Tin Oxide ratio as the temperature was elevated. This resulted in a more "metallic" surface, thus a lower emittance. Contamination effects during STV (that may or may not occur in flight) also contributed, theoretically, to increased solar absorptance.

The TRW coupon tests tended to support the above theories, but the high temperatures seen in STV were not simulated. A later simple temperature test at levels above the STV experience was performed at JPL which showed an additional small reduction in emittance.

This entire issue resulted in very late reanalysis of several instruments. The result was higher temperatures for worst-case expected mission conditions (further degradation of solar absorptance due to UV and solar wind effects, thus higher temperatures than seen in STV). It was not possible (schedule wise) to requal the instruments, and in one case, technically impossible. Thus the previous qualification margin was used up or almost totally eliminated.

Recommendations: Outer surface materials (especially thermal control surfaces) should be fully characterized before acceptance for design. In particular, the synergistic effects of time at temperature, long solar UV and possibly solar wind should be simulated. The transformation of ITO should always be considered.

JPL should invest in better materials characterization equipment. In particular, the portable optical property measurement devices (which are acceptable to measure trends, but not absolute values) should be supplemented with more state-of-the-art equipment. We should not have to depend on our colleagues at TRW to provide reliable absolute values of absorptance and emittance.

**7.2.1.b Solder Joint/Solithane Fatigue (Thermal Cycle Testing)**

A MGN problem showed that the presence of Solithane between piece-parts and the PWB can lead to fatigue failures of the part solder joints. The fundamental cause is the higher coefficient of thermal expansion for the Solithane than other elements of the part/lead/PWB system. The number of test thermal cycles (either intentional, due to power on/off, assembly retests, etc.) becomes the fatigue environment.

GLL assemblies were found to have similar packaging issues with Solithane conformal coated PWBs.

Although thermal cycling testing was not generally performed on GLL, the multiple retests over the years for upgrades, suspect part replacement, etc., simulated a thermal cycle test history.

Review of GLL assemblies resulted in parts removal, Solithane elimination under the part, some haywires, etc. The retest was generally limited to Flight Acceptance levels (typically 0°C to 55°C) to avoid any additional solder joint damage to other elements. In some cases, this meant less demonstrated margin than desired since there were examples where Protoflight levels (-20°C to 75°C) were clearly justifiable due to the nature of the changes.

Operations personnel are desirous of the Galileo mission turning certain instrument heaters on and off frequently. This would allow closer control of the overall power margin and the RPM tank shunt heaters in particular. This may subject portions of instruments to a thermal cyclic environment for which they were not qualified.

Recommendations: Electronic assembly packaging must be designed and qualified for the combined ground test/mission thermal cycle environment. Qualification must be on non-flight hardware and should be taken to failure. The expected ground test cycle estimates must include plausible retesting scenarios for fixes and modifications.

Flight electronic assemblies should not be thermal cycle tested. The risk of using up available solder joint fatigue life is significant if the cycle approach is used. The standard JPL single cycle dwell approach is proper. It provides workmanship verification of mechanical stress failure physics (without significant loss of fatigue capability), as well as an Arrhenius time-at-temperature reliability demonstration.

Environmental requirement groups (especially Thermal Environments) should receive more information about the total thermal exposure of all assembly elements. PWBs, for example, are sometimes thermal cycle tested as a workmanship screen prior to part laydown. Conformal coating cure processes sometimes involve elevated temperature. Unplanned mission operational cycling scenarios need to be examined early. All of these aspects are needed to understand the total ground test/mission fatigue requirements.

**7.2.1.c Temperature Agreement Memos**

Early in the GLL program, predicted temperature levels were generally within the JPL standard allowable flight range of +5°C to + 50°C for most bus electronics. Thus the normal JPL protoflight test range of -20°C to +75°C was applicable. However, most instruments started with exceptions and smaller margins (as discussed in 7.2.2.a below). Thus a set of agreement memos was generated to keep track of the exceptions to normal requirements. These delineated the latest allowable Flight Temperature range, Flight Acceptance test range (if applicable) and the Protoflight test range for the specific assembly. Signatories included the Cognizant Engineer, the Thermal Control Engineer and the Environmental Requirements Engineer.

Although the development of these memos was time consuming, it provided the only means of tracking a dynamic thermal control prediction process such as occurred with the VEEGA mission changes. In addition, all parties were able to understand all aspects of the issue. Where a technological temperature limit (a detector for example) existed, it was defined. Where the prediction uncertainty was large, it was noted.

Recommendation: The JPL standard allowable flight levels (+5°C to +50°C for electronics) and protoflight test levels (-20°C to +75°C) and their associated margins

($\pm$25°C) should be adhered to as much as possible throughout future projects. This reduces the requirements for requalification as thermal predictions evolve.

Some form of the agreement memo process should be continued on future projects, especially for instrument sensors. One option might be to attach these forms as an appendix to the General Assembly Level Test specification.

### 7.2.2 Assembly Level Design/Test

#### 7.2.2.a Appendage Instrument Temperature Margins

Most GLL instruments required initially only a ±15°C margin beyond allowable flight temperature levels. This should be compared with the ±25°C margin and minimum test levels of -20°/+75°C for bus mounted electronics.

The Thermal Control of the S/C bus is usually tighter than appendages. Thus the expected range for appendage equipment is usually wider than for the bus. The uncertainty associated with a wider expected range is larger, and the uncertainty in the overall environment definition for appendages may be bigger than for bus mounted equipment.

There is an apparent paradox here. The larger uncertainties in appendage mounted equipment should clearly cause greater test margins, not smaller.

It is recognized that many instruments carry state-of-the-art detector elements which cannot function over wide temperature ranges. It is believed that this was the rationale for the smaller margin.

As the design of the GLL S/C mission evolved, temperature predictions became more extreme (especially due to the VEEGA mission). This led to smaller margins on many of the instruments. In some cases this margin is now effectively zero.

Recommendation: Design and test temperature levels/margin should be maximized for appendage mounted equipment (especially instruments). A different philosophy for margin may be appropriate when the predicted temperatures are extreme in either direction. The concept of margining energy (i.e. $T^4$) rather than simple temperature may be better. Most elements that operate relatively near room temperature (i.e. +5 to +50°C) and are tested at -20°C to 75°C have an energy margin of about 1.4, similar to structural margins. This concept would result in a lower actual temperature margin for very cold items; similarly, hot assemblies would require a greater margin than the current philosophy of +25°C.

#### 7.2.2.b Vacuum versus Atmospheric Testing of Electronic Assemblies

Over the years, a perception developed at JPL that thermal testing at atmospheric pressure with $GN_2$ is acceptable for most electronic assemblies even though the flight environment is vacuum. Much of this is based on an old criteria that if the watt density is $\leq$ 0.04 watts/cm$^2$, vacuum effects are negligible. Also, much of industry uses an atmospheric test.

In 1987 a thermal analysis of the CDS trays was performed for both atmospheric and vacuum conditions. The CDS watt density is on the order of 0.03 watts/cm$^2$. The results showed that the overall effect of atmospheric free convection was a reduction in internal element temperature rise by a factor of about 2. In fact, piece-parts could be cooler than vacuum conditions by 20°C to 30°C.

A special test of CDS tray 14 was performed which directly compared vacuum versus atmospheric conditions. The vacuum case exhibited a piece-part temperature 18°C warmer than the atmospheric case. Thus the theoretical analysis was substantiated.

Several other examples on several projects have shown the same general trend.

Atmospheric testing is cheaper, and easier for GSE support equipment connections. However, the planned test margin can be reduced significantly. In fact, if the desired test margin is only 10°C to 15°C, the real demonstrated margin for piece-parts/packaging <u>may be negative</u>!

Some have tried to compensate for the vacuum effect by increasing the test level. The effects of atmospheric convection are twofold; reduction of internal temperature rise, and smoothing of the temperature distribution. In other words, an atmospheric test does not demonstrate the assembly function/performance with the actual flight piece-part temperature differences. For timing circuit elements, etc., this may be significant.

Also, just raising the test temperature increases the mechanical stress on certain elements. In particular, solder joint fatigue life can be adversely affected by this approach compared to a proper vacuum test at the original test requirement levels.

Recommendation: Electronic assemblies should be Protoflight thermal tested under vacuum conditions (where vacuum is a flight environment).

A well thought out conservative thermal analysis of the assembly to the piece-part level should be performed for design purposes. An addition of convective terms to such an analysis should be performed if atmospheric testing is proposed in lieu of vacuum. If the predicted reduction in piece-part case temperatures under atmospheric conditions is less than 5°C (for all parts), then an atmospheric test may be acceptable.

### 7.2.2.c Thermal Analysis of Electronic Assemblies to the Piece-Part Level

Thermal analyses of electronic assemblies including all piece-parts are seldom performed at JPL. Instead, a 10°C rise from the shearplate to the piece-part is usually assumed.

A Thermal analysis of the CDS was performed by the Thermal Environment Group in 1987 (for reasons other than piece-part temperatures). Results showed that most parts were about 20°C above the shearplate temperature, and that some were almost 30°C above the shearplate.

Analyses performed to the piece-part level by Thermal Environments for other projects showed consistently that the 10°C rise previously assumed was unconservative. They also showed that 70% of the high temperature piece-parts dissipated less than 100 milliwatts. This is because of specific part mounting techniques and the local interactive temperature environment of other assembly elements.

