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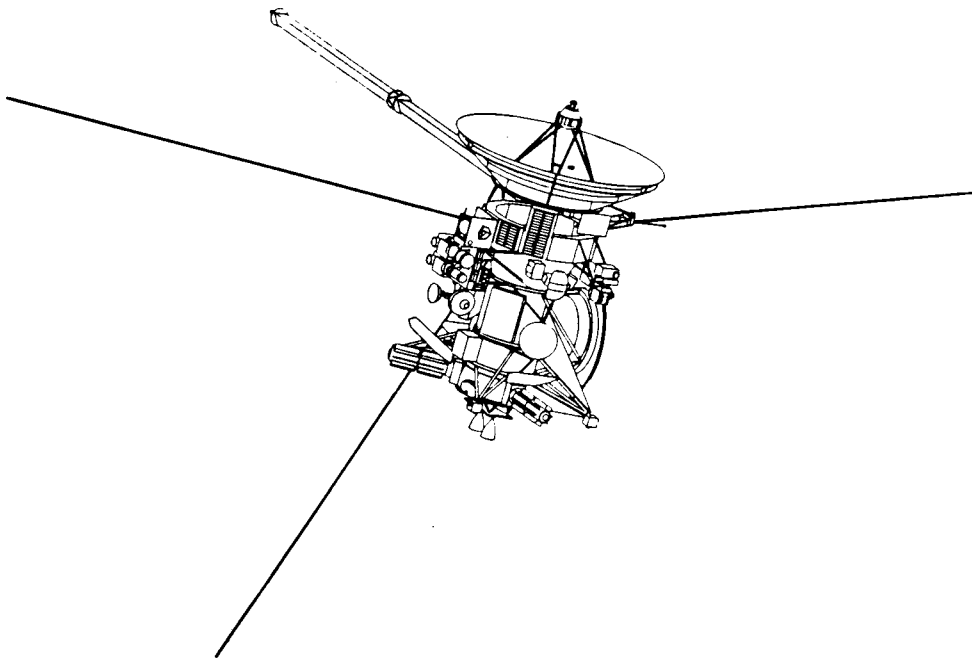
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Cassini Program Environmental Impact Statement Supporting Study

Executive Summary



November 18, 1993



Jet Propulsion Laboratory
California Institute of Technology

PREFACE

The National Aeronautics and Space Administration (NASA) is preparing an Environmental Impact Statement (EIS) for its Cassini mission to the planet Saturn. To support the EIS, the Cassini Project office at the Jet Propulsion Laboratory (JPL) has compiled three volumes of technical information on the Cassini Program. Volume 1 describes the baseline Program, including spacecraft, launch vehicle, and mission design. Volume 2 assesses potential alternative mission and spacecraft power designs. Volume 3 assesses the probability of inadvertent spacecraft reentry into the Earth's atmosphere after injection onto an Earth-escape trajectory and describes the strategies used by the Project to minimize that probability. This Executive Summary provides an overview of the information contained in Volumes 1, 2, and 3.

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SECTION 1

SUPPORTING STUDIES VOLUME 1: PROGRAM DESCRIPTION

1.1 EXPLORING THE SATURNIAN SYSTEM

The planet Saturn has intrigued Earth-bound observers for centuries. Saturn is more than nine times as distant from the Sun as our home planet. Its intricate rings, stormy skies, and variety of icy moons are believed to have changed little since the birth of the solar system. Saturn's largest satellite, Titan, is slightly larger than the planet mercury and is the only moon in our solar system with an appreciable atmosphere. Photochemical reactions in Titan's nitrogen-rich skies obscure an unknown surface that may be at least partially covered by oceans of organic molecules. A detailed study of this moon may provide clues to the solar system's evolution and how life began on Earth.

The Cassini mission to Saturn will conduct long-term, detailed explorations of the Saturnian system, following up on the findings of the Pioneer 11, Voyager 1, and Voyager 2 Saturn flybys of 1979, 1980, and 1981, respectively. Conducted jointly by NASA, the European Space Agency (ESA), and the Italian Space Agency (ASI), Cassini will perform a four-year close-up study of Saturn, its rings, magnetosphere, and moons, with an emphasis on Titan. This exploration strategy is similar to the Galileo mission to Jupiter, using an orbiter and a parachuted probe.

