CASSINI ENVIRONMENTAL TEST AND ANALYSIS PROGRAM SUMMARY

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1.0 ABSTRACT

This paper presents an overview of the Cassini Project's environmental test and analysis program during the spacecraft development phase - October 1989 to launch in October 1997. It describes the program's objectives and requirements, and then summarizes the approach used to achieve them, and provides the margins that were achieved in the final design. Assembly and system level environmental tests that were performed included dynamic, thermal, electromagnetic compatibility (EMC), and magnetic tests. Analysis was used to verify that the environmental requirements of radiation, solid particles including micrometeoroids, and single event effects have been satisfied. The environmental program implemented on Cassini satisfied the spirit and intent of the requirements imposed by the Project during the spacecraft's development. The lessons learned from the Cassini environmental program are discussed in this paper.

2.0 INTRODUCTION

The Cassini spacecraft was launched on a Venus-Venus-Earth-Jupiter gravity assist (VVEJGA) trajectory to Saturn on October 15, 1997 from Cape Canaveral, FL. A Titan 4B/Centaur launch vehicle was used to lift the spacecraft and booster into earth orbit. The second burn of the Centaur then propelled the spacecraft from Earth orbit into its interplanetary trajectory. (See Figure 1)

The Cassini spacecraft carries 12 instruments on the Orbiter, and 6 instruments on the Huygens Probe that will perform 27 investigations of Saturn and other bodies in the vicinity of the planet [1]. The primary scientific objectives are to investigate the elemental, molecular, isotopic and mineralogic compositions of Saturn, Titan, the smaller satellites, and the rings of the Saturnian system; to determine the physical, morphorological, and geological nature of these objects; to determine the physical and chemical processes operating in the atmospheres of Saturn and Titan, and on the surface of the rings and satellites of the system; and to determine the physical and dynamic properties of Saturn's magnetosphere and its interactions with the rings and satellites.

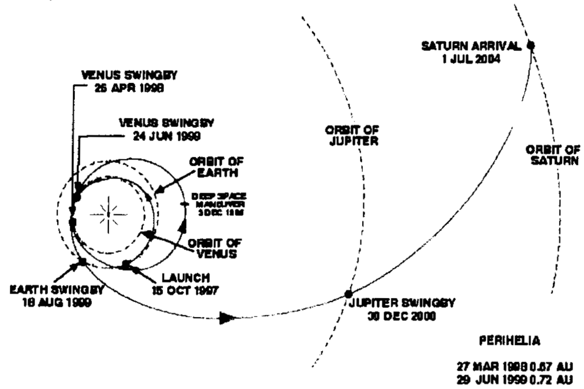

Figure 1. Cassini Mission Trajectory

The Cassini spacecraft consists of a planetary orbiter and the Huygens Probe (Figure 2). The Cassini Program is a joint development by the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the Italian Space Agency (ASI). The United States portion of the mission is managed for NASA by the Jet Propulsion Laboratory (JPL). The probe provided by ESA will separate from the orbiter and will land on Titan, one of the moons of Saturn. The orbiter derives its power from three radioisotope thermoelectric generators (RTG's). Table 1 shows the mass distribution of the Cassini spacecraft.

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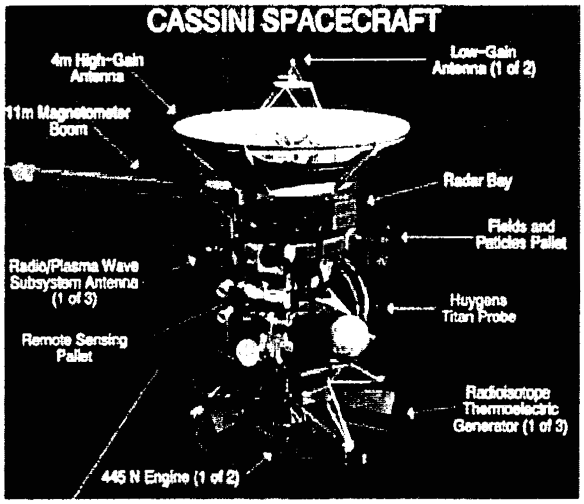


Figure 2. Cassini Spacecraft Configuration - Interplanetary Cruise

Table 1. Cassini Mass Summary

ITEM	MASS (kg)	MASS (lb.)
S/C (at separation from Centaur)	5,711 kg	12,590 lb.
Saturn Orbiter (Dry Mass)	2,094 kg	4,616 lb.
Huygens Probe	320 kg	705 lb.
Probe Support Structure	30 kg	66 lb.
Bipropellant	3,000 kg	6,614 lb.
Hydrazine	132 kg	291 lb.
Centaur Adapter	135 kg	298 lb.

Cassini's in-flight trajectory control, orbit insertion and orbit tour control are provided by a bipropellant propulsion system. The Orbiter main structures are the High Gain Antenna (HGA) provided by ASI at the top, the main bus with most of the electronics in the middle, and the propulsion module at the bottom. The spacecraft is 6.8 meters (22.3 feet) tall. Some of the other dimensions are noted in Figure 2. The magnetometer boom and several other science antennas and masts deploy after launch. Figure 2 shows the spacecraft in its interplanetary cruise configuration.

The environmental program implemented for Cassini consisted of a thorough test and analysis effort at the assembly/subsystem level as well as the system level. This program is summarized in Table 2.

Table 2. Cassini Environmental Verification Summary

	Environment	Assembly/ Subsystem	Spacecraft
Test	Dynamics	X	X
	Thermal	X	X
	Electromagnetic Compatibility	X	X
	Magnetics	X	Analysis
Analysis	Electrostatic Discharge	X	--
	Radiation	X	--
	Solid Particles	X	X
	Atomic Oxygen	X	--

3.0 OBJECTIVES

The overall objective of the Cassini environmental program was to design and demonstrate during the spacecraft development phase that the flight hardware was environmentally reliable and could function as required through all the environments it will encounter during its mission. This objective was met by satisfying two types of environmental tests or analysis:

1) Design Qualification test (Qual Test) or analysis:
Demonstrate that the design capability has margin over the expected mission environmental requirements. Testing was performed on either an engineering model (EM) or a protoflight model.

2) Flight Acceptance test (FA Test):
Demonstrate that the flight hardware is representative of the qualification design and has workmanship integrity

to function as required throughout the mission's environments. Testing was performed on flight hardware that had been preceded by qualification/ protoflight testing of an engineering model or a protoflight unit.

The Cassini Environmental Program Policy and Requirements, Project Document 699-228 [2] established the polices for the environmental qualification of the spacecraft for its intended mission.

Since the Cassini Orbiter and Huygens Probe are one-of-a-kind vehicles, much of the hardware is unique. Engineering models of critical engineering hardware were built and tested. For other hardware, the only opportunity to qualify the design, and show margin, was to test the flight hardware. In these cases, a Protoflight (PF) level test was performed. PF tests are performed so that they demonstrate margin in the hardware design, but do not stress the hardware to a level that would render it unacceptable for flight. The PF test is a combined Qualification Test, and Flight Acceptance Test.

The Cassini Orbiter Functional Requirement Book, Environmental Design Requirements (Project Document CAS-3-240) established the project's tailored environmental design requirements [3]. The assembly-and system-level test requirements and margins as applied on the Cassini hardware are given in Table 3.

Table 3. Summary of Cassini Test Requirements and Margins

Test Description	Assembly			Spacecraft System
	Flight Acceptance	Protoflight	Qualification	Protoflight
SINE VIBRATION Amplitude Sweep Rate	 ≥ 95th Percentile 6 oct/min	 1.5 x FA 6 oct/min	 1.5 x FA 2 oct/min	 Low Frequency Random 1 min
ACOUSTICS Amplitude Duration	 ≥ 95th Percentile 1 min	 FA + 4 dB 1 min	 FA + 4 dB 3 min	 ≥ 95th Percentile + 4 dB 1 min
RANDOM VIBRATION Amplitude Duration	 ≥ 95th Percentile 1 min/axis	 FA + 4 dB 1 min/axis	 FA + 4 dB 3 min/axis	 No Test
PYRO SHOCK	None	1.5 x 95th Percentile 1 shock/axis	1.5 x 95th Percentile 1 shock/axis	1 Firing of Each Device
TEMPERATURE	0 to 55°C Allowable Flt ± 5°C	-20 to 75°C Allowable Flt ± 25°C	-20 to 75°C Allowable Flt ± 25°C	Within Allowable Flt and not to Exceed Assembly PF
PRESSURE PROFILE	None	1.5 x Max dP/dt	1.5 x Max dP/dt	Facility Limited
EMC RF Susceptibility Emissions	 None None	 Pred. + 6 dB Freq. Dependent Margin > 60 dB	 Pred. + 6 dB Freq. Dependent Margin > 60 dB	 Pred. + 6 dB Freq. Dependent Margin > 60 dB
ELECTROSTATIC DISCHARGE (ESD) (Test Requirements)	None	13 kV ESD at 25 cm	13 kV ESD at 25 cm	No Test
MAGNETICS DC Field Subsystem Less Subsystem AC Field (DC to 1 Hz) (1 Hz to 20 kHz) Powered (AC&DC Fields)	 ≤ 5 nT (at 1m) ≤ 2.5 nT (at 1m) No Test No Test No Test	 ≤ 5 nT (at 1m) ≤ 2.5 nT (at 1m) ≤ 10 nT (at 1m) Distance Dependent (at 1 to 3m) 1.2 x DC Field	 ≤ 5 nT (at 1m) ≤ 2.5 nT (at 1m) ≤ 10 nT (at 1m) Distance Dependent (at 1 to 3m) 1.2 x DC Field	 No Test No Test No Test No Test No Test

4.0 ASSEMBLY LEVEL ENVIRONMENTAL TESTING

A rigorous assembly-level test and analysis program was developed and implemented for the Cassini orbiter hardware as part of the overall environmental program. The test specification that established the assembly test levels and durations is JPL Specification TS 515526 [4]. The major steps in that process were:

1) Establish design and verification requirements early.