It was concluded that no simple criteria for piece-part temperature rise could be developed that would cover all parts. Thus an analysis of each new electronic assembly was recommended. Note that most of industry performs such analyses.

Recommendation: Perform a thermal analysis of each new or modified electronic assembly to the piece-part level. Power dissipation should be based on realistic worst-case levels expected in the circuit (not maximum part specification values).

Parts Stress Analyses are based on the Protoflight shearplate temperature (usually 75°C). This is the recommended thermal analysis boundary condition.

Worst-Case Analysis for performance are based typically on an 85°C shearplate. The thermal model can be rerun for this condition, or a 10°C delta can be added to the part temperature predicted for the Parts Stress Analysis.

#### 7.2.2.d Electronic Assembly Thermal Retest Approach

Appendix D provides retest guidelines developed during the GLL program. Of particular interest are the Category D refurbishment types: single part changeout, part lead resoldering (few parts), simple haywire changes, etc. Since these did not involve a circuit electrical design change, and did not constitute anything like a new assembly, the traditional long duration Flight Acceptance test (0°C for 8 hrs, 55°C for 60 hrs) could not be technically justified. The long 60 hr hot soak is an excellent Arrhenius reliability demonstration for new assemblies (that have a previous qualification history at 75°C for ≥ 144 hrs). Also, new assemblies should be tested in vacuum for the reasons delineated in 7.2.2.b above.

However, for the minor changes associated with Category D refurbishment, the real intent of a thermal retest is a thermally induced mechanical stress test for workmanship of the refurbished solder joints or haywires or etc. A mechanical stress demonstration requires only temperatures above and below room temperature to Flight Acceptance levels (i.e. ±5°C beyond Allowable Flight levels). Duration is not important, and as noted in 7.2.1.b above, thermal cycling can use up significant fatigue life.

The GLL retest that evolved was a 3 to 4 hour soak at 0°C and 3 to 4 hours at 55°C.

Although vacuum is always the preferred thermal test condition, most GLL Category D retests were performed under atmospheric conditions. This was generally justifiable on the basis that atmospheric free convection effects on the affected solder joints, haywires, etc., were small.

Recommendation: The GLL Category D refurbishment thermal retest requirements are generally applicable to future JPL projects.

### 7.2.3 System Level Test

#### 7.2.3.a System Level Thermal Margin Demonstration

The objectives of a System level Thermal Vacuum test (STV) should include to:

1) Demonstrate the adequacy of the overall thermal control design.

2) Demonstrate operation of the spacecraft system/subsystems in a flight-like environment.

3) Demonstrate that the overall spacecraft is not thermally marginal.

The third objective was accomplished on GLL during the 1985 STV program with two "Protoflight" test phases. The cold condition was essentially a cold soak with minimum internal power.

The hot Protoflight phase was more difficult to accomplish. S/C-test facility power safety considerations had led to the installation of internal "safing" heaters. In the case of certain facility power failures, the S/C could be maintained at "safe" temperatures. These same heaters were used during the hot Protoflight phase (in addition to maximum internal S/C power and increased solar energy) to raise most assembly temperatures somewhat above their highest expected flight levels.

Thus system/subsystem performance/functions was demonstrated with some margin. Subtle thermal effects such as connectors about to pull free due to thermal expansion were demonstrated by such test phases. Margin in louver control ranges and thermal interactions between subsystem elements were also demonstrated.

The Magellan spacecraft's thermal control design required low solar absorptance-to-infrared emittance ratio coatings. The hot design case included degradation of these coatings (increased solar absorptance) that could not be simulated in STV (new "clean" coatings). Heaters somewhat similar to GLL were installed for its STV with power dissipation on the order of the S/C bus power. As in GLL, temperatures somewhat above highest expected flight were achieved. Without these heaters, temperatures well below expected flight levels would have occurred due to the "clean" coatings.

Recommendation: System Thermal Vacuum tests should continue to include Protoflight test phases that demonstrate thermal margin. This can be accomplished with added internal test heaters, or where infrared simulation (instead of solar) is used, the total external energy levels can be raised. Judicious elevation of the chamber sink temperature is one possibility. A goal of about a 5°C margin (i.e. traditional JPL Flight Acceptance levels) is recommended.

### 7.2.4 Spacecraft Transporter

#### 7.2.4.a GLL Transporter Qualification

The transporter was theoretically designed to proper requirements. However, during qualification testing at Point Mugu, it was found that the air-conditioning (A/C) units could not maintain internal temperature requirements (< 59°F) if the outside temperature was > 91°F (the qualification requirement was 120°F). In other words, the A/C units were undersized.

In addition, the motor generator systems were unreliable. Failure occurred too frequently.

The capacity of the A/C units were increased after the Point Mugu tests, but no requalification was ever attempted. This led to continual assessments of capability versus planned time-of-year trips across the country with GLL.

The motor generator reliability issue continued until the last delivery of GLL to KSC in May 1989. At that time, two new and one additional motor generators were installed. A six day operating test and a test run to Indio, California, provided some confidence, and indeed no motor generator problems were encountered.

Recommendation: Failure of a spacecraft transporter system during qualification should require the same process as a flight hardware failure. Find the problem, fix it, <u>and perform the necessary requalifications</u>.

#### 7.2.4.b GLL Transporter Humidity/Seal Issues

Following delivery of GLL to KSC in December 1985, it was placed in the SAEF airlock with the transporter air conditioning running to keep the Probe at ≈55°F while the airlock was at ≈70°F. The transporter box seals were inadvertently deflated. This allowed infiltration of the higher temperature (higher enthalpy) airlock air into the box. This led to condensation and frost buildup on the A/C evaporator coils inside the box. As the frost eventually covered most of the coils, an A/C overpressure shutdown occurred. This led to the frost thawing rapidly which caused a dramatic increase in the box humidity. This happened twice over a several day period, and each time the S/C was subjected to ≈100% relative humidity condensing conditions.

During transports of GLL to KSC in December 1985 and the return to JPL in February 1987, a combination of high external temperature and humidity were not encountered. Each was seen separately, but not both. No significant humidity excursions were seen inside the transporter box on these trips.

During the May 1989 trip to KSC, high temperature (≈90°F) and high humidity (>80% relative) were seen simultaneously in the Southeast U.S. This caused internal box humidity rises to high enough levels that a backup $GN_2$ purge was required. It seems clear that the box seal system was not adequate for this combination.

The qualification test at Point Mugu included this combination, but the previously discussed inability to perform temperature-wise in a hot environment created much concern and real-time test plan changes. This trauma may well have masked the ability to see evidence of a seal issue.

Recommendations: Obtain design, test, and use data on the KSC PETS transporter. Develop a better seal system for future transporters, perhaps a double seal with a $GN_2$ purge inbetween them. Avoid leaving transporters unattended with A/C units operating if the storage environment is different than the internal transporter conditions. Provide redundant, continuous readout, recordable measurements of both temperature and humidity with audible alarm levels.

### 7.2.5 Other Issues (Facility Environmental Control)

### 7.2.5.a KSC Environmental Control

During the 1989 stay of GLL at KSC, at least four(4) instances of loss of Environmental Control occurred. These are listed below:

THE SPACECRAFT WAS EXPOSED TO AN UNKNOWN ENVIRONMENT FOR ABOUT 2 HOURS DUE TO A POWER OUTAGE ON KSC'S SAEF II BUILDING:

On May 22, 1989, severe thunderstorms were responsible for a power outage on KSC's SAEF II building. The power outage lasted for about 2 hours until a back-up generator was brought to the building. Due to the power outage the air-conditioning system was off and no temperature or relative humidity recordings were possible. During the thunderstorm water leaked from the SAEF II roof to the floor, but no water dripped on flight hardware.

THE PROBE CAVITY AREA WAS EXPOSED TO HIGH RELATIVE HUMIDITY DUE TO A FAILURE OF KSC ECS.

On August 15, 1989, a failure of one of the four ECS condenser fans caused the relative humidity on the probe cavity to increase rapidly. 20 minutes after the failure occurred the duct was removed from the VPF ECS and connected to the JPL air-conditioning cart. During visual inspection no signs of condensation were found on the probe or surrounding hardware except for the 400 N REA plume shield near the probe where small signs of condensation were found.

THE CARGO BAY AIR PURGE TEMPERATURE REACHED ABOUT 126 F DUE TO IMPROPER DISCONNECTION OF THE ECS AT THE LAUNCH PAD:

On September 21, 1989, the Environmental Control System was disconnected improperly and caused the cargo bay air purge temperature to increase from approximately 52°F to 126°F in about 13 minutes. The temperature in the payload bay was estimated not to have exceeded 92 F. The duration above the HIC detector limit of 82°F was about 3 minutes; the total excursion was about 23 minutes.

PAYLOAD BAY AIR RELATIVE HUMIDITY INCREASED TO 95% DUE TO ECS COIL FAILURE:

On October 2, 1989, a failure of the Environmental Control System (ECS) cold coil caused the payload bay conditioned air relative humidity to increase to 95%, but for less than 2 minutes.

In all of these incidents, an evaluation of GLL hardware was made. No significant risk was identified.

Recommendation: Future projects should be aware of these recent KSC problems. It is hoped that KSC will improve its redundancy and procedures to preclude such incidents in the future.