1.2 THE CASSINI MISSION TO SATURN

1.2.1 The Trajectory

The baseline Cassini mission is scheduled to begin with an October 6, 1997 launch on a Titan IV Solid Rocket Motor Upgrade (SRMU)/Centaur launch vehicle from the Cape Canaveral Air Force Station in Florida. The spacecraft will follow a 6.7-year path using a Venus-Venus-Earth-Jupiter-Gravity Assist trajectory (or VVEJGA), traveling twice by the planet Venus in April 1998 and June 1999, once past Earth in August 1999, and then by Jupiter for a final gravity assist in December 2000 before proceeding on to Saturn (Figure 1-1). This roundabout course is designed so that each time the spacecraft swings by a planet, it gathers more speed and receives the change in direction needed to achieve the next leg of the trajectory.

1.2.2 The Science

After entering into orbit around Saturn in June 2004, the spacecraft will approach Titan in November 2004. About three weeks before arriving at Titan, the spacecraft will release ESA's Huygens Probe. Delivery of the Probe is essential to an investigation of Titan's surface structure, as well as the chemical composition of and energy exchanges within its atmosphere. The Probe will collect data during its 2.5-hour descent. The Orbiter's radar will penetrate Titan's atmosphere to image its surface, just as the Magellan spacecraft did at Venus. (Because Titan is enshrouded by dense clouds, little is known about its surface topography or physical composition.)