2) Hold interaction between hardware cognizant engineer and project environmental requirements engineer to determine the need for and the method of verification (test or analysis) for each assembly. A test/analysis requirements example is shown in Table 4

3) Perform the design, test and analysis.

4) Submit the test results to the project environmental requirements engineer for pass / fail determination.

5) Verify final compliance at hardware delivery for systems integration.

The formal assembly-level tests began when the first engineering hardware became available to test.

An environmental documentation process was established that consists of the following types:

Environmental Test Specification Summary (ETSS)
- Defined the specific environmental tests to be performed on an assembly or subsystem.

Environmental Test Authorization Summary (ETAS)
– Verified the integrity and pedigree of the article to be tested.

Test Results Summary Form (TRSF)
– Reported the test results for a given test on a given serial number.

Other documentation that affected the environmental program included: Environmental Analysis, Problem Failure Reports, Waivers and Engineering Change Requests. The amount of environmental documentation processed by the environmental team is shown in Table 5.

Table 4. Cassini Subsystem/Assembly Test/Analysis Requirements Matrix (Example)

ITEM	PROTOFLIGHT/QUALIFICATION																									DESIGN CHARACTERISTICS				FLIGHT ACCEPTANCE/ CHARACTERISTICS								REMARKS
	STATIC LOADS	EARTH ATMOSPHERE LOADS, HEATING	PACKAGE DROP & TRANS VIBRATION	HUMIDTY	EXPLOSIVE ATMOSPHERE	QUASI-STEADY ACCEL.	ACOUSTIC	VIBRATION - SINE	VIBRATION - RANDOM	PYRO. SHOCK	TEMP. GROUND HANDLING	TEMP./ATMOSPHERE	LAUNCH PRES. PROFILE	CONTAMINATION	THERMAL VAC. (CORONA)	THERMAL SHOCK	EMC CONDUCTED SUSC.	EMC RADIATION SUSC.	ESD SUSCEPTIBILITY	RTG & RHU RADIATION	ELECTRON RADIATION	PROTON RADIATION	SINGLE EVENT EFFECTS	ATOMIC OXYGEN	SOLID PARTICLES	MAGNETIC	EMC COND. EMISSION	EMC RADIATION EMISSION	EMC ISOLATION	ACOUSTIC	VIBRATION - SINE	VIBRATION - RANDOM	TEMP. GROUND HANDLING	TEMP./ATMOSPHERE	THERMAL VACUUM	MAGNETIC	EMC ISOLATION	
4. PPS Bay EA 3	-	-	3	3	3	-	-	X	X	X	-	-	-	-	X	-	X	X	A	A	A	A	A	-	-	X	X	X	X	-	X	X	-	-	X	X	X	
90. UVIS	-	-	3	3	3	A	X	X	X	X	-	-	X A	A	X	-	X	X	X A	A	A	A	A	-	A	X	X	X	X									

Legend:
- X Test required
- A Analysis required in compliance with PD699-228
- X/A Test and/or analysis required
- – Neither test nor analysis required
- 1 Qualified during developmental testing on subsystem/assembly identical to qualification unit.
- 2 Qualification test not required. Qualification status retained from Galileo or other projects
- 3 Test not required if approved procedures are followed and acceptable environmental conditions maintained
- 4 Qualified for environment at higher level of integration or in conjunction with other assemblies
- 5 Subsystem qualification achieved through its composite assembly tests.

PPS = Power and Pyro Subsystem
UVIS = Ultra-Violet Imaging Spectrograph

Table 5. Cassini Environmental Documentation Summary

	Cassini Total	Reviewed by Environmental Requirements
TEST DOCUMENTATION		
Environmental Test Specification Summaries (ETSS)	244	244
Environmental Test Authorization Form (ETAF)	316	316
Test Results Summary Forms (TRSF)	863	863
ENVIRONMENTAL ANALYSES		
Analyses (Non-Radiation)	174	174
Radiation Analysis Completion Statements	62	62
PROBLEM FAILURE REPORTS (PFR)		
Cassini Total (At Launch)	2709	478
WAIVERS		
Cassini Total (At Launch)	1087*	189
ENGINEERING CHANGE REQUESTS		
Cassini Total (At Launch)	2000*	70+
Totals	7455	2396

*includes canceled or not written.

4.1 DYNAMICS

This section presents a summary of the Cassini assembly and subsystem level dynamic testing that was completed. Table 6a shows the tests that were required and completed in the program, and indicates the percentage that passed the first test attempt. Table 6b shows two examples of test failures at the assembly level, and their disposition. Table 6c shows the pass / fail statistics for Cassini dynamic testing.

Table 6a. Assembly Level Dynamic Tests Percent Completed by Test Type

Test Description	Protoflight or Qualification		
	Acoustic	Sine & Random Vib.	Shock
Required Tests	18	96	56
Passed Original Test	15 (83%)	74 (77%)	55 (98%)
Passed 1st Retest	2 (11%)	17 (18%)	1 (18%)
Passed 2nd Retest	1 (6%)	4 (4%)	-
Passed 3rd Retest	-	1 (1%)	-
Never Passed	0	0	0
	Flight Acceptance		
	Acoustic	Sine & Random Vib.	Shock
Required Tests	1	151	2
Passed Original Test	0 (0%)	147 (97%)	2 (100%)
Passed 1st Retest	1 (100%)	4 (3%)	-
Never Passed	0	0	0

Table 6b. Assembly-Level Dynamic Testing Problem/Failure Summary (Example)

Assembly	Test Level	Test Type	Axis	PFR	Failure	Time of Detection	Tests Prior To Failure	Disposition
Radio & Plasma Wave Science (RPWS)	PF	sine & random vibration	Y	60116	During random vibration a caging pin unlatched and the antenna deployed prematurely	45 sec. from the start of Y axis random vibration	Y axis sine vibration	Caging pin mechanism was redesigned and vibration test was repeated
Brushless Motor for the Articulated Reaction Wheel Mechanism	PF	sine & random vibration	All	58218	A drive transistor had broken loose and there were broken leads on other components	After 3 axes of sine & random vibration	3 axes of sine & random vibration	The electronics package for all motors of this type were remanufactured and retested.

Table 6c. Assembly Level Dynamic Test Problem/Failure Statistics

Assembly	Failed Test			Total Failures *		
	Qual.	PF	FA	Qual	PF	FA
Radio Freq. Subsys. – Deep Space Trans.	2		1	4		1
Articulated Reaction Wheel Mech.		1			2	
High Gain Antenna	4			7		
VRHU Mechanism	2			5		
Thermal Control Louvers	1			2		
VIMS IR Channel/Optics		1			2	
RPWS Antenna Assy	1			2		
RPWS Langmuir Probe	3			6		
Ion & Neutral Mass Spectrometer (INMS)	1	2		3	1	
MIMI Electronics		2			4	
CDA Electronics			1			1
Radar RFES	2			2		
Cassini Plasma Spectrometer		1			1	
Composite IR Spec. (CIRS) Electronics		1			1	
Composite IR Spec. (CIRS) Optics	1		1	1		1
RFS/Microwave Component Assy (3 bay)		1			2	
RFS/Waveguide Transfer Switch			2			2
Total	17	9	5	32	13	5
Total of Qual., PF and FA	31			50		

**A failure is counted if an action to correct the hardware under test was initiated. Some tests had multiple failures resulting in a greater number of total failures than failed tests.*

4.2 THERMAL

Figures 3a-d are some examples of Cassini subsystem and assembly level temperature data. Thermal test data and in flight data is included for comparison. Also included are the test temperature requirements, the allowable flight temperature range, and the temperature range during spacecraft level solar thermal vacuum (STV) testing.