#### 7.2.5.b Storage of Spacecraft Assemblies

Following the return of GLL from KSC in 1987, the project initiated a Shelf Life/Aging Review. Part of this included a review of storage conditions which resulted in the "Environmental Exposure Guidelines for GLL Spacecraft Hardware."

In essence these guidelines suggest that as both temperature and humidity levels of exposure increase, the allowable exposure time decreases. When a low temperature storage environment (≤15°C) exists, and the humidity is less than 70%, the storage duration is indefinite. For ambient conditions (15°C to 25°C), if the humidity is less than 60%, storage can be indefinite. Storage at temperatures of 25°C to 40°C with ≤50% humidity can be indefinite. Certain short-term excursions to higher temperature/high humidity conditions were also defined.

Other recommendations in the guidelines involve the monitoring of the environmental conditions in locations where hardware is stored or handled as well as transportation requirements.

Recommendation: The Environmental Exposure Guidelines developed for GLL should be implemented for all JPL projects.

## 7.3 Electromagnetic Compatibility

### 7.3.1 General Comment

#### 7.3.1.a MIL STD vs Tailored EMC Testing Program

With JPL's increasing involvement with other agencies, it is becoming more and more appropriate to have a conventional MIL STD test program as a base. JPL's traditional tailored approach to meet specific needs should be continued as well. The reasons for the former are the need to meet STS paperwork requirements as a minimum, and the fact that sometimes the requirements imposed by outside agencies are based on environments or rationale that may be unknown at the start of a program. The requirements derived and understood by JPL for a particular mission, of course, must also be included. This increases the demand on the EMC program compared to prior missions, but can help in the long term. For example, when a new RF source at ETR was noted late in the Galileo program, it would have helped to provide assurance of compatibility if the 10 kHz to 10 GHz radiated susceptibility test, normally required by MIL STD tests, had been performed. The susceptibility requirement had been tailored to the Jovian environment.

Recommendation: A conventional military standard EMC program should be implemented and should be coupled with a tailored approach for addressing specific needs (for example, science instruments with special EMC requirements).

#### 7.3.1.b Radiated Emissions

Although it was not practical to follow the test requirements in full detail, the EMC test program did accomplish the intended objectives. A waiver (No. 33618) was required for the STS radiated emissions requirements at the system level. Fortunately the out of specification levels were well below the STS susceptibility levels and there was no problem in having the waiver approved. The STS specifications impose a very large margin between the radiated emissions allowance for payloads and the STS level of susceptibility; at some frequencies this is as large as 100 dB. The use of expendable launch vehicles on future missions should result in less severe radiated emissions requirements.

Recommendation: An assessment of the Radiated Emissions requirements and margins being imposed on the spacecraft design should be evaluated early among the affected organizations.

### 7.3.1.c Interference Between STS and Galileo

An anomalous situation arose late in the program when it was found that the STS uplink frequency was within 60 MHz of the Galileo command frequency. Fortunately it was possible to have the STS shifted to a alternate frequency and interference was avoided. It is not clear how this conflict in frequency assignment occurred.

Recommendation: Future programs would benefit from early co-ordination between Telecommunications Engineering, Systems Engineering and the EMC Group relative to frequency assignment.

### 7.3.1.d Unexpected Occurrences During Final Spacecraft Assembly

Two unanticipated areas of concern were encountered during final spacecraft assembly. One was the possible adverse effects of induced voltages resulting from an anomalous arc discharge which occurred during a required welding process on the propellant fuel lines. The second was the possible adverse effects of X-ray induced voltages which could occur during the inspection of mechanical and electrical parts on the assembled spacecraft.

Recommendation: Both areas noted above should receive further analysis and test prior to the next assembly of a spacecraft.

### 7.3.2 Assembly Level Testing

The normal policy of testing all assemblies, while difficult and costly, gave good assurance that all was well when "consent to ship" time came, and also made diagnosis more easy when anomalies were noted during system tests. A strong assembly level EMC test program continues to be recommended.

It was noted that while many assemblies exceeded the radiated emission requirements, it was not evident that significant corrective measures were taken to minimize the out-of-specification conditions. Considerable reliance seemed to be placed on the assumed effectiveness of the Faraday cage formed by the assembled spacecraft.

At the assembly level there was a general radiated susceptibility requirement of 3 V/m over a swept frequency range of 14 kHz to 40 MHz based on the Jovian environment. As a general, good engineering practices test, future programs should consider increasing this to 5 V/m and extending the frequency sweep to 10 GHz.

An anomalous event was discovered during system level testing, when turning on the TWTA's affected the AACS. It was found that the large filter capacitors on the power input (which violate system isolation requirements) caused large bus currents, resulting in interference. The lesson learned is to inspect and/or test all assemblies' power inputs for AC isolation (not done) as well as DC isolation (current practice for all subsystems).

Schedule constraints adversely impacted the testing of two major assemblies: the CDS and the AACS. The CDS did not receive assembly level testing and was qualified on the basis of its satisfactory performance during the Magellan system level EMC testing and subsequent flight, and by its satisfactory performance during the Galileo system level EMC testing. A full assembly level test would have been preferable. The flight AACS was not available for EMC testing and testing had to be performed on a spare unit. This testing did not occur until the spacecraft was in its final stage for shipment to ETR.

Plasma wave experiments impose very low level E and H field requirements which are beyond the measurement capability of standard EMC instrumentation. A technology development effort should be directed toward the design of an adequate measurement system, including techniques for improving the ambient environment within the test facility.

### 7.3.3 System Level Testing

The JPL norm for performing both general and specific radiated emissions testing for science instruments was helpful and should be continued. The JPL practice of performing radiated susceptibility tests only at specific frequencies was useful and might be expanded to a MIL STD based test, but it would require the expense of greater equipment cost. System level conducted susceptibility and conducted emissions tests are not done in general, and it does not seem to have caused any difficulties. Greater confidence in compatibility would have been achieved if the conducted ripple on the spacecraft DC power bus had been measured and characterized, since as noted below, some problems were found with sensitive payloads operating in unusual modes. System level measurements of noise on some typical system signal interface lines were made to validate the signal line noise requirements, and this practice should be continued. The practice of measuring isolation of circuits by Section 374 at system integration should be continued.

A major limitation imposed on the system level radiated emission testing of Galileo was due to the lack of an electromagnetically shielded facility which could accommodate the spacecraft. The radiated emission measurements were contaminated by the ambient noise. Detailed assembly level test data, acquired in a shielded environment, were of considerable help in evaluation of the system level data.

One test which was not included in the requirements was a "transport phase" RF susceptibility test. Future projects should consider a general test, from 14 kHz to 20 GHz, at a level compatible with transmitters found along the highway route between JPL and the launch site.

In normal practice conducted susceptibility tests are not performed on heater circuits. Since heater elements are usually resistors, noise susceptibility is not usually a problem. However, on the Galileo spacecraft two assemblies, the DDS and the EPD, were located very close to heaters. Noise on the Orbiter DC bus coupled from the heaters to this nearby circuitry. A proper test for this situation would involve very careful planning, since heater turn-ons are not always possible during ground based tests. This situation should be noted for future projects.

The radiated emissions tests planned for measurement at the antenna output ports would have probably been of marginal value. Their objectives were accomplished by alternate means. The need for including these test requirements in future programs should be examined.

The radiated susceptibility test of the Probe led to a fortuitous result. The test was flawed because leakage energy from the RF simulation amplifier, used during the EMC testing, affected the Probe's L-Band circuitry. Although the L-Band energy emitted was not an intended part of this test, it resulted in the need to re-examine the Galileo S-Band TWT amplifier's output, where L-Band energy was also found. The lesson learned here was that all RF power sources should be measured in bands of interest for all receiving devices on the spacecraft.

The deletion of the system level ESD test by the project left a small element of doubt in that respect but was considered an acceptable risk because of the control which had been placed on exposed dielectric surfaces. There was not an opportunity for a walk through of the final spacecraft, as assembled for flight, by a cognizant EMC engineer. This is considered a deficiency because some ESD details of non-conductive surfaces cannot be seen anywhere but by inspection of the flight assembled hardware.

Recommendations:

System level measurements of noise on some typical system signal interface lines were made to validate the signal line noise requirements, and this practice should be continued. The practice of measuring isolation of circuits by Section 374 at system integration should be continued.

The building of an electromagnetic facility to accommodate spacecrfat should be pursued.

Future projects should consider a general test, from 14 kHz to 20 GHz, at a level compatible with transmitters found along the highway route between JPL and the launch site.

A feasibility assessment should be performed to determine if conducted susceptibility tests can be implemented on heater circuits for ground based tests.

The need for including radiated emissions tests for measurement at the antenna output ports should be re-examined.

All RF power sources should be measured in bands of interest for all receiving devices on the spacecraft.

For future projects, a cognizant EMC engineer should perform a walk through of final spacecraft, as assembled for flight, for ESD verification.

## 7.4 Magnetics

The satisfactory completion of the magnetic control program for Galileo was due to large extent to the diligence of J. Bastow and P. Narvaez and the strong support of the Principal Investigator. Through frequent interaction with hardware cognizant engineers, early developmental testing of hardware, and a continuous updating of magnetic field contributions from measured assemblies, an awareness of the importance of the magnetic control plan was kept paramount. Excellent co-operative working arrangements with the personnel supporting the spacecraft activity in SAF assured that specified guidelines and practices were implemented.