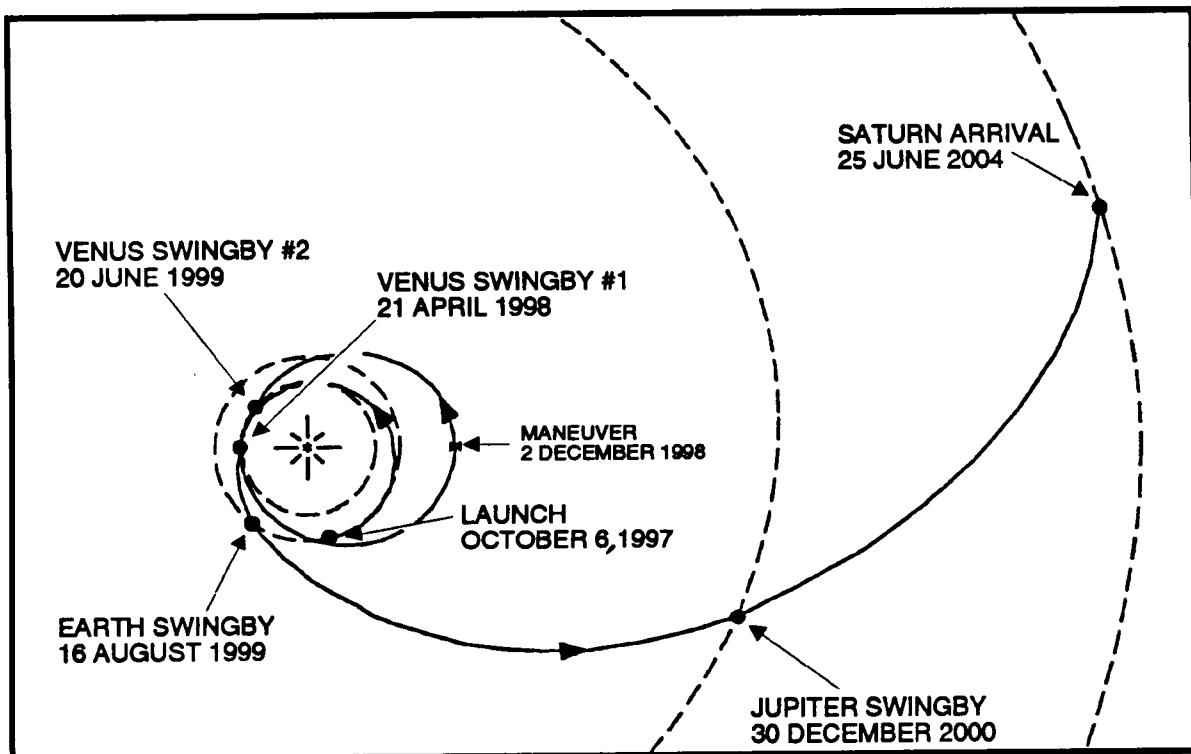


Figure 1-1. Cassini Interplanetary Trajectory, October 1997 VVEJGA

Saturn's other moons are ice-covered bodies. Multiple swingbys on differing orbits will allow researchers to collect extensive science data on these icy moons. Cassini will examine their physical characteristics and investigate their geological histories. of particular interest is the half-dark, half-light moon, Iapetus. The light side of this moon is believed to be composed of ice; the dark side possibly of organic material. Cassini's findings may shed light on the nature of dark material observed on other bodies such as comets, asteroids, and Phobos and Deimos, the moons of Mars.

The Voyager observations proved Saturn's ring system to be more complex than previously realized. However, little is known of how Saturn acquired and organized the orbital debris comprising these rings. Cassini will permit detailed studies of the ring system structure, its composition and its interactions with Saturn's magnetosphere and satellites.

Saturn's magnetosphere is that region of space influenced by the planet's magnetic field. Cassini will carry instruments to study the magnetospheric environment and its influence on Saturn's satellites and rings. These investigations may help to explain the interaction between planetary material and radiation in the early solar system.

Objectives for the above-mentioned science investigations are summarized in Volume 1, Table 3-1.

1.2.3 Secondary and Backup Missions

In the event Cassini is unable to launch as scheduled in October 1997 due to a malfunction, inclement weather, or some other circumstance, two alternative-launch missions have been identified. Since the release of the supporting studies, a secondary mission using a December 1997 launch date and a Venue-Earth-Earth-Gravity-Assist (VEEGA) trajectory with an 8.8-year trip to Saturn has been defined. The backup mission, which could be launched in March 1999, would also use a VEEGA trajectory, but would take 9.8 years to reach Saturn. The secondary and backup missions would arrive at Saturn in 2006 and 2008, respectively. Either arrival date would present a less scientifically advantageous geometry of Saturn's rings in relation to both the spacecraft and the Earth. These missions would also have degraded science return due to the effect of their longer duration on the power output from the RTGs. The later arrival dates would also entail programmatic impacts in terms of increased cost and the ability to sustain U.S. agreements with Cassini's international partners.

1.3 THE CASSINI SPACECRAFT AND LAUNCH VEHICLE

1.3.1 The Spacecraft

The Cassini spacecraft (Figure 1-2) consists of an Orbiter and the Huygens Titan Probe. With a full fuel load and the launch vehicle adapter, the mass of the Orbiter and Probe approaches 5824 kg (nearly 12,840 lb) and will be the largest interplanetary vehicle ever launched from Earth. The main body of the Orbiter is in a cylindrical shell housing the propellant tanks on top of this structure in a 12-sided "bus" containing the spacecraft's electronics and the high gain antenna.