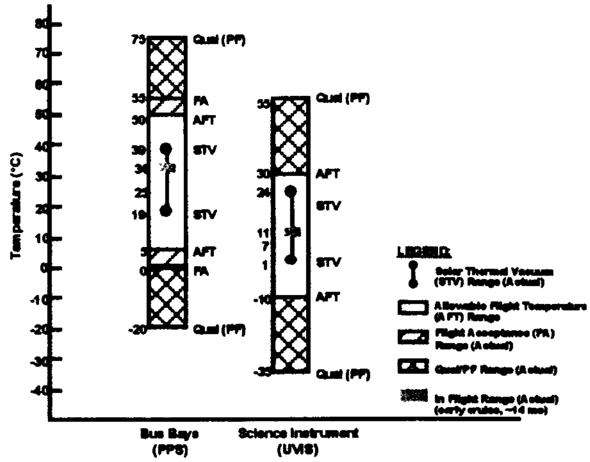


Figure 3a. Cassini Subsystem Thermal Verification Example

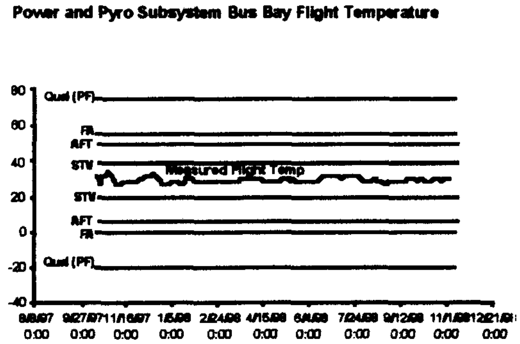


Figure 3b. Representative Temperature Profile for Bus Bays -Power and Pyro Subsystem and Attitude Control (Bays 1,2,3)

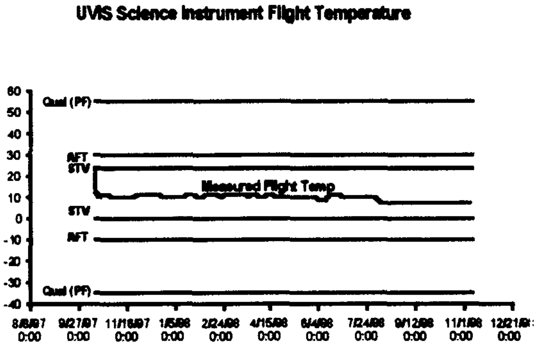


Figure 3c. Representative Temperature Profile for a Remote Science Platform Instrument-Ultraviolet Imaging

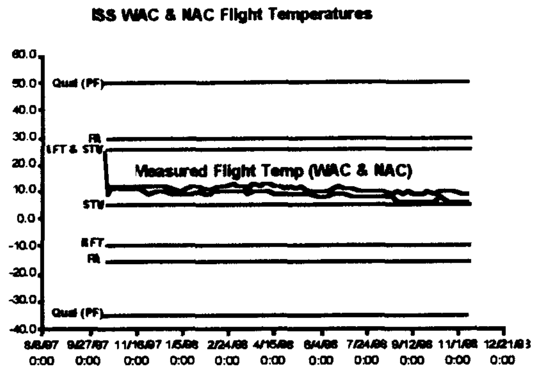


Figure 3d. Representative Temperature Profile for a Remote Science Platform Instrument - Imaging Science Subsystem

4.3 Electromagnetic Compatibility

An extensive electromagnetic compatibility (EMC) test program was implemented at the assembly level for Cassini. Development models and engineering models were characterized early in their development cycle and the test results applied to the flight hardware design. The formal qualification testing was performed on either the engineering model configured in the flight design or a protoflight unit. An example of the EMC testing performed on Cassini assemblies is given in Table 7. The sources of these EMC requirements are summarized in Table 8. The radiated emission requirements and results for the e field and h field are given in Figures 4a and 4b respectively.

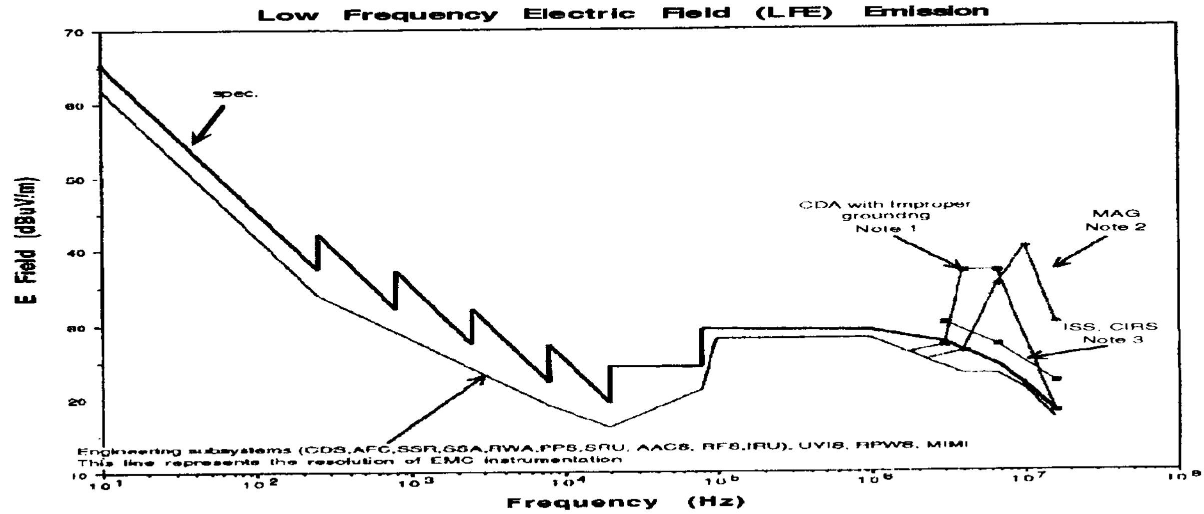
Table 7. Example of EMC Testing Results

		Radiated Emissions				Conducted Emissions		Conducted Susceptibility		Radiated Susceptibility		
Subsystem	DC Isolation	14k-10G	LFE	LFH	Specials	Power	Signal	Power	Signal	Launch	Special	ESD
Power and Pyro Subsystem (Bay 2 and 3)	Passed	Failed Waived	Failed Waived	Passed	Passed	Failed Waived	Passed	Passed	Passed	Passed	Passed	Analysis
Ultra Violet Imaging Spectrograph	Passed	Passed	Passed	Failed Waived	Passed	Passed	Passed	Passed	Passed	Passed	Passed	Analysis

Table 8. Cassini EMI Requirement Sources

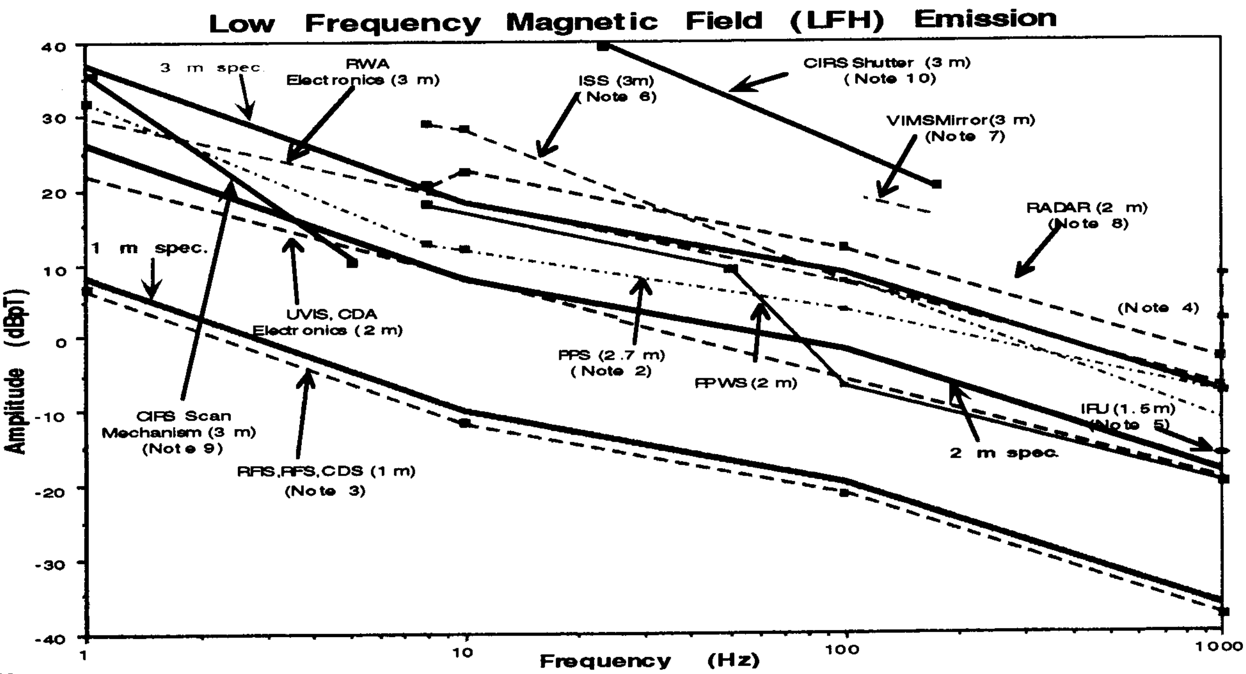
High Level EMI Requirement Sources														
How Requirement is Driven	Isolation	Radiated Emissions				Radiated Susceptibility		Conducted Emissions				Conducted Susceptibility		DC Magnetics Emissions
		RE02	LFE	LFH	RE SF	RS03	RS SF	PL - Time	PL - Freq	CM - St	Signal Lines	PL - Ripple	PL - Transient	
MIL STD	X	X				X		X	X			X	X	
Launch Site / Launch Vehicle	X				X		X							X
Engineering Hardware					X		X	X	X	X	X	X	X	
SCIENCE INSTRUMENTS														
Cassini Plasma Spectrometer (CAPS)														X
Cosmic Dust Analyzer (CDA)														
Composite Infrared Spectrometer (CIRS)														
Ion and Neutral Mass Spectrometer (INMS)														
Imaging Science Subsystem (ISS)														
Magnetometer (MAG)				X										X
Magnetospheric Imaging Instrument (MIMI)														
Cassini Radar (RADAR)					X		X							
Radio Frequency Instrument Subsystem (RFIS)					X		X							
Radio and Plasma Wave Science (RPWS)			X	X						X				X
Science Calibration Subsystem (SCAS)														
Ultra Violet Imaging Spectrograph (UVIS)														
Visual and Infrared Mapping Spectrometer (VIMS)														