Of the more than 171 assemblies, components, and structural elements measured, it was possible to narrow the list of units of primary concern to 33. In most cases the source of magnetic influence was a magnetically "soft" alloy, such as Invar and Kovar, which was used for its stable thermal properties. An increased use of composite materials would lessen this source of magnetic uncertainty.

The limited size of the existing Helmholtz coil system severely constrained the physical size of the units which could be properly characterized in a "zero" field environment. Consequently innovative techniques were frequently required to handle large assemblies (e.g. the Probe and SXA).

The use of magnetic "tattletales" to monitor maximum magnetic field exposure during shipment of the spacecraft to KSC demonstrated that the handling practices were consistent with the magnetic control plan.

Recommendations:

Future projects should avoid using Invar and Kovar, if possible, to minimize magnetic uncertainty and improve magnetic cleanliness if flying a magnetometer.

A larger Helmholtz coil system should be obtained for the JPL magnetics laboratory.

Magnetic "tattletales" during spacecraft shipment should become a normal part of the instrumentation complement for spacecraft with a magnetics cleanliness requirement.

## 7.5 Natural Space Environment

The major areas in which lessons were learned are as follows:

1) Radiation Shielding Analyses
2) Solar Proton Events Model
3) Micrometeoroid Model

While these three areas were selected, much of what was learned is applicable in general, i.e., to other natural space environments.

### 7.5.1 Radiation Shielding Analyses

Perhaps the biggest lesson learned here was that continuity of expert personnel is very important, if not essential. When a senior analyst retired it seemed that not only did he leave, but the total JPL ability to do radiation shielding analyses vanished.

Recommendations: Have a younger engineer work with the older experienced person before the expert leaves, not after. This should probably be extended to any area and not just to someone nearing retirement - in critical areas, have a capable back-up; this is just common sense but we don't always do it.

Before someone like a senior analyst leaves, make sure all the important computer models of the spacecraft (used with the radiation transport code) are archived and, if at all possible, are somehow or other transferred or translated to a new code; the calculations for the new hardware and new environment on GLL were made using the code NOVICE whereas prior calculations were done using SIGMA.

If possible, don't change key people and codes at the same time. This adds to problems when comparing previous SIGMA calculations (and SIGMA calculations for new hardware) with NOVICE calculations for same. Much of this difficulty was because of differences in geometry (details) but sometimes the problem was just in trying to make sure we were comparing apples with apples.
Make absolutely sure that all assumptions, details, etc., are included in the memos. A prime example is the environment - it is absolutely pointless to supply shielded dose values; without the external environment they are meaningless.

### 7.5.2 Solar Proton Events Model

Because the VEEGA mission involves an ~6 year cruise phase in interplanetary space, the effects of solar energetic particle events became important. The effects that needed to be considered were total ionizing dose and displacement damage from protons and single-event-upsets (SEUs) caused by heavy ions. The model used for the proton environment was that developed by Feynman et al (Ref. 1).

This model was developed and funded by the MMII project. A 95% confidence level was used and it was found that the total ionizing dose for the mission did not change significantly as expected since this dose is dominated by the Jupiter electron environment. However, in terms of displacement damage, the solar proton fluence increased to the point where some parts no longer met the RDM of 2 based on a part requirement of a 20 MeV equivalent fluence of $4 \times 10^{10}$ $cm^{-2}$. This led to the questioning of the origin of the $4 \times 10^{10}$ $cm^{-2}$ requirement and the answer was rather vague. Two lessons here: first don't ignore proton displacement and second, clearly document in a traceable way the part requirements for displacement damage.

Recommendations: Do not underestimate the sun - many people questioned the conservatism of the new proton model. They argued there had been no major proton events since the August 1972 event; this was an anomalously large event and so there probably wouldn't be any more big events this cycle. On the contrary, there have been 3 or 4 major proton events since March of this year, with the last one in October being equal in size (peak flux and total fluence, >10 MeV) to the 1972 event within the error of the measurements. However, we still have not exceeded the 95% confidence level predicted by the model for the fluences (@ the >10, >30, >60 and >100 MeV levels).

- Keep models for the solar proton events updated on a regular basis -- don't wait until there's a problem. Funding should be provided to update the model either institutionally or spread among the major projects. If this is done then an accurate model will be available when needed. For example we now have data from cycle 22 which should be used to update the existing model and there are no models for peak flux nor for the electrons. These updates should be started now!

### 7.5.3 Micrometeoroid Model

As with the interplanetary proton environment, the change to VEEGA trajectory caused a large increase in the micrometeoroid fluences which in turn led to an overall reduction in the probability of mission success due to micrometeoroid impact. This increase in the probability of failure produced some hard questioning on the micrometeoroid model being used. Tracing the history of the model being used was (as with the radiation analyses and parts proton displacement damage requirements) somewhat difficult. It turned out that the model being used was based on the recommendations of a blue-ribbon panel. The model used the NASA standard micro-meteoroid model (Ref. 2) modified to take account of Pioneer measurements. The modified model used 2 x the NASA model cometary flux at 1 AU, assumed a constant flux with increasing heliocentric radical distance and deleted the asteroidal component of the NASA model (because Pioneer found no evidence of such an environment). The documentation on the modified model was however, dispersed in many different places.

Subsequent work on the meteoroid environment for the Nuclear Safety Study revealed several additional difficulties in the Micrometeoroid Model. First, the uncertainties in the meteoroid fluences became even more clear and the need for updating the models more important. The existing models, as a result of their conservatism, have led to a major $\Delta V$ impact on the VEEGA trajectory in order to lower the likelihood of an Fauth impact to acceptable levels. Secondly, the issue of all-normal meteoriod impact and the meteoroid velocity distribution have both been shown to seriously impact the failure estimates. These uncertainties will need to be settled before micrometeoroid analysis can become truly reliable - much time and effort were spent by the Galileo project addressing the problems introduced by this issue.

Recommendations: The model being used for the environment in question should be documented in one place.

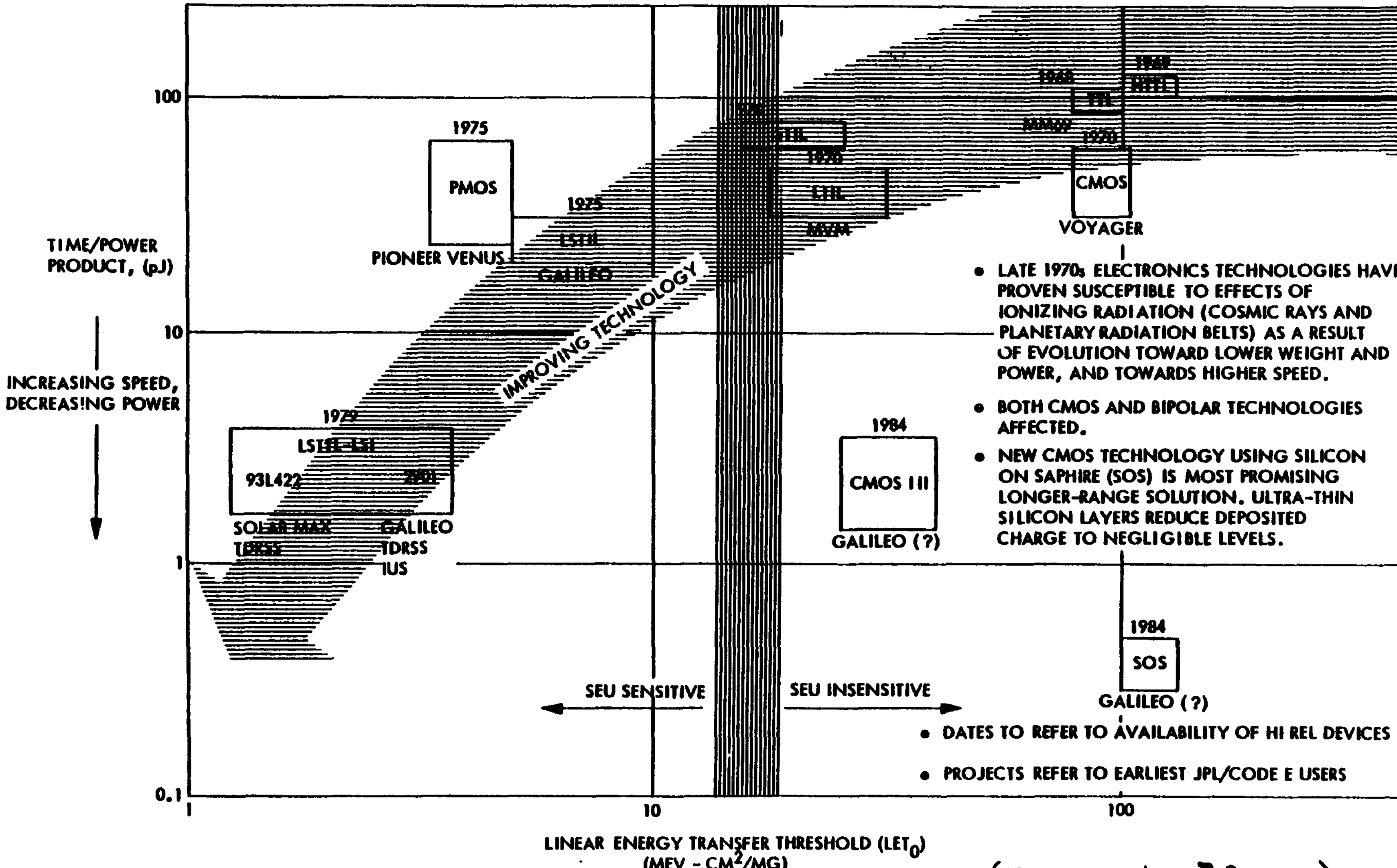
Additionally, the model needs to be updated on a reasonably frequent basis. The NASA standard model dates back to circa 1970 and is badly in need of revision.