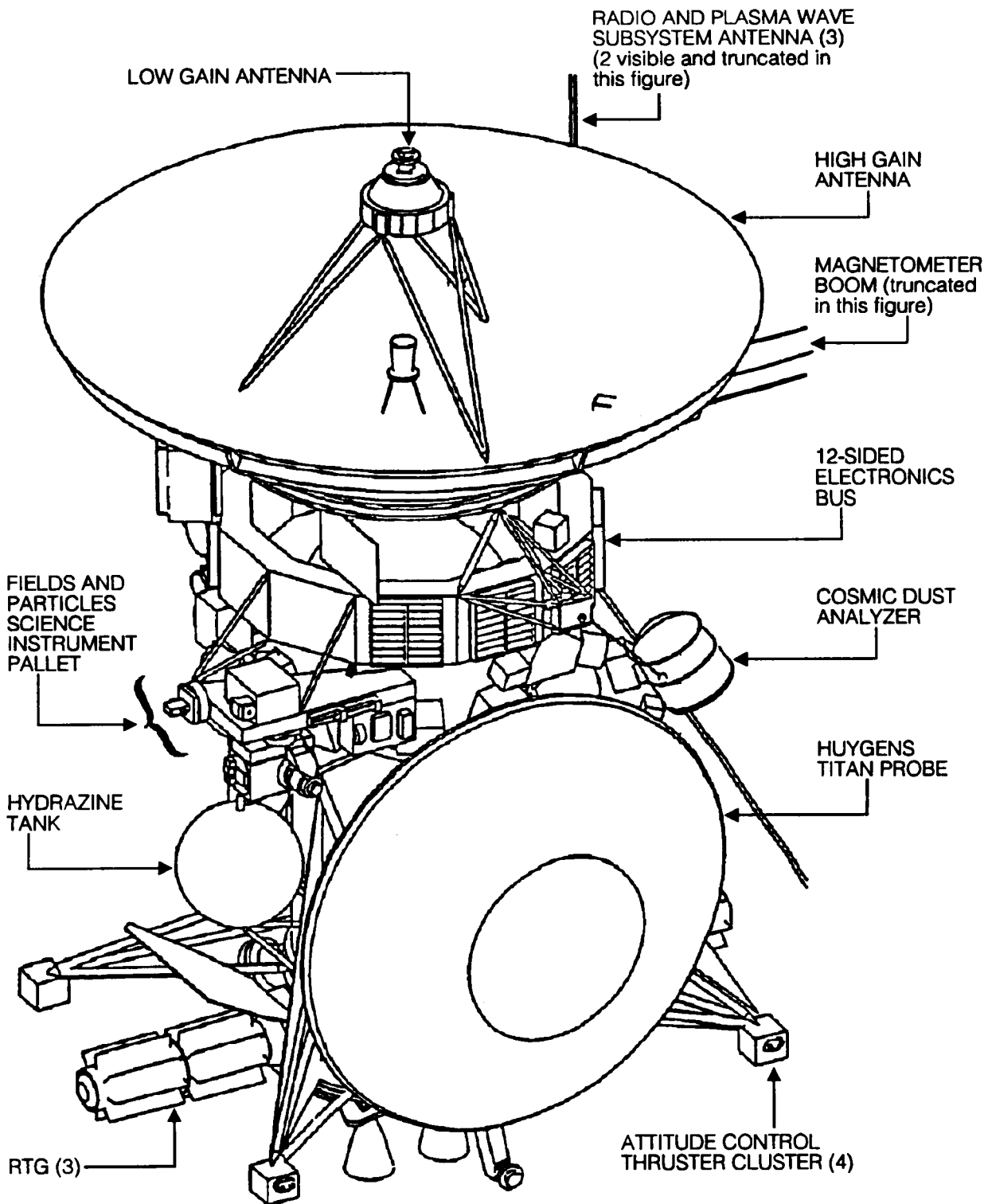


Figure 1-2. View of the Cassini Spacecraft

Suspended from the bottom of the Orbiter are two liquid propellant rocket engines. Science instruments, attitude control thrusters, and the Huygens Probe are externally attached to the Orbiter's main body. of all the elements on the Cassini spacecraft, those most relevant to assessing potential environmental impacts in the unlikely event of a severe launch accident or inadvertent reentry during an Earth swingby are the Radioisotope Thermoelectric Generators * (RTGs) and the Radioisotope Heater Units ** (RHUs).

Among the factors considered when selecting a spacecraft power source are safety, reliability, durability, and availability. After weighing all the requirements, three RTGs have been selected as the power source best suited for the baseline Cassini spacecraft. Each RTG is fueled with approximately 10.8 kg (24 lb) of the plutonium dioxide fuel form. (Only about 80 percent of the fuel is Pu-238 dioxide at launch.) These power sources are rugged, compact, dependable, and have been used safely for three decades of planetary exploration.

Aboard Cassini, RHUs will be essential for many of the components to survive the frozen reaches of the outer solar system. Filled with about 2.7 g (0.006 lb) of plutonium dioxide fuel form, each RHU will produce one thermal watt of heat. They will be located near spacecraft components that must be kept above a certain temperature to operate properly. The Cassini Orbiter and the Huygens Probe together will use approximately 157 of these RHUs.