CM = Common Mode
LFE = Low Frequency Electric field emissions
LFH = Low Frequency H - field emissions
PL = Power Lines
RE = Radiated Emissions
RE02 = Radiated Emissions 14k Hz to 35 G Hz Test Method 02
RS = Radiated Susceptibility
SF = Special Frequencies
St = Structure Current



Notes
1. CDA moving part grounding added. Emission reduced, in spec., passed.
2. Mag power supply circuit board reworked to reduce capacitive coupling from component case onto chassis, emissions significantly reduced, out of spec., waived.
3. ISS and CIRS emissions are due to leakage at test connectors and cables. Shielding added, emissions reduced, out of spec. Residual waived.

Figure 4a. Low Frequency Electric Field (LFE) Emission (Courtesy P. Leung/B. Ruff)



Notes
1. This plot displays the emissions from 1 Hz to 1 kHz only. CAS-3-240 spec. Is from 1 Hz to 20 kHz.
2. PPS emission is based on analysis using the worst case conducted emission as the source current of LFH.
3. CDS LFH emission is extrapolated from the flight PCU and EM CDS test results.
4. The 1.4 kHz emissions of RADAR and ISS are shown here as 1 kHz emissions.
5. IRU emission at 2 kHz is 12 dB out at worst case orientation, waived 1 spike.
6. ISS filter wheel and electronics shielded, emissions reduced, out of spec., residual waived.
7. VIMS Mirror small current loop in mirror, fix not practical, use as is, waived.
8. Radar (Bay 11) Mu metal shields added to power conditioning unit and energy storage unit., passed.
9. CIRS emission from scan mechanism. Added compensating coil, in spec., passed.
10. CIRS emission from shutter up to 190 Hz. Shutter duty cycle very short periods at hourly intervals, use as is, waived.

Figure 4b. Low Frequency Magnetic Field (LFH) Emission (Courtesy P. Leung/B. Ruff)

4.4 MAGNETICS

To assure compliance with the science-magnetics cleanliness requirements, a total of 56 sources were measured preceding delivery of the hardware for spacecraft integration. The qualification and protoflight tests required the hardware to be magnetically measured with the assembly both operating and non-operating. The flight acceptance tests were all performed unpowered. An example of test results for a Cassini engineering and science subsystem is given in Table 9. These results were used to calculate magnetic dipole moments for those assemblies exceeding 5 nT at 1 meter so that the net effect at the outboard low-field magnetometer could be estimated.

Table 9. Assembly Level Magnetics Test Results

Assembly Identification	Magnetic Test Requirements nT at 1 m	Magnetic Test Results nT at 1 m
Power and Pyro Subsystem (Bay 2 and 3)	5	5
Ultra Violet Imaging Spectrograph	5	5

5.0 SYSTEM-LEVEL ENVIRONMENTAL TESTING

The system-level environmental tests for Cassini were performed from November 5, 1996, to May 7, 1997. The objective of these tests was to verify that the spacecraft system would perform within acceptable limits during and after exposure to launch and space environments. These tests included acoustic noise, random vibration, pyrotechnic shock, solar thermal vacuum, and electromagnetic compatibility. The hardware supplied for system level testing by Cassini International partners ESA and ASI is shown in Table 10a. The test dates and test reports are noted in Table 10b.

The test specification that established the system level test levels and durations is JPL Specification TS 515526 [5]. The following sections describe the system-level tests performed.

Table 10a. System Level Environmental Testing Configuration - Huygens Probe and High Gain Antenna

	Probe	Probe Support Equipment	High Gain Antenna
Vibration	STPM	Flight	Flat Plate Simulator (JPL Supplied)
Acoustic	STPM	Flight	Protoflight Model
Pyroshock	STPM	Flight	Flat Plate Simulator (JPL Supplied)
• RF Radiated Susceptibility (Launch Mode)	STPM	Flight	Flat Plate Simulator (JPL Supplied)
• RF Radiated Emission (Launch Mode)	STPM	Flight	Flat Plate Simulator (JPL Supplied)
Solar Thermal Vacuum	Thermal Simulator (JPL Supplied)	Flight	Protoflight Model
Electromagnetic Compatibility			
• RF Radiated Susceptibility (Encounter Mode)	Probe EM	Flight	Protoflight Model
• RF Radiated Emissions (Encounter Mode)	Probe EM	Flight	Protoflight Model
RF Compatibility	Probe EM	Flight	Protoflight Model

STPM = Structural Thermal Pyro Model
EM = Engineering Model
RF = Radio Frequency

Table 10b. Cassini System Level Environmental Test Program Test Reports

TEST	TEST PERIOD	PROJECT DOCUMENT NUMBER	JPL DOCUMENT NUMBER	DOCUMENT TITLE	REPORT DATE	AUTHOR
Dynamic Tests	Nov 5-26, 1996					
Acoustic	Nov 5-6, 1996	None	D-14187	Cassini Spacecraft Protoflight Acoustics Test Report	Dec 01, 1996	Boatman Fernandez
Low Frequency Random Vibration	Nov 21-23, 1996	None	D-14198	Cassini Flight Spacecraft Protoflight Random Vibration Test Report	Mar 29, 1997	Rentz
Pyroshock		None	D-14199	Cassini Flight Spacecraft Protoflight Pyrotechnic Shock Test Report	Apr 11, 1997	Chang
Phase 1 (Devices Deploy)	Nov 14, 1996					
Phase 2 (S/C-LV Separation)	Nov 26, 1996					
Electromagnetic Compatibility	May 5, 1996 to March 25, 1997	699-263	D-15708	Cassini System Level EMC Test Report	Jan 15, 1999	Kuberry
Conducted Emissions: - Encounter Mode w/probe	May 5-6, 1996					
Radiated Emissions: - Encounter Mode	Oct 2-10, 1996					
Radiated Emissions: - Launch Mode	Oct 20, 1996					
Radiated Susceptibility: - Launch Mode	Oct 19-20, 1996					
Conducted Emissions: - Launch/Encounter Modes	Oct 2-10, 1996					
Radiated Emissions: - Launch Mode	Feb 2, 1997					
Conducted Emissions: LV interfere	March 20-25, 1997					
Solar Thermal Vacuum	Jan 17, 1997 to Feb 6, 1997	699-255	D-14463	Cassini Project System Level Solar Thermal Vacuum Test Report	Apr 30, 1997	Juanero Miraeles
Phase 1 (Tour Configuration)	Jan 17, 1997 to Jan 26, 1997					
Phase 2 (Cruise Configuration)	Jan 31, 1997 to Feb 4, 1997					
Prelaunch Simulation	Feb 4, 1997 to Feb 6, 1997					

5.1 ACOUSTIC TEST

Protoflight full level acoustic testing was performed on the Cassini spacecraft on November 6, 1996. Several lower level runs were performed first, at increasing levels, to calibrate the equipment. This was so that the full level run would be in the specified range across the entire frequency spectrum. The required acoustic magnitudes were achieved at all frequencies.

For the system level acoustic test, the spacecraft was in its flight configuration, except that the thermal blankets were not installed. The thermal blankets were not expected to have an influence on the test. In some cases, flight assemblies were not available, so engineering models were used. Mass models with the same mass and stiffness characteristics were used in place of the RTGs. Figure 5a shows the spacecraft in the acoustic chamber.

The three major objectives of the test were to:

1) Demonstrate that the spacecraft can withstand the Titan 4B acoustic environment during launch.

2) Verify that the random vibration specifications for assembly level hardware are adequate.

3) Provide a measure of workmanship verification for the fully assembled spacecraft.

During the test, the acoustic control and spacecraft instrumentation all performed well. The acoustic levels were within specification.

The spacecraft was operating in the launch mode during the test. The motor nozzle moved as expected, and the rest of the spacecraft controls and electronics had no indication of any anomalies.

There were some fasteners that backed out on principal investigator provided science instruments. No other mechanical failures were observed. Problem Reports were written for these anomalies and action was taken to correct the hardware so that these problems would not occur during launch.

The test objectives were considered to have been satisfied.