## 7.6 Single Event Upsets

One of the major new concerns for Galileo that Voyager did not have was the effects of single event upsets, (or more accurately, the whole area of single event phenomena). This class of environmental interactions concerns the effects of a single charged particle on electronics. For example, in single event upsets, a single heavy ion (as part of the galactic cosmic ray population or produced in an iron rich solar particle event) may deposit enough charge in the off node of a flip-flop circuit to cause the circuit to change state. There are many references and detailed descriptions of single event phenomena available in the literature which describe how upsets, latch-ups transients, noise, etc., are caused by single particles. Protons and even electrons can cause problems in modern electronics through the interaction of a single particle with the part. **The principal lesson learned here is that new technology brings with it new problems.** Advancing technology needs to be monitored for its reaction to the environment. Effects which were benign before can have a major impact on new technology that depends on increasing subtle mechanisms for its operation. This is illustrated in the figure 7-1 for SEU sensitivity, which plots the access time times the power per bit (the energy representing the information stored in the circuit) versus the threshold of single event upsets. The large arrow represents the progress of technology. Economically the smaller the power and the shorter the time, the more profitable the chip. Thus, the market tends to force part development in that direction. At the same time the smaller the energy per bit, the smaller the energy deposited by a single particle required to upset the device.

Galileo played a key role for the space community in understanding and quantifying the single event upset mechanism. That experience showed the importance of understanding both the environment and the spacecraft system in designing a spacecraft that will operate as required in its mission. The Galileo experience underlines the wisdom of careful preproject parts selection and continual technical monitoring of problems as the project progresses. Galileo demonstrated that even when resources or schedule do not permit a full understanding of a problem, careful cataloguing of problems, their impact on the spacecraft, and progress being made in independent research efforts can help focus limited resources at the right time on a solution.

Recommendation: The application of new technology into spacecraft hardware should be assessed from an environmental interactions perspective.




(Figure courtesy J. Casani)

Figure 7-1 Progress in Technology Leads to SEU Concern

## 7.7 Electrostatic Discharge

### 7.7.1 External Electrostatic Discharge

Because of the severe Jovian radiation environment, an ESD control plan was implemented to keep the differential surface charging to less than 10 volts and the maximum discharge event to less than 3 mJ. Although some ESD testing was performed on a few critical assemblies, to a large extent the ESD mitigation was achieved by design and control of materials. In order for this approach to be effective the ESD design requirements must be finalized early in the program. In the case of Galileo the internal charging (IESD) requirements were not established until 1983 after much of the hardware had been built.

One weakness in this approach was in the inspection process whereby non-compliant materials were not detected until late in the program. There needs to be a designated engineer to monitor compliance from design through fabrication. Frequent interactions with the cognizant hardware engineer are necessary.

Assembly level testing should be implemented. This will require improved test methodology and thorough review with the hardware cognizant engineer to establish a meaningful test.

Continuing delays in the Galileo launch raised serious questions about aging and handling effects on surface properties.

Recommendation: Aging and handling effects on surface properties should be addressed on future programs.

### 7.7.2 Internal Electrostatic Discharges (IESD)

A study of the Voyager 1 anomalies at Jupiter concluded that Internal Charging and Electrostatic Discharging (IESD) was the most likely cause of the 42 observed POR's. IESD refers to the charging and subsequent discharging of components internal to spacecraft surface (not on the surface of the spacecraft). Since electrons have longer ranges than protons, more electrons than protons are present under the spacecraft surface. Consequently, the flux level of energetic electrons (>0.1 MeV) is the dominant factor in determining the likelihood of IESD. In late 1981, a developmental program was initiated for the quantifying the risks associated with IESD. This program consisted of two parallel efforts; they were: (1) testing and analysis, and (2) industry survey.

All of the IESD tests were conducted at the JPL

All of the IESD tests were conducted at the JPL dynamitron facility. In a typical test, candidate GLL components were subjected to the expected (determined by analysis) Jovian energetic electron fluence and flux levels. The most important conclusion obtained from this test program was that floating conductors tend to cause a large amplitude discharge. That is, the energy and current of an IESD event was much higher in the presence of floating conductors. After a review of the test data and a study of the sensitivity of parts, it was determined that floating conductors with length greater than 25 cm and area greater than 3 $cm^2$ need to be grounded. An ECR (#23779) was issued to implement these IESD requirements. Following the distribution of this ECR, all subsystems were required to identify all the floating conductive elements within their subsystem. In most cases, floating conductive elements with area/length which exceeded the ECR specifications were grounded or eliminated.

The IESD investigation was carried out over a period of about one year (1981-1982). Hence, there was insufficient time to address all the items of concern. In particular, the program did not provide sufficient test data to derive the appropriate design guidelines/requirements for dielectric materials. The test data did show that common spacecraft insulation and circuit board materials will discharge in an environment of energetic electrons. In the absence of floating conductors, these discharges tend to be of low amplitudes. However, a definite relationship of the discharge parameters (energy and current) scaling with the geometry of dielectric materials was not reached during this IESD program. Future missions, which will encounter the same harsh radiation environment as Jupiter, will need to address this issue.

At approximately the same time as the GLL IESD investigation, the Air Force conducted a similar program to study IESD risks. The name of that program is Electron Caused Electromagnetic Pulse (ECEMP). The ECEMP investigations arrived at the same conclusion; that the presence of floating conductors is undesirable, and needs to be tightly controlled.

IESD is a real threat. Within the last few years, several Earth-orbiting satellites have reported IESD related anomalies.

The GLL IESD investigation has been very fruitful. This effort has indirectly led to the development of an Air

Force funded flight instrument at JPL, the Internal Discharge Monitor (IDM). The IDM, which is part of the CRESS satellite, will be launched in 1990. The principals of the GLL IESD program are the principal investigator and co-investigator of the IDM (P. Robinson and P. Leung).

Recommendation: IESD requirements should be imposed on all future JPL projects.

## 7.8 Programmatic

### 7.8.1 General Comments

#### 7.8.1.a Basis of Environmental Program

The planning, requirements development, and program implementation for Galileo environmental requirements were based on the Voyager environmental program. However, there were differences primarily because Galileo was one-of-a-kind spacecraft without a second flight spacecraft and no proof test model. As a result several subsystems did not have a spare unit or a separate qualification unit. Protoflight testing, where the testing serves as the qualification and flight acceptance of the hardware was implemented at the system level and on one-of-a-kind assemblies. This approach was different from that applied to Viking or Voyager, which were both dual launches of identical spacecraft and had PTM hardware serving as assembly and system precursors. Another significant difference was the change from a direct mission to Jupiter in 1986 to a VEEGA trajectory to Jupiter with a 1989 shuttle/IUS launch. As a result additional testing and analyses were required on some of the existing hardware previously qualified for the 1986 opportunity. To formally specify these requirements revisions to the design requirements (3-240), test and analysis configuration document 625-260) and test specifications were required.

Recommendation: The Voyager/Galileo environmental test programs and documentation should serve as models for major in-house flight projects.

#### 7.8.1.b Hardware Test and Analysis Configuration

Early in a project, soon after the basic instruments and structure are determined, the Test Analysis and Configuration document (PDxxx-260) is prepared by Environmental Requirements. The Environmental/Reliability Engineer* ascertains who the responsible hardware engineers are for each reference designation category for the spacecraft (or major instrument, if appropriate). Once the responsible hardware engineers have been identified the E/RE must meet with each one, along with a senior representative from each environmental requirements technical discipline. The purposes of these meetings are to determine the proper breakdown of each reference designation category into subsystems and/or assemblies for effective reporting and tracking and to determine the types and levels of environmental testing and analyses. It is important that the E/RE impress upon the responsible hardware engineers the importance of adhering to the agreed upon breakdown of the reference designation category into subsystem/ assembly items in PDxxx-260. It is this breakdown that enables the proper and effective tracking of the hardware through environmental testing via the Environmental Test Specification Summary (ETSS) form and the Test Result Summary Form (TRSF). (See additional comments and recommendation regarding the test and analysis configuration document paragraph 7.7.2.b).

Recommendation: The process for developing the test and analysis configuration list and matrix should be performed early and be a cooperative effort among hardware cognizant engineers and environmental requirements personnel as it was done for Galileo. The comments and suggestions noted in the discussion above and in paragraph 7.7.2.b should be addressed.

* Galileo had an Environmental Requirements Engineer (ERE) along with a separate Reliability Engineer. Other projects may have this function combined into an E/RE.

**7.8.1.c Test and Analysis Matrix**

When incorporating the retest requirements for the 1989 opportunity into 625-260, a new table (4-4) was added to the document. Since some of the existing hardware required only minimum workmanship retests, it was appropriate to distinguish between sine and random vibration testing in the matrix. Separate columns were added for these two environments. Also, an environment not specifically noted in the original table (4-2) was contamination. Because some science instruments and other optical sensors require analyses, a new column for this environment was added.

Recommendation: The test and analysis matrix on future programs should use the format that includes distinguishing between sine and random vibration testing and includes explicit requirements for performing contamination analysis.