1.3.2 The Launch Vehicle

The baseline Cassini launch vehicle is the Titan IV Solid Rocket Motor Upgrade (SRMU)/Centaur. This unmanned launch system (Figure 1-3) consists of a core vehicle, two solid rocket motors, the Centaur upper stage, and a payload fairing. The core vehicle, a two-stage liquid propellant rocket, has one SRMU attached to each side. The Centaur upper stage is held atop the core vehicle by an adapter, and supplements the Titan IV in lifting the spacecraft into Earth orbit. After the spacecraft has reached its optimal position in Earth orbit, the Centaur is restarted, boosting the spacecraft along the first leg of its planned route to Saturn. The Centaur is propelled by two engines fueled by liquid hydrogen and liquid oxygen. The Cassini spacecraft is attached to a structural adapter on top of the Centaur. A payload fairing covers both the spacecraft and Centaur upper stage, providing aerodynamic and thermal protection during the ascent to Earth orbit.

* Used to power the spacecraft.

** Used for temperature control.

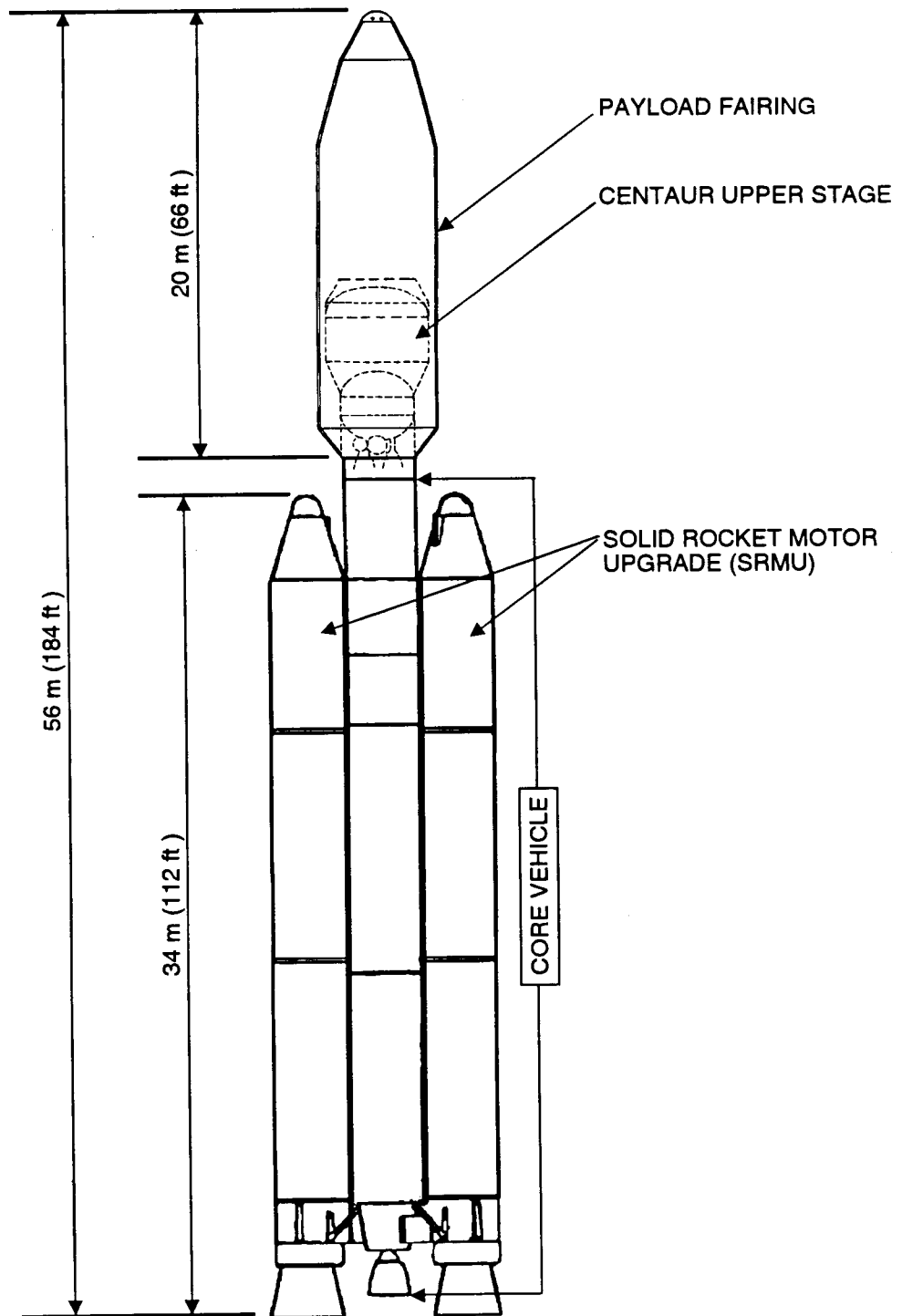


Figure 1-3. The Titan IV (SRMU)/Centaur Launch Vehicle

SECTION 2

SUPPORTING STUDIES VOLUME 2: ALTERNATE MISSION AND POWER STUDY

2.1 METHODOLOGY

The study described in this summary was executed in three stages: 1) identification of alternatives, 2) characterization, and 3) comparison. The first stage, alternative identification, involved selecting the mission and power options satisfying the following three criteria. First, the alternatives had to be capable of achieving the science objectives established for the Cassini mission. Second, they had to have the potential for substantially reducing the possible environmental impact associated with the baseline mission, the principal source of that impact being the potential release of radioactive material from the RTGs in the unlikely event of a severe accident. Third and finally, the alternatives had to be technically feasible to implement within the time frame associated with the baseline mission. Alternatives satisfying all three of these criteria were then carried into the second stage of the study.

In the second stage, characterization, the feasible mission and power alternatives received more detailed analyses in terms of their science- and program-relevant spacecraft and mission characteristics.

In the study's final stage, comparison, the science- and program-relevant spacecraft and mission characteristics of each alternative were used to assess its overall scientific and programmatic impact relative to the baseline mission.

2.2 IDENTIFYING MISSION ALTERNATIVES