5.2 LOW FREQUENCY RANDOM VIBRATION TEST

Low Frequency Random Vibration was performed on November 23, 1996 on the large shaker in the Environmental Test Laboratory at JPL. During the random vibration test, the spacecraft was in its flight configuration, except that the HGA was removed, and thermal blankets had not been installed. These were not expected to have an influence on the test. Mass models with the same mass and stiffness characteristics were used in place of the RTGs. Figure 5b shows the spacecraft on the shaker in its random vibration test configuration with the "Blue Bowl" fixture. Airbags were used between the shaker and the "Blue Bowl" to support the static weight of the spacecraft and the fixture. Hydrostatic bearings were used between the fixture and interconnected pylons to resist lateral forces and overturning moments.

The objectives of the system-level random vibration test was to demonstrate design qualification and workmanship verification of the mechanical integrity of spacecraft interfaces for low/mid frequency mechanically transmitted vibration when subjected to the system level protoflight random vibration environment.

The test frequency range was 10 to 200 Hz with 0.01 g^2/Hz between 60 to 200 Hz. All test objectives were achieved. No structural damage was evident as a result of the test except for loss of electrical isolation between the RTG case and the Spacecraft structure. To correct this anomaly, the insulation between the RTG adapter and the lower equipment module was redesigned. There were no spacecraft functional anomalies observed. Detailed descriptions of the force limiting random vibration testing performed on the spacecraft and selected Cassini assemblies/subsystems are given by Scharton and Chang [6-8]. The project test report is identified in Table 10b.

5.3 PYROSHOCK TEST

The system level pyroshock test was performed on the Cassini spacecraft during two test periods, Phase I on November 14th and Phase II on November 26th, 1996. The tests were performed at the Environmental Test Laboratory at JPL. The tests were performed by firing flight like pyro devices while the spacecraft was in a configuration similar to its flight configuration at the time the pyro devices were to be fired.

During the pyroshock test, the spacecraft was in its flight configuration, except that the HGA was removed, and thermal blankets had not been installed. These were not expected to have an influence on the test. Mass models with the same mass and stiffness characteristics were used in place of the RTGs.

The test consisted of firing three devices:

Phase I: November 14th, 1996

1) The Langmuir Probe deployment pyro device was fired.

Phase II: November 26th, 1996

2) The launch vehicle separation pyro was fired.

3) The MEA Cover ejection pyro device was fired.

During the Langmuir Probe pyro test, the spacecraft was resting on its stand on the ground. For the launch vehicle separation test, the spacecraft was lifted by a crane a few inches off the ground, so that the launch vehicle adapter could fall away. The spacecraft remained suspended by the crane for the Main Engine Assembly (MEA) Cover ejection test.

The objective of the Cassini pyro-shock test was to demonstrate that the pyro devices performed their function correctly, and to show that the hardware near the pyro-devices was able to withstand the shock environment.

For the Langmuir Probe deployment pyro test, the probe was in the stowed configuration, and the cable cutter was fired to allow the probe to swing out. The pyro device successfully cut the cable, but the probe failed to fully deploy. It was determined that without gravity the probe would have swung to the fully deployed position.

For the launch vehicle separation test, the spacecraft was raised off of the floor with a crane. The spacecraft stand was connected to the spacecraft by the launch vehicle separation ring. When the pyro device was fired, the bottom half of the separation ring, and the stand, fell a few centimeters to a pad on the floor. The test was successful, and no Problem Failure Reports (PFRs) were written.

The MEA Cover ejection test was performed after the launch vehicle separation test while the spacecraft was still suspended by the crane. The cover was restrained so that its fall would be limited after the pyro-devices were fired. The cover released as expected, however two of four bolts that mount the MEA Cover drive sheared from the pyro-shock. A PFR was written, and the bolt design was changed so that this would not happen in flight.

After all three pyro-shock tests were completed, the spacecraft was electronically checked out. All systems were operating normally, with no indication of any damage. The objectives of the system level pyro-shock test were met.

5.4 SOLAR THERMAL VACUUM TEST

The Cassini solar thermal vacuum test (STV) was performed in the 25 foot diameter Space Simulator at JPL. The purpose of the solar thermal vacuum test was to evaluate the thermal integrity and limited orbiter functions in the space environment. The maximum solar intensity of the mission is encountered during the first perihelia at 2.2 suns. The minimum solar intensity is during Saturn orbit at 0.1 suns. The STV test was designed to demonstrate the orbiter temperatures will remain in specification during both extremes of the mission and to verify the accuracy of the spacecraft thermal model.

The Cassini spacecraft was mounted in the thermal vacuum chamber with the High Gain Antenna pointed towards the simulated solar radiation. In this manner, the spacecraft is shaded by the HGA in the same manner as it will be during the cruise portion until 2.7 AU of the flight except during maneuvers. Figure 5c shows the spacecraft in the space simulation chamber as it was configured during the STV test. During the STV test, the flight magnetometer (MAG) boom was tested with the flight magnetometers in the stowed configuration, while a simulator was employed for the MAG boom in its deployed configuration. The simulator consisted of Thermal Development Models of the Flux Gate Magnetometer (FGM) and Vector/Scalar Helium Magnetometer (V/SHM) and sufficiently long boom sections which permitted establishment of the boom cavity temperatures.

The system level STV test was performed in two phases, Phase 1 and Phase 2. Both phases included a hot and cold soak. The first phase was slightly more conservative so that some results would be obtained with low risk of a facility failure. Between the first and second phases, adjustments were made to the spacecraft based on the test results from the first phase. In the second phase, the effects of the adjustments were verified. Also, temperatures were pushed to a greater extreme, to reduce the amount of extrapolation necessary to account for the thermal extremes that will be encounter in the mission.

The maximum solar intensity that the spacecraft was subjected to was 1.6 suns. 2.2 suns was never reached because of a facility limitation with the solar lamps. Above 1.6 suns there was a risk that there could be enough lamp failures that the solar level could not be maintained throughout the test. It is necessary to maintain a steady solar intensity until thermal equilibrium is reached to achieve meaningful results. It was determined that it would be better to run at 1.6 suns and to perform a simple extrapolation to the temperatures that would be reached at 2.2 suns, than to operate at a higher solar intensity and risk not being able to maintain a steady solar load if there were any more lamp failures. The schedule did not allow for a retest, if the first test was not performed correctly.

During STV, the walls of the chamber were cooled with liquid nitrogen. This was to simulate the radiated temperature of deep space. For testing the Composite Infrared Spectrometer (CIRS), a liquid helium target was added.

There were no hardware failures noted. The PFRs related to the temperature control subsystems were closed out by redesigning thermal blankets, requalifying selected subsystems by test or analysis, and adjusting functional requirements temperature limits.

The test was considered successful in meeting the specified requirements and objectives.

Detailed descriptions of the Cassini thermal development test program[9], the system level thermal balance testing [10,11], and early cruise inflight performance [12] are available in the referenced publications. The project test report is identified in Table 10b.

Figure 5a. Acoustic Test Configuration

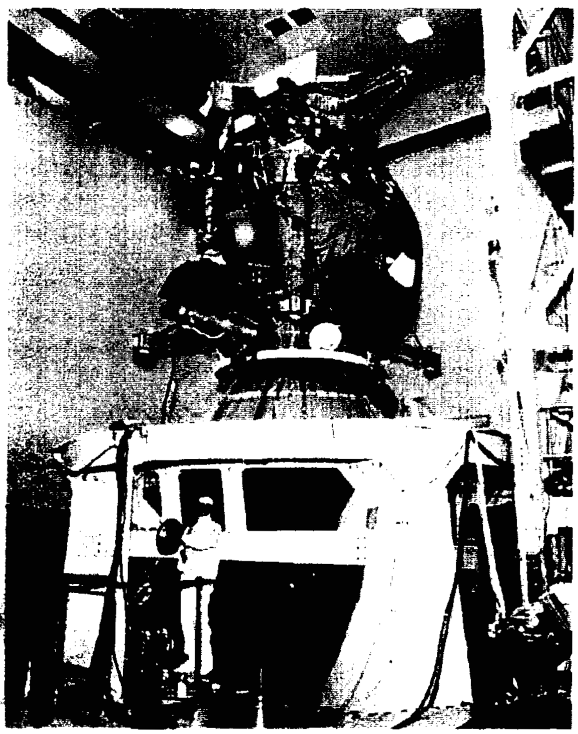


Figure 5b. Vibration Test Configuration

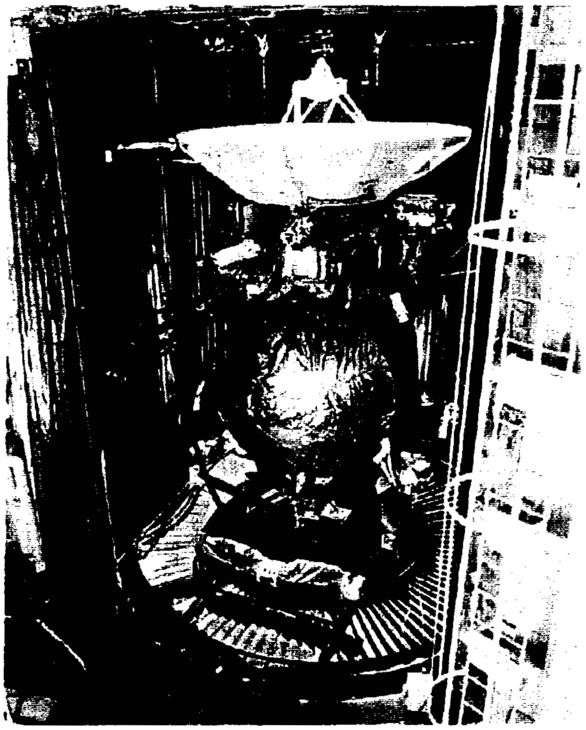


Figure 5c. Solar Thermal Vacuum Test Configuration

5.5 ELECTROMAGNETIC COMPATIBILITY TEST

A series of electromagnetic compatibility tests were performed on the spacecraft during the system level test program. These included radiated emissions in the encounter and launch mode, radiated susceptibility in the launch mode, and conducted emissions in the encounter and launch modes.