**7.8.1.d Radiation Analyses**

Early in Project Galileo it was determined that none of the hardware would have their radiation analysis completed before CDR. Under the auspices of the CDR Board, a Radiation Analysis Review Committee was formed to review the Radiation Analysis Completion Statements (RACS) to be submitted for each subsystem/assembly as required in PD625-260 per requirements found in the

Radiation Control document (PD625-229). A difference of opinion arose during Galileo development over the review process of the RACS pertaining to some of the science instruments. This difference of opinion resulted in an environmental lien being placed on an instrument (EPD) and a waiver at the Project level to fly the instrument.

Recommendations: If a Radiation Analysis Review Committee is formed, the duties and responsibilities of the committee should be clearly delineated in the Radiation Control Document. For example, explicit requirements that the committee is the review board for the RACS and can reject the RACS when it is evident that it is incomplete or not in compliance with requirements should be established.

The Radiation Analysis Completion Statement form should be reviewed and revised to make it easier to understand and to prepare.

For new projects with a radiation design requirement, neither the Worst Case Analysis nor the Radiation Analysis should be waived for any engineering or instrument subsystems. These analyses are necessary for determination and verification of the Radiation Design Margin.

### 7.8.2 Assembly Level

#### 7.8.2.a Test Reporting-Assembly Level

For the assembly level testing, the cognizant engineer prepared a Test Results Summary Form (TRSF) for each test and each serial number of assembly environmentally tested. This was transmitted to the Environemntal Requirements Engineer, who, after review, assembled the results into status report that was provided to the project. The overall process is excellent and should be continued on future programs. However, there are some implementation problems that should be identified. Subsystems which have subassemblies located in different parts of the spacecraft caused difficulty in unambiguously specifying the environmental requirements and accurately reporting the testing status. The Power, Pyro Subsystem (PPS) for Galileo is a good example. Most of the spun subassemblies are located in spun Bay 1, however there are two subassemblies located in Bay 6, one in despun Bay A, and two in despun Bay E. To functionally test the PPS hardware for either a powered on vibration or during thermal test an appropriate subset of the hardware was required. But the subset of hardware was also a function of the particular environment being tested, ie temperature, vibration, or EMI. As a result the TRSF generated for a vibration test would list a different number of subassemblies than a TRSF for the temperature test. Subsequent rework was usually performed at the subassembly level, with some degree of workmanship verification performed at that level. The testing and test reporting complications noted above were tracked by generating hardware matricies to the subassembly level for the following subsystems: Radio Frequency Subsystem; Power, Pyro Subsystem; Dust Detector Subsystem; and Plasma Wave Subsystem.

Recommendation: In establishing the testing and analysis grouping in 625-260, consider grouping the hardware by the following heirarchy: 1) set of subassemblies normally environmentally tested as complete assembly, delivered and stored in Quality Assurance Bonded Stores and subsequently integrated on to the spacecraft as a unit, 2) set of subassemblies of a given subsystem that must be functionally or physically grouped together to perform meaningful environmental testing or analyses, and 3) hardware supplying organization. A tier numbering scheme may prove useful,eg 63A, 63B, in identifying the equipment grouping in 625-260.

### 7.8.2.b Approved ETSS Before Performing Environmental Testing

The environmental program policy and requirements document (625-228) requires an approved Environmental Test Specification Summary (ETSS) before performing an environmental test. Several incidents occurred when a cognizant engineer representative attempted to schedule an environmental test in the JPL Environmental Test Lab for flight or spare hardware without an approved ETSS in hand. Test and QA personnel did not permit the testing to proceed without the proper paperwork. Another facet, illustrating a similar lack of understanding of the requirement, are the attempts to apply old ETSSs for an assembly to a retest of that assembly. The old ETSS may or may not be relevant and the adequacy for the retest would depend on the particular situation and amount of rework performed on the hardware.

Recommendation: Remind new cognizant engineering personnel of the requirement. Enlist QA and test facility personnel's help in implementing the requirement.

### 7.8.3 Systems Level

See comments in technical discipline lessons learned.

7.8.4 **Spacecraft Transporter**

See comments in technical discipline lessons learned.

7.8.5 **Other**

7.8.5.a **Problem Failure Reporting Process**

The processing of problem failure reports from an environmental requirements perspective needs to be reviewed. Many instances were discovered as part of an informal environmental monitoring task on Galileo as well as a formal PFR review in which the P/FR appeared to be incorrectly marked with regard to the environmental block on the form. What occurred was apparently some confusion on the part of some P/FR originators as to how to reflect an environmental P/FR versus a non-environmental P/FR. An example: not everyone knows that "ETL" means JPL's Environmental Test Lab. Another is that "TA" (Type Acceptance) is no longer used and has been replaced by Qual Test. It was found on many occasions that for Bench Testing and Fabrication/Assembly P/FRs a specific environment other than ambient would be marked. This resulted in the P/FR being identified as an environmental P/FR in the Problem Failure Accountability Center (PFAC), when in actuality it was not a formal environmental program P/FR. Other instances were found in which the description of the problem/failure clearly indicated that it was an environmental test problem/failure, but was not correctly marked in the "Specific Environment" block or in the "Problem Failure Noted During" block. In these cases the P/FR would not be identified as an environmental P/FR.

Recommendation: As with the lesson learned for preparing environment test and analysis forms (7.7.2.d) an education process is clearly indicated. Future project/tasks need to make sure that everyone knows how to properly enter information onto the P/FR form. It would also be very helpful if the Reliability Section, who has oversight of the PFAC to modify the P/FR to clearly distinguish between a formal environmental test environment and a bench-fabrication/assembly-systems environment test. It should be distinct on the form that they are not the same. Each individual who is in the P/FR review process should be asked to verify that the header information is correct. If errors are found, the corrections should be noted, the originator should concur in any change, and the PFAC should correct their data base.

It should again be noted that the non-adherence to the breakdown of subsystems/assemblies in PD625-260 was also in evidence on P/FRs. this non-adherence meant that some "digging" had to be performed to determine to what piece of hardware the P/FR belonged.

**7.8.5.c Environmental Files**

It was very important that supporting documentation accompany the environmental forms. The form is the summary; the supporting documentation supplies the details and explanation. The forms become part of the environmental files. It was found on several occasions during Galileo development that hardware engineers had to come to the ERE to reconstruct their environmental test history. This was necessitated by files being misplaced, lost, or never transferred when hardware personnel changed.

Recommendation: Future projects should continue to have the ERE as the focal point of the environmental test and analysis program documentation. Cognizant personnel should be encouraged to provide the necessary documentation as requested on each test and analysis form.

## 7.9 Early In-Flight Experiences

During Galileo's first two months of flight, some additional environmentally related items were noted.

### 7.9.1 Spacecraft Charging/ESD

The launch occurred just as the current solar cycle appears to be peaking. This cycle may well be the largest solar cycle in recorded history. In the past six months, there have been four "7 year" solar flare events. Before and after the Galileo launch, many satellites in geosynchronous orbits had, and are continuing to have, anomalous behavior attributed to spacecraft charging/ESD events. Galileo, however, seems to be having no difficulties thus far in the interplanetary environment. No ESD anomalies were detected during the transition through the Earth's radiation belts.

### 7.9.2 Solar Flare Event - 19-22 October 1989

The next day. following the launch of Galileo, one of the largest solar flare events observed since the beginning of the Space Age commenced. On 19 October, the solar flare event began at 1258 UT. For reference, by about 1900 UT on the 19th, the 10 MeV proton flux measured by the GOES-7 Spacecraft (Figure 7-1) peaked at about 7.3E4 $cm^{-2}$ $-s^{-1}$ $-sr^{-1}$ (compared with 8.3E4 $cm^{-2}$ $s^{-1}$ $sr^{-1}$ for the 1972 event. The fluence of 10 MeV protons for the event was 1.9E10 $cm^{-2}$ as compared with 2.25E10 $cm^{-2}$ for the 1972 event.

Many spacecraft were severely affected by this event - solar arrays typically lost 6% of their power in 1-2 days! As a specific case in point, Magellan had ~6% power loss and severe proton-induced upsets on its star scanner. Galileo, with its extreme hardening, experienced no observable effects on its spacecraft systems- thus attesting to its superior radiation design (it should be remembered, however, that Galileo was not fully operational at the time as it was undergoing check out). Subsequent turn-on of the SSI did show this system, as expected, to be sensitive to protons. This was anticipated and as yet has had no effect on the mission (ISA 7574).

Fortunately, the Galileo HIC instrument was turned on at 0200 UT on 20 October. This allowed a measurement of the heavy ion fluxes responsible for SEU's. [Note: This may well be the <u>only</u> heavy ion data available on this historic event!]. Although the Galileo SEU models predict only about a ~10% or less probability for an observable SEU in the AACS for the event, it is hoped that subsequent flare events will lead to an SEU. Then, using the HIC data, it should be possible to verify the Galileo SEU models- an exciting possibility -prior to JOI.

Recommendation: First, prior to the 1989 solar flares, the solar proton fluence models were believed to be overly conservative. The current extreme increase in activity has gone far toward validating them and verifies the Galileo project decision in adopting them. Secondly, it is proposed that solar activity be continuously monitored prior to, during, and following launch. If the flare had occurred a few days earlier, it might have affected the mission success. A forecast of impending activity might have allowed contingencies to have been taken; luck ruled this time. Thirdly, the heavy ion model of solar flares will need to be continuously reviewed and updated during the course of the mission given the importance of SEU survivability to Galileo and the data now becoming available.