As stated above, the principal source of an environmental impact by the baseline Cassini mission would be the potential release of radioactive material from the RTGs in the unlikely event of a severe accident. An attempt was made 1) to identify missions that would eliminate the reentry potential posed by an Earth swingby and 2) to identify power source alternatives to the RTGs. In seeking to identify mission alternatives, the study investigated using three types of trajectories (direct, gravity-assist, and low-thrust) in combination with a multitude of different launch vehicle combinations. These mission and power alternatives are described below.

2.2.1 Direct Trajectories

A highly desirable course for a planetary mission is to travel directly from Earth to the desired planet. Direct trajectories provide relatively short flight times and earlier science return, lower operations costs, less mission complexity, and reduced possibility of a spacecraft malfunction. For Cassini, a direct trajectory would reduce flight time by approximately two to five years and save mission operations costs, relative to various gravity-assist trajectory options. No U.S. launch vehicle currently provides sufficient launch energy to enable a direct trajectory to Saturn for the baselined Cassini spacecraft design. While a

Russian Energia with an appropriate upper stage appears potentially capable of achieving a direct trajectory, insufficient information exists to support evaluation of this launch vehicle as an alternative to the baseline Cassini mission (see Subsection 2.2.2.2).

2.2.2 Gravity-Assist Trajectories

Gravity-assist trajectories use one or more planetary swingbys to increase speed and change a spacecraft's direction. Compared to direct trajectories, gravity-assist trajectories significantly lower the energy needed to launch a spacecraft to another planet from Earth. Pioneer 11, Mariner 10, and Voyagers 1 and 2 used gravity-assist trajectories to change their velocity enough to travel to more than one planet. The Galileo spacecraft flew by Venus once and Earth twice, sending the spacecraft on to a December 1995 arrival at Jupiter.

2.2.2.1 Gravity-Assist Trajectories Using U.S. Launch Vehicles

Performance and availability were the overriding considerations in selecting a feasible candidate from the multitude of launch systems examined in this study. Currently, large planetary missions using U.S. launch vehicles are limited to: 1) the Space Transportation System (STS) with an Inertial Upper Stage (IUS), or with an IUS and a Payload Assist Module-Special (PAM-S); 2) the Titan IV Solid Rocket Motor (SRM)/Centaur; and 3) the soon-to-be-available Titan IV Solid Rocket Motor Upgrade (SRMU)/Centaur. All of these launch systems are currently in existence, with the exception of the Titan IV (SRMU). The SRMU program is funded for system development, which satisfies the feasibility requirements for technology readiness. When available, the Titan IV (SRMU)/Centaur will be the most capable U.S. launch system for planetary missions. The requirement to consider only those launch vehicles that exist or are on a firm development schedule eliminated the Upgraded and Single Engine Centaurs and any other "now booster concepts" from further consideration.