The system level radiated susceptibility test was performed on the Cassini spacecraft in October 1996. The purpose of this test was to ensure compatibility with launch and in-flight radio frequency (RF) sources. The test also qualified the pyrotechnic devices and control systems in the RF environment. This satisfied a functional requirement and a safety requirement for the pyrotechnic systems.

All the test objectives were satisfied.

6.0 ANALYSIS SUMMARY

Several environmental requirements for the Cassini spacecraft were satisfied by analysis rather than by test. Much of the analysis is based on the test results of piece parts, components, material, development hardware, and lower levels of assembly. Most of the analysis performed for Cassini environmental requirements is documented in memoranda, and formally reported in Environmental Analysis Completion Statements. Table 11 gives an overview of the analysis and acceptance criteria.

Table 11. Verification by Analysis

Environmental Requirement	Analysis Description	Acceptance Criteria
Hardware Magnetic Field Limits (at System Level)	Measured Assembly Magnetic Field Data Used to Compute System Magnetic Field at Magnetometer Sensors	Magnetic Field of Spacecraft System $\leq$ 0.2 nT at Vector/Scaler Magnetometer Sensor
Electrostatic Discharge (ESD) - External Charging - Internal Charging	Charged Particle Environment/Orbiter Material Interactions Assessments and ESD Coupling Analyses	ESD Eliminated or Reduced to Acceptable Level or ESD Immunity Provided
Natural Space and Nuclear Radiation Design Margin (RDM)	Electronic Piece Parts Capability/Shielded Radiation Environment Ratio Computed	RDM $\geq$ 2
Meteoroid Protection	Meteoroid Penetration Model Used in Deterministic or Probabilistic Analyses to Calculate Probability of Success Value	P_s = 95% for Spacecraft System
Atomic Oxygen	Materials Assessment of Exposed Surfaces	Erosion Rate Not Excessive
Contamination	Contamination Assessment of Optical and Thermal Surfaces	Obscuration and Molecular Deposition Not Excessive

6.1 MAGNETICS

The primary consideration in establishing the system magnetic requirements was to limit the total magnetic field produced at the Vector Helium Magnetometer (VHM), which is the outboard magnetic sensor on the spacecraft. The maximum allowable static and dynamic magnetic fields generated by the spacecraft at the end of the magnetometer boom are 0.2 nT and 0.66 nT respectively. (Dynamic magnetic fields are created by hardware that has spin or scan motion.) These requirements are imposed by the sensitivity of the magnetometer, and by the low expected magnitude of the magnetic fields that are to be measured in the vicinity of Saturn. System level magnetic testing was not possible because of the physical limitations of the available test facilities and coil system at JPL. To assure compliance with the science requirements, the magnetic field of a total of 56 hardware elements were measured and analyzed and the net effect of each assembly exceeding 2.5 nT at one meter was calculated at the VHM. Both the static and maximum dynamic fields were estimated at the VHM, the dynamic value being the worst case possible. The spacecraft's total post-launch static and dynamic fields at the sensor are estimated to be 0.113 nT and 0.0025 nT respectively. This satisfies the specified requirement. Table 12a and 12b show a summary on the results of magnetic testing at both the outboard sensor location (VHM) and the inboard sensor location (Flux Gate Magnetometer).

Table 12a. Cassini DC Magnetic Field – Final Prelaunch Summary
Overall Field before Huygens Probe Deployment (Courtesy of P. Narvaez)

Field at Vector Helium Magnetometer (VHM) Location

BVHMx		BVHMy		BVHMz		Btotal	
Huygens	-0.048 nT	Huygens	0.003 nT	Huygens	-0.016 nT	Huygens$_{tot}$	0.051 nT
Spacecraft	0.029 nT	Spacecraft	0.104 nT	Spacecraft	0.018 nT	Spacecraft$_{tot}$	0.110 nT
Total	-0.019 nT	TOTAL	0.107 nT	TOTAL	0.002 nT	TOTAL	0.1087 nT
				NOMINAL RTG COMPENSATION AT VHM LOCATION			0.0041 nT
				OVERALL TOTAL *			0.113 nT

Field at Flux Gate Magnetometer (FGM) Location

BFGMx		BFGMy		BFGMz		Btotal	
Huygens	-0.356 nT	Huygens	-0.071 nT	Huygens	-0.122 nT	Huygens$_{tot}$	0.383 nT
Spacecraft	0.226 nT	Spacecraft	0.976 nT	Spacecraft	0.112 nT	Spacecraft$_{tot}$	1.008 nT
TOTAL	-0.130 nT	TOTAL	0.905 nT	TOTAL	-0.01 nT	TOTAL	0.914 nT
				NOMINAL RTG COMPENSATION AT FGM LOCATION			0.056 nT
				OVERALL TOTAL *			0.970 nT

Table 12b. Cassini DC Magnetic Field – Final Prelaunch Summary
Overall Spacecraft Field after Huygens Probe Deployment (Courtesy of P. Narvaez)

Field at Vector Helium Magnetometer (VHM) Location

BVHMx	BVHMy	BVHMz	Btotal
0.029 nT	0.104 nT	0.018 nT	0.110 nT
		OPTIMUM RTG COMPENSATION AT VHM LOCATION	0.004 nT
		MAX TOTAL *	0.114 nT

Field at Flux Gate Magnetometer (FGM) Location

BFGMx	BFGMy	BFGMz	Btotal
0.226 nT	0.976 nT	0.112 nT	1.008 nT
		OPTIMUM RTG COMPENSATION AT FGM LOCATION	0.056 nT
		MAX TOTAL *	1.064 nT

* Huygens Probe provided magnetic compensation to the overall spacecraft fields, therefore after probe release the field is slightly higher.

6.2 SOLID PARTICLES

The approach used to provide micrometeoroid (solid particles) protection for the spacecraft is given in Figure 6. The micrometeoroid analysis for the VVEJGA trajectory is documented in memoranda, environmental analysis completion statement, and a nuclear safety report [13]. The solid particle environment consists of interplanetary micrometeoroids, planetary ring material, and manmade orbiting debris. The Cassini spacecraft encounters all of these during its flight. However, because of the long interplanetary cruise period (7 years) which includes four planetary gravitational assists coupled with the total primary mission duration (11 years), the micrometeoroid environment was the solid particle environment of concern. As a result of analysis and test assessments during design and development, the following solid particle protection enhancements were added to the spacecraft: shearplates used to house spacecraft electronics were thickened; multilayer insulation thermal blankets were spaced farther from the surfaces to dissipate energy over a larger area and up to two layers of beta cloth were added to the thermal blankets covering critical hardware elements; and a Main Engine Assembly shield was added to protect the rocket engine nozzles during cruise.

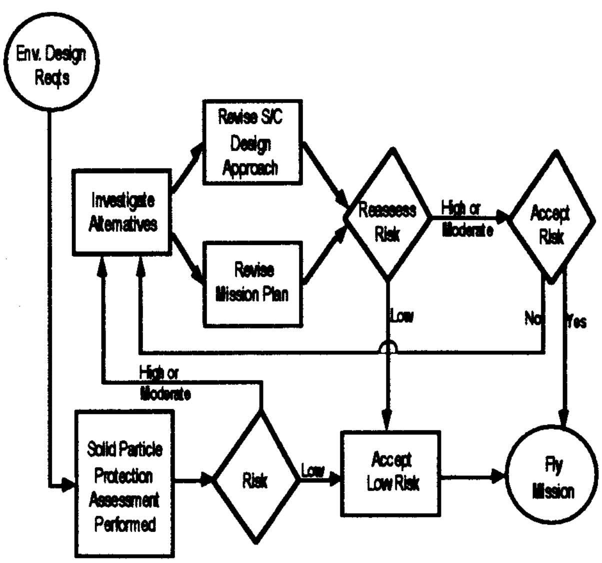


Figure 6. Cassini Solid Particle Protection Process

6.3 RADIATION ANALYSIS

Verification of compliance of the Cassini spacecraft with the natural radiation environment, and the radiation environment created by the onboard nuclear devices, was initiated at the beginning of the design effort of the assemblies. The controlling document was the Cassini Radiation Control Plan (Project Document 699-229) [14]. After the initial layout of the electronic boards, radiation analysis was performed. The parts analysts, the radiation analysts and the packaging engineers determined the requirements for shear plate thickness and the need for any spot shields for radiation "soft" parts. In parallel with these activities, a worst-case analysis was being performed. Waivers were prepared if parts were used that were not on the JPL approved parts list, if the radiation design margin was not satisfied, or if radiation spot shielding was required. The memoranda and supporting information were assembled into a radiation analysis package. The package was submitted to the Radiation Analysis Review Committee. The committee members consisted of a representative from packaging, materials, parts, reliability, and radiation transport, and was chaired by a representative from environmental requirements. After the review was satisfactorily completed, the committee issued a Radiation Analysis Completion Statement. This process is depicted in Figure 7. Three categories of hardware were addressed, engineering subsystems, science instruments, and subsystems with no active electronics (e.g. thermal blankets and the High Gain Antenna) where material radiation tolerance was the principal concern. The number of statements approved and released for each category are given in Table 13.