### 7.9.3 EMC

In regard to the previously mentioned concern in the EMC Lessons Learned paragraph about the Plasma Wave experiment (and others) which are so sensitive that the usual EMC instrumentation cannot test other hardware to meet their requirements. The Galileo spacecraft is apparently fairly quiet, and this is attributed to the high level of EMC concern for quiet behavior at these frequencies.

Recommendation: The lesson learned is that, although a test verification program is required, an especially intensive and carefully implemented design program in both spacecraft ESD immunity and for shielding for the plasma experiment quietness seems to have bene successful when comprehensive testing was not considered possible or appropriate.

### 7.9.4 Temperature

Flight temperatures to date have generally been as expected. Several appendage mounted instrument sensors (DDS, Outboard Mag Sensor, etc.) are somewhat cooler than anticipated based on STV test data; however, they are within allowable flight levels. Such cooler flight trends support the earlier recommendation (7.2.2.a) that appendage mounted equipment should have the highest practical margins.

The bus temperatures during the launch transient (shuttle payload bay closed door/open door periods) were well within worst-case prediction. Since release from the shuttle, they are generally stable as predicted. The RPM temperatures are cooling somewhat more than nominal predictions, but match the latest math model very well and are within allowable levels.

### 7.9.5 Dynamics

Therefore were no payload (Galileo) measurements onboard STS-34 to record dynamic loads or environments during the launch phase, as there was inadequate justification provided to shuttle program management to have the instrumentation installed. Thus the two excellent onboard recording systems owned by NASA, OASIS I and II, were left in storage. The remaining shuttle dynamic instrumentation, used for measuring engine vibration and potential POGO conditions and telemetered for ground recording, showed no anomalous behavior, according to Rockwell dynamicists. The crew did not report any extraordinary conditions. Therefore it is assumed that STS-34 dynamic loads and environments were similar to those found in previous flights.

There were no measurements made of dynamic loads or pyroshocks (i.e., severe high-frequency mechanical transients from explosive separation devices) after GLL/IUS deployment from the Orbiter. However, spacecraft operation within tolerance following post-deployment flight events demonstrate the adequacy of the spacecraft design to these conditions.

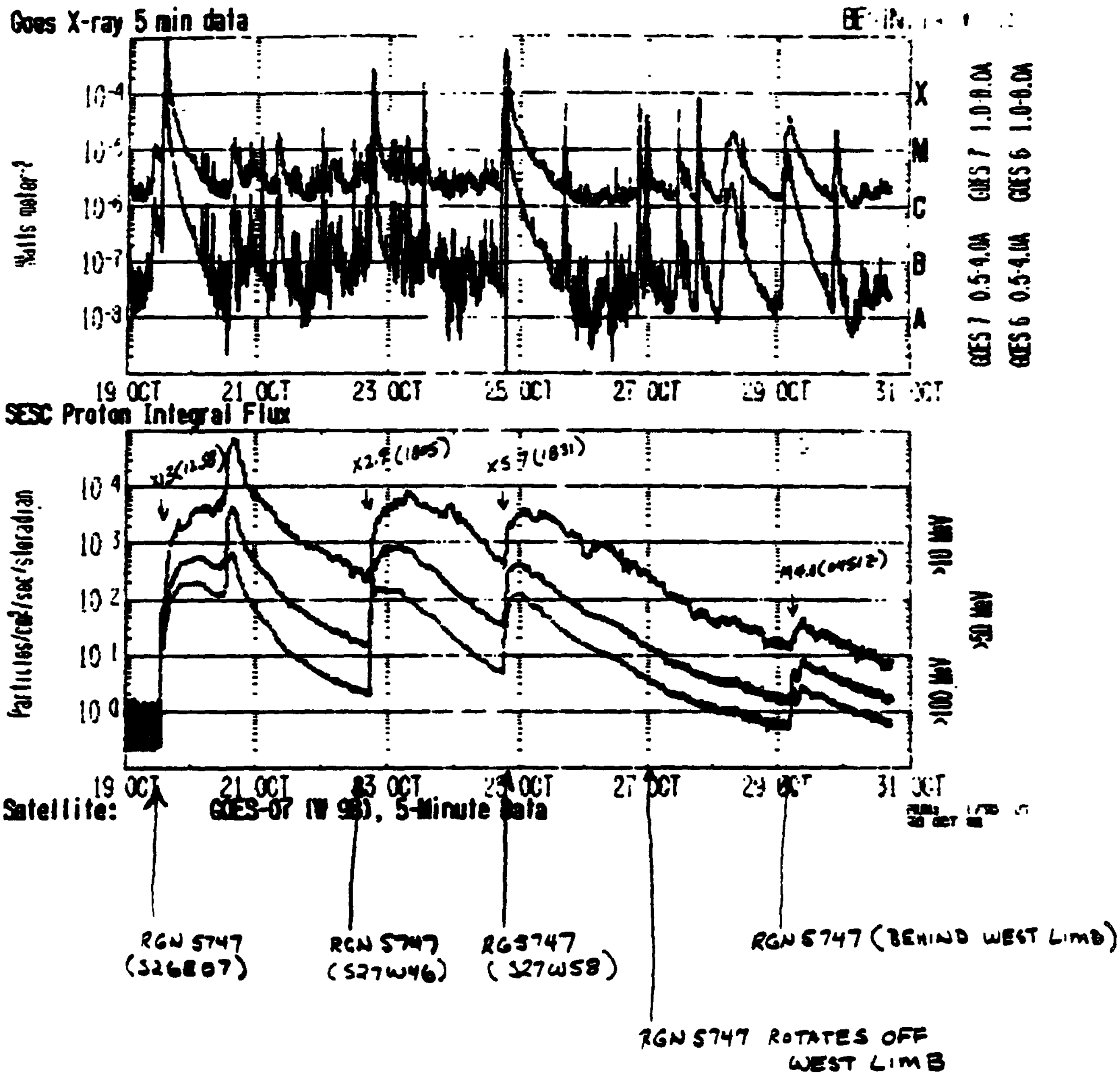



FIGURE 7-#. In-flight Solar Flare Event 10/19-21/89

## 8.0 CONCLUSIONS

The Galileo environmental program was based on the philosophy and approach that had been applied to the very successful Voyager project. The reprogramming and redesign resulting from changing the launch date from 1982 to 1984 to 1986 and then to 1989 required a significant amount of reevaluation, rethinking, and flexibility in specifying the environmental requirements (especially dynamics, thermal, and natural space) and monitoring the test program. However, throughout all of this 'dynamic' development phase, the underlying policies and objectives were unchanged. There were several new environments that had to be addressed including: single event upsets, atomic oxygen, and space debris in earth orbit. Many of the design requirements were more severe than applied to Voyager, such as electron and proton radiation, micrometeoroids, solar intensity (0.69AU to 5.0 AU vs 1.0 AU to >10.0 for Voyager), and contamination.

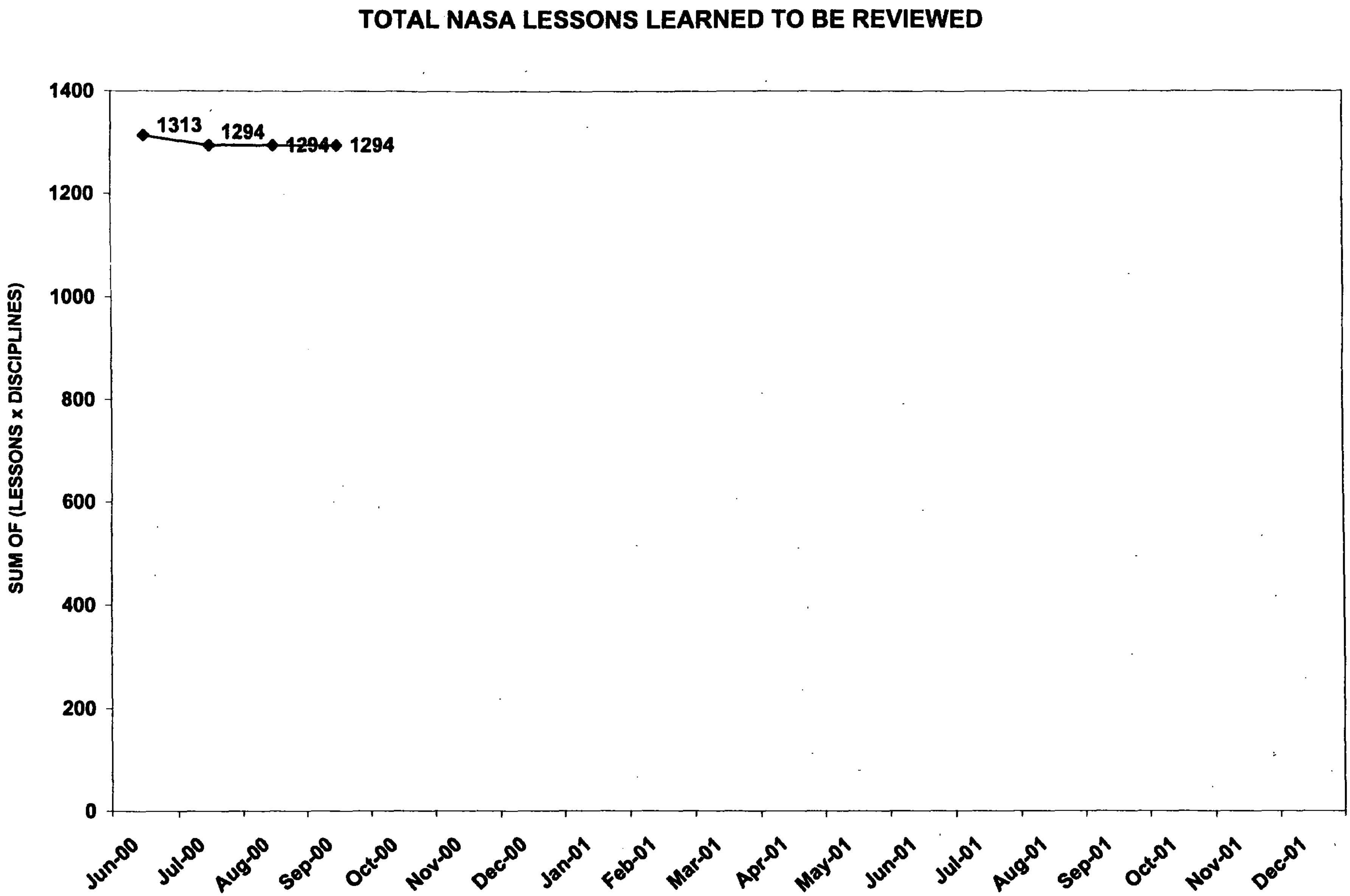
A rigorous assembly level test program was performed on the hardware which was followed by a comprehensive system level test program on the flight spacecraft. An appropriate level of analyses was done for those environments that could not be verified by test, such as radiation, micrometeoroids, and single event upsets. The conclusion is that the environmental program implemented on Galileo satisfied the spirit and intent of the requirements imposed by the project during spacecraft development. There are numerous lessons to be learned from a program as extensive as this one that can significantly benefit future projects. If these lessons are seriously considered, addressed early and--very importantly--aided by sufficient resources, a future project would implement a meaningful and cost effective environmental program.

# Europa Lessons Learned

| INSTRUCTIONS | |
|---|---|
| | |
| 1 | Lessons can be found at the following website (note - double clicking on the cell below should take you there): |
| 2 | http://llis.nasa.gov/llis/llis.html |
| 3 | One can search by lesson number or retrieve all lessons by doing a search with all fields blank. |
| 4 | Record your efforts on the worksheet named "LOG SHEET". Enter your name under "initial reviewer". |
| 5 | Identify parties to who lesson was allocated by putting a "1" in the appropriate column. |
| 7 | Parties receiving forwarded lessons should review the lesson and record whether the design, plan, or procedure complies as-is or needs modification to comply in the log sheet. |
| 8 | If your design, plan, or procedure meets the intent as-is then enter your **last name** in your organization's column (replace the "1"). If a modification is required enter "**need mod**". If the lesson applies to a product (e.g. a procedure) that is not yet in development enter "**review by milestone**". Designate the appropriate milestone, e.g. "review by ATLO start." If the lesson does not need to be incorporated into any particular product, but is something good to know then enter "**advisory**". You may also conclude that the lesson is not applicable. If so, enter "**N/A**". |
| 9 | If you feel that the lesson applies to another element of the Project indicate such by adding a "1" to the element's column in the row corresponding to the lesson. |
| 10 | When updating this file use the **checkout feature** of Docushare. This keeps others from updating the file while you are working on it and prevents the problem of having the same thing being updated by multiple people at the same time. The checkout feature is activated by clicking on the checkmark icon to the right of the file name in the elibrary. |
| | |
| **SEARCH TIPS** | |
| | The "Applicable Crosscutting Processes", "Applicable NASA Enterprises", and "Key Phrases" fields are not good search criteria as most lessons have not populated these fields. |
| | |
| **OBSERVATIONS** | |
| 1 | Gravity makes untethered things fall down. This happens a lot. |
| 2 | Fluids are escape artists. |

| | |
|---|---|
| 3 | If one is testing in a facility that is having maintenance/repair work done know what the maintenance people are up to because their mistakes can put your hardware or your people at risk. |
| 4 | Be very careful lifting things. Lots can go wrong. |
| 5 | Forcing things to fit will lead to trouble. |
| 6 | Ya gotta dig through a lot of coal to find the diamonds |

1 Have a plan to retire obsolete requirements, for example, lessons about part fabrication processes that are no longer used.
2 Combine lessons that are related, e.g., the many about crane/lifting operations
3 Make a version available in a database format so projects can download and add fields for their use
4 Some lessons are very general, others quite specific. Suggest identifying which are which.
5


TOTAL NASA LESSONS LEARNED TO BE REVIEWED
SUM OF (LESSONS x DISCIPLINES)
1400
1200
1000
800
600
400
200
0
1313
1294
1294
1294
Jun-00
Jul-00
Aug-00
Sep-00
Oct-00
Nov-00
Dec-00
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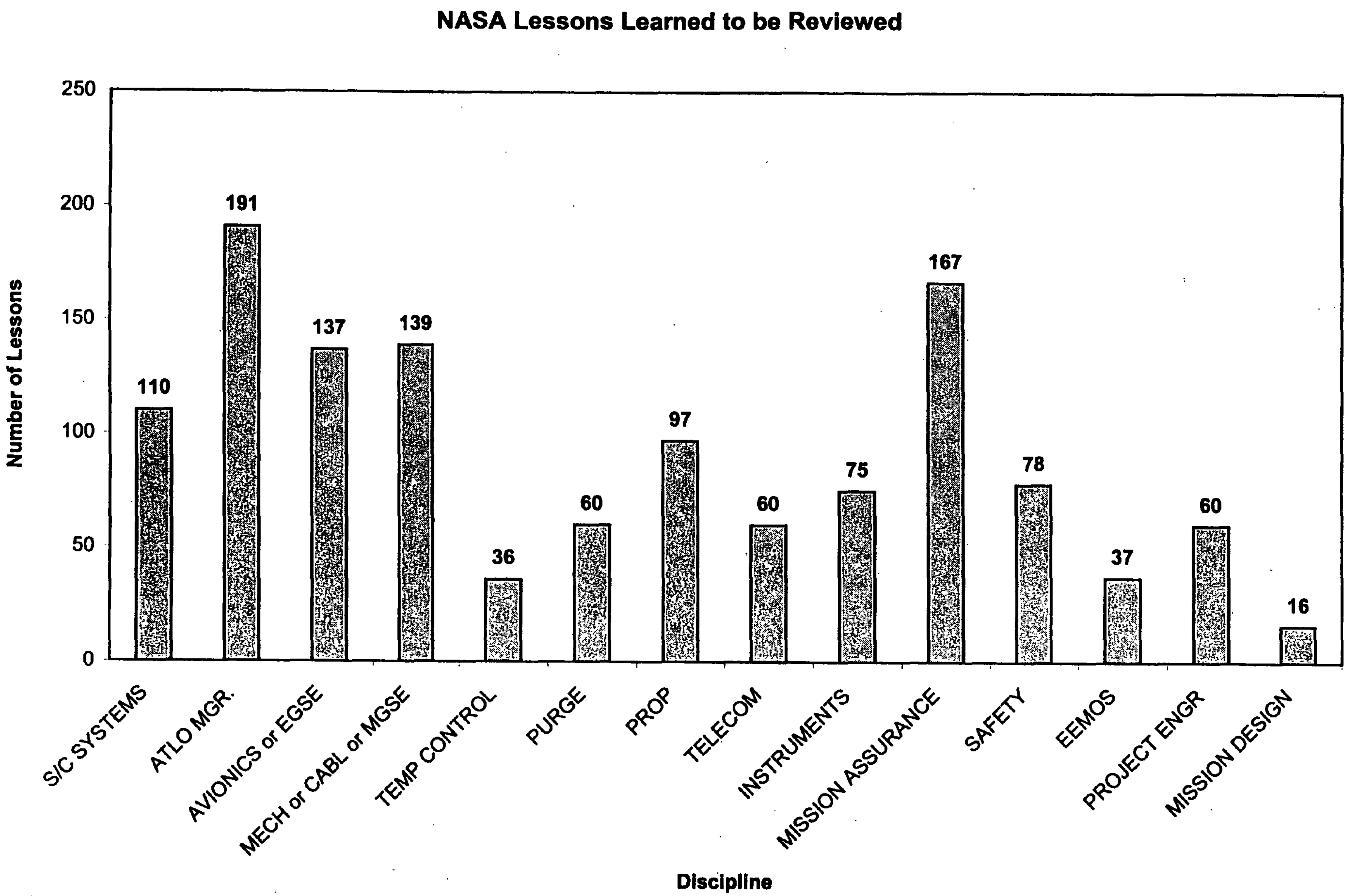
Oct-01
Nov-01
Dec-01


NASA Lessons Learned to be Reviewed
Number of Lessons
250
200
150
100
50
0
110
191
137
139
36
60
97
60
75
167
78
37
60
16
S/C SYSTEMS
ATLO MGR.
AVIONICS or EGSE
MECH or CABL or MGSE
TEMP CONTROL
PURGE
PROP
TELECOM
INSTRUMENTS
MISSION ASSURANCE
SAFETY
EEMOS
PROJECT ENGR
MISSION DESIGN
Discipline