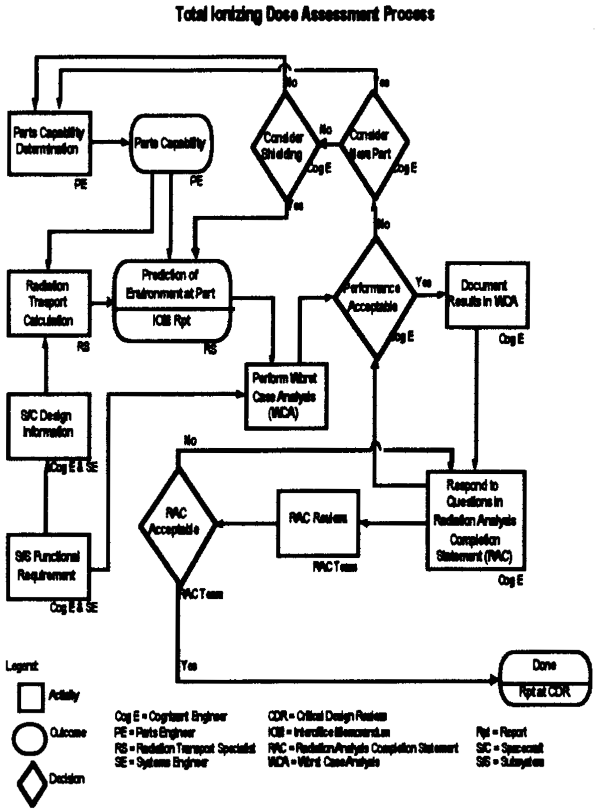


Figure 7. Cassini Total Ionizing Dose Assessment Process

Table 13. Radiation Analysis Completion Statements

	Engineering Subsystems	Science Instruments	Material Subsystems	Total
Approved /Released	32	17	13	62

6.4 SINGLE EVENT EFFECTS

Single Event Effects consist of Single Event Upsets (SEUs) that cause bit flips in microelectronics, single event gate rupture (SEGR), Single Event Latchup (SEL), Single Event Burnout (SEB), Single Event Transients (SET), with new effects being added as they are observed and identified. All of these environmental interactions were addressed for Cassini with special emphasis on Single Event Upsets. The following environments were examined; galactic cosmic rays (spectrum), solar flares (Adams Composite Flare), and the local environments along the VVEJGA spacecraft trajectory. An estimate of the rate of occurrence of SEUs was calculated.

The latest flare rates fall in the range defined by the known typical and large flare rates. The risk assessment for this environment is in line with the current knowledge of solar flares.

The Spacecraft Operations Team was advised to expect upsets during the mission and to be prepared for the possibility of one occurring at a critical time during the mission. The Cassini Project Office is also aware of, and has accepted that there is a small amount of risk that an SEU may occur at a critical time.

6.5 ELECTROSTATIC DISCHARGE

An extensive survey of the Cassini hardware was made to verify that the spacecraft was not subject to electrostatic discharge (ESD). The spacecraft was designed to meet the ESD external and internal charging specifications in Cassini Doc. CAS-3-240 [3]. All conductive surfaces greater than 0.5 cm^2 were grounded so a charge cannot build up. Exterior non-conductive surfaces which can store more than 3 mj of electrostatic energy were not permitted. In the case of noncompliance, waivers were processed. During final flight preparations, a walk-around inspection of the spacecraft was performed by an ESD specialist to verify compliance. In addition to the efforts for surface ESD concerns, there was also significant activity in understanding and characterizing internal ESD.

6.6 ATOMIC OXYGEN

The exposure to atomic oxygen for Cassini is very limited due to the Titan 4B launch profile that was used. This profile placed Cassini into an interplanetary trajectory immediately after launch, with minimal exposure to the atomic oxygen environment in earth orbit.

6.7 CONTAMINATION

The design requirements for Cassini [3] included provisions that all external surfaces be cleanable with isopropyl alcohol, that a science purge of clean gaseous nitrogen be provided to specific contamination sensitive science instruments, that flight assemblies withstand a 100% helium concentration for 11 hours in the case of a launch attempt abort, and that hardware potentially exposed to propulsion subsystem exhaust plumes be evaluated.

To protect and maintain cleanliness of surfaces, tanks, and optics during launch preparations and flight, several spacecraft design features were added including: dust covers on the science instruments, a GN2 purge of the science instruments and selected engineering subsystems, plume shields , and flash heaters on some science hardware. Also, a rigorous contamination control program was implemented for the Assembly Test and Launch Operations (ATLO) activities [15].

As part of the Cassini Contamination Program, hardware was baked out prior to system level integration to reduce the possibility of molecular contamination on critical surfaces during system level solar thermal vacuum testing and subsequent flight. Throughout the program, test and analysis assessments were performed as needed.

In flight to date (January, 1999), no contamination issues or concerns have been noted [16, 17].

7.0 TRANSPORTATION ENVIRONMENTS

Design requirements for shipping and handling of Cassini hardware were provided [3]. These requirements were satisfied by restricting the hardware to controlled environments and shipping in approved containers using approved transportation methods. In addition for spacecraft transport, temperature, humidity, and acceleration were measured continuously.

At Cape Canaveral, the spacecraft was transported from the Payload Hazardous Spacecraft Facility (PHSF) at the Kennedy Space Center where final spacecraft integration and test occurred to Launch Complex 40 at the Cape Canaveral Air Force Station for integration with the launch vehicle. The humidity and temperature as well as acceleration experienced by the spacecraft during the transports to and from the launch complex are give in Tables 14a and 14b. The measurements made during the Cape Transport were well within the design limits for the hardware.

Table 14a. Cassini Transport Temperature Humidity Results at Cape Canaveral
(Courtesy of T. Zavala)

Date	Itinerary	RH %	Range Temperature °C	Duration h
8/27/97	PHSF to LC40	33 to 42	20 to 23	5.5
9/7/97	LC40 to PHSF	33 to 44	23	1.8
9/15/97	PHSF to LC40	37 to 44	19 to 25	2.5

Table 14b. Cassini Transport Acceleration Results at Cape Canaveral
(Courtesy of T. Zavala)

Date	Itinerary	Quasi Steady Static Acceleration	Vibration
8/27/97	PHSF to LC40	±.25 g(p-p) @ 2.5 Hz	$4x10^{-5}g^2/Hz$
9/7/97	LC40 to PHSF	±.25 g(p-p) @ 2.5 Hz	$4x10^{-5}g^2/Hz$
9/15/97	PHSF to LC40	±.25 g(p-p) @ 2.5 Hz	$4x10^{-5}g^2/Hz$

8.0 LESSONS LEARNED

The Cassini environmental program extended throughout the spacecraft's development phase of 8 years, and represents approximately 85 work years of effort. During this period, some tasks were performed 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 can be applied to the aerospace industry.

Lessons we learned in several disciplines included: dynamics, thermal, electromagnetic compatibility, magnetics, electrostatic discharge, natural space environments, and programmatic issues. The recommendations presented are those of the authors.

8.1 DYNAMICS

8.1.1 Force Limiting

The dynamics test program for some of the Cassini hardware utilized dual control of acceleration and force in random vibration tests in order to mitigate the artificial resonances and high responses which occur in conventional vibration tests. The force limiting approach is described in the Scharton and Chang technical papers [6-8]. This innovative technique resulted in the performance of more realistic vibration tests on Cassini hardware and in significant cost avoidance by being able to perform tests that did not cause test induced damage that would have led to expensive redesigns. Specific hardware to which this was applied include: Cassini Visible and Infrared Mapping Spectrometer, Cosmic Dust Analyzer, Radioisotope Thermoelectric Generators, Imaging Science Subsystem, Propulsion Module Subsystem, Radio and Plasma Wave Science, as well as the flight spacecraft. The dual control approach is being adopted throughout the US aerospace industry as the technique of choice for performing random vibration on complex instruments and engineering subsystems and spacecraft.

Recommendation: Force limiting control methods should be applied during the random vibration testing of any hardware that has the potential for damage from artificial resonances and unrealistically high responses if conventional vibration tests were performed.

8.1.2 High Gain Antenna Paint Fleck Problem

Late in the Cassini spacecraft test program, it was discovered that the spacecraft's protoflight model High Gain Antenna, which was used for system level environmental testing, had a problem that its paint produced flecks during vibration, particularly acoustic testing. If this happened on the flight antenna during launch, these flecks had the potential to settle on the apertures and sensing surfaces of detectors and instruments and introduce errors, or reduce resolution. The antenna contamination problem had several potential design solutions that could have been pursued if the problem had been observed much earlier. These included specifying another paint, improving the paint application process, and installing more aperture covers. Specifying another paint was difficult due to the limited choices of paints available that meet the natural space environment and the RF transmission requirements. Further development and testing would have been necessary to improve the paint application process, and installing ejectable covers to all the instruments would have added to the expense and complexity of the spacecraft.

The flight High Gain Antenna did not exhibit the paint shedding characteristics of the protoflight model antenna. No evidence of flaking has been observed in flight. [16, 17]

Recommendation: The process for selecting and applying space qualified paints to surfaces must be established early and carefully reviewed, especially when there are new combinations of materials being used.

8.1.3 Facility Preparedness:

During the Cassini system level random vibration test, there was a problem with the shaker amplifier. When the amplifier was run to full power, a cascade of transistors would fail, destroying a large portion of the amplifier. It took several weeks to determine the cause of the problem, and the completion of the random vibration test was severely threatened. Fortunately, the problem was resolved and the test successfully completed.

The amplifier used for the Cassini random vibration test was approximately 15 years old. The amplifier has not been used to run a test requiring as much power as the Cassini test since the Galileo spacecraft sine vibration testing in 1985.

A few weeks prior to running the Cassini test, the shaker was tested with a set of weights, and ran to the same power as the Cassini test was to use. The shaker shut down with a large bang, and the amplifier had a cascade of transistors fail. Several attempts to repair the amplifier resulted in the same failure upon running at full test levels. The cause of the failure was finally attributed to a capacitor in the transistor balancing circuit that had drifted over time to a new capacitance.

Recommendation: The lesson learned is that laboratory equipment can degrade over time. If there is critical test equipment that has not been used recently to the required test level, it should be tested to that level far enough in advance of the test, so that the cause of the problem can be identified and fixed before the test needs to be performed. A large margin of time should be allotted for facility problem identification and repair to be sure that the test schedule will not be adversely impacted by a facility problem.

8.2 THERMAL

8.2.1 Thermal Development Testing

The Cassini flight spacecraft completed a very successful Solar Thermal Vacuum Test at JPL in early 1997. All objectives were accomplished within the allocated scheduled time with minimal surprises. There were no post hardware modifications required, only changes to a few operational constraints and temperature requirements. The success of this program can be attributed to accurate temperature prediction modeling based on an extensive thermal development testing program. The thermal analysts identified problem areas early in the hardware design cycle, planned and implemented development tests to address their concerns, and then revised the designs and the thermal models as appropriate.

Recommendation: Early thermal development testing should be implemented on spacecraft programs that require robustness in their thermal designs to accomplish their planned missions. This supplements the system thermal vacuum test program and helps avoid costly redesigns late in spacecraft development program.

8.2.2 Spare Laboratory Equipment

The Cassini system level Solar Thermal Vacuum (STV) test was affected by the reliability and the low level of spare xenon arc lamps for simulating solar radiation. The space simulation chamber can use a total of 37 lamps which will create about 2.2 suns at full power. The lamps are long lead items, even if a premium is paid, and could not be replaced on demand.

During the checkout of the chamber, one lamp exploded and destroyed several more lamps in its vicinity. New lamps were ordered, but their rate of delivery was not sufficient to provide enough lamps for 2.2 suns, and enough margin to ensure that the test could be completed.

The test levels were reduced to 1.6 suns. This allowed for fewer lamps to be used. Each lamp was also used at a lower power setting, which reduced its chances of failure. If a lamp failed, the power to the remaining lamps could be increased to maintain the same solar intensity.

Recommendation: The lesson learned is that more lamps should be available as spares at the beginning of an STV test.

The lesson learned can also be expanded to any environmental test that contains laboratory equipment of questionable reliability. Spacecraft programs are generally very expensive, and dwarf the expense of spare laboratory equipment. It is prudent to have a large inventory of spare laboratory hardware to be certain that a test will be completed. Incomplete or reduced scope tests add risk to a mission by not ensuring the spacecraft meets that environmental requirements.

For future programs it is necessary that the Environmental Test Lab personnel identify laboratory hardware that should be backed up by an inventory of spare parts. Also, it is necessary for project management to recognize that these spare parts are important to the program and fund the purchase of these parts well in advance of the test.

8.3 ELECTROMAGNETIC COMPATIBILITY AND MAGNETICS CONTROL PROGRAMS

8.3.1 Early Characterization of Hardware Designs

Comprehensive and rigorous electromagnetic compatibility and magnetics control programs were planned and implemented for the Cassini spacecraft. Early in the Cassini development phase, the requirements were explained and interpreted for the hardware engineers. Characterization tests were performed on development hardware (breadboards or engineering models) and changes in designs (such as wiring layout or component placement) were suggested. This was early enough in the design cycle that changes could be implemented easily in the flight designs at minimal cost and risk. A specific example is the Cassini Imaging Science Electronics. These electronics had significant magnetic components that would affect the quality of the magnetometer and plasma wave science. As a result of the early characterization testing, a magnetic shield was designed and developed that was placed around the electronics which effectively attenuated the disturbing AC fields but did not disturb the DC magnetics constraints.

Recommendation: Electromagnetic Compatibility characterization of new hardware designs should be performed early in the development cycle.

8.4 NATURAL SPACE ENVIRONMENTS

8.4.1 Single Event Effects Concerns

Single Event Effects are a significant environment that Cassini has encountered in flight, especially single event upsets. This environment had been carefully addressed for all flight designs during the development program, and resulted in numerous application usage decisions as well as some design changes, such as addition of shielding or of revisions to flight software error detection and correction algorithms. Despite these notable efforts, the flight team observed that the double bit error rate for the Solid State Recorder was higher than expected shortly after launch. After an investigation, it was determined that this problem was related to the detailed layout of the dynamic random access memory chips and their usage in the Solid State Recorder, specifically that a single particle could cause corruption in two bits of a 40 bit word stored in the memory. A flight operations workaround has been implemented.

Another example is for the FETs used in the Command Data Subsystem. The Cassini design engineer decided not to use some internal flip-flops in the piecepart because of possible SEU sensitivity. These parts were subsequently utilized on another project with the internal flip-flop functions activated. The non Cassini application has subsequently experienced in-flight problems attributed to SEUs of these pieceparts.

Recommendation: Design engineers and their peers should carefully review the application of any electronic pieceparts that are suspected of being susceptible to single event effects. The physics of failure are very complicated and the resultant effects in the hardware are subtle and not intuitively obvious. As the interstitial distance within electronic parts become smaller these kinds of spacecraft problems will increase.

8.5 PROGRAMMATIC ISSUES.

8.5.1 System Level Environmental Testing Management

The Cassini system level environmental test program was very complicated. Many issues needed to be resolved "in real time" during the test preparation and implementation period. The program involved several engineering disciplines, and a large number of personnel and a very tight schedule.

The managerial method to keep the system level test program organized and proceeding forward was to have a daily meeting chaired by environmental requirements. Representatives of all engineering disciplines involved were present at the meetings. The progress and plans of each discipline was reported. Conflicts between each discipline were resolved. Action items were assigned to individuals as necessary.

The progress, plans and action items were all recorded in the meeting minutes and sent by e-mail to all the parties involved by the next day. At the following meeting the plans and action items from the previous meeting were reviewed. Completed plans were recorded. Completed action items were noted and removed from the list, new plans were made and new action items assigned.

The Cassini system level environmental test program was a model of good organization of a very complex test program.

Recommendation: Programs that require extensive environmental testing and are on a tight schedule should implement an early management approach that requires attention to implementation detail, problem identification, and timely follow-up.

9.0 CONCLUSION

The Cassini environmental program was based on the philosophy and approach that had been applied to the successful Voyager and Galileo [18] outer planet projects. There were several new environments that had to be addressed, including possible helium exposure from the Centaur upper stage; multiple radio frequencies associated with the different receivers and transmitters; and new classes of Single Event Effects such as Single Event Gate Rupture, Single Event Latchup, Single Event Transients. Many of the environmental design requirements were more severe than those applied to Galileo, such as the gamma and neutron radiation environments, micrometeoroids, and solar intensity (e.g. 0.6 AU to 10 AU for Cassini versus 0.69 AU to 5 AU for Galileo).

A rigorous assembly-level test program was performed on the hardware, 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 effects. The conclusion is that the environmental program implemented on Cassini satisfied the spirit and intent of the requirements imposed by the project during spacecraft development. There are numerous lessons to be learned from an environmental program as extensive as this one that can significantly benefit faster, better, cheaper flight projects. Several of these lessons have been presented with specific recommendations for consideration for new projects. If these lessons are addressed early and aided by sufficient resources from the projects, continued improvements in reliability and cost effectiveness of the environmental programs can be expected outcomes.

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