2.2.2.1.1 The March 1996 VVVJGA Alternate Mission

The March 1996 VVVJGA mission would launch more than 1-1/2 years earlier than the baseline and arrive at Saturn in July 2005, more than a year later than the baseline. Accelerating development consistent with this earlier launch date would require the support of BSA and ASI. It is likely that several instruments would have to be dropped from the spacecraft, as they could not be completed in time to meet the earlier launch date. The spacecraft would also have less testing time, which would increase development risk. Accelerated spacecraft hardware deliveries would result in contract cost increases: while these cost increases have not been quantified, JPL has concluded that the earlier launch would not reduce development costs below the total development costs for the 1997 mission. In particular, significant spending increases in FY 1994 through FY 1996 would be required. Also, the 9.4-year flight time (compared to 6.7 years for the baseline mission) would increase mission operations costs by approximately \$30 M per year, a total of \$81 M (FY 1993 dollars).

In general, Saturn system science return from this alternative would probably be similar to that anticipated from the baseline. However, the later arrival date corresponds to a Saturn ring orientation that is increasingly edge-on relative to the Earth and Sun. This edge-on orientation allows less sunlight to illuminate the rings and interferes with spacecraft-to-Earth signals probing the rings' structure. These effects lead to somewhat degraded optical and radio observations of Saturn's rings. Saturn system science would also be degraded by the effect of the longer mission duration on the power output from the RTGs. As the RTG thermoelectric and fuel degrade with time, the power available for simultaneous science instrument observations diminishes.

The VVVJGA mission also involves the heightened possibility of spacecraft malfunctions relative to the baseline, a result of the longer cruise time's prolonged exposure to risks inherent in the space environment and the increased wear on spacecraft components. Even though the VVVJGA trajectory does not entail an Earth swingby, there is a remote possibility that the spacecraft could eventually reencounter the Earth if the spacecraft becomes uncommandable before Saturn orbit insertion (SOI) and embarks on an Earth-crossing orbit around the Sun.

The March 1996 alternate mission also lacks a timely backup mission. The March 2001 VVGA trajectory (described below as an alternate mission) would have to serve as the backup mission, but would necessitate storage of the spacecraft and maintenance of Cassini personnel for several years. There are, on the other hand, a number of trajectories utilizing Earth swingbys which were considered as backups for the current baseline VVEJGA mission and launch as little as six months after the baseline. However, such Earth swingby backups would not constitute environmentally significant alternatives.

2.2.2.1.2 The March 2001 VVGA Alternate Mission

This mission would launch in March 2001 and arrive at Saturn about 10.4 years later. However, once at Saturn, the spacecraft's propellant would be depleted before Cassini's complete science objectives and investigations are fulfilled. This fact emphasizes the marginal nature of this mission as an alternative to the baseline or as a backup to the March 1996 VVVJGA alternate mission. Similar to the VVVJGA trajectory, using a VVGA trajectory entails the remote possibility of reencountering the Earth if the spacecraft becomes uncommandable before SOI. Furthermore, no potential non-Earth gravity-assist backups to the March 2001 VVGA alternate mission have been identified.

A number of measures would have to be taken to reduce the propellant requirements and make the March 2001 VVGA alternate a usable mission. A combination of trimming spacecraft mass and trajectory adjustment would probably allow a Titan IV (SRMU)/Centaur to provide sufficient launch energy to accomplish the mission. However, the mission would not be possible with a Titan IV (SRM)/Centaur. In any event, this alternative would have little resiliency to unexpected increases in spacecraft mass or reductions in launch system performance. Due to the longer mission duration associated with the VVGA, the RTGs would experience more power degradation than the baseline.

The WVGA's 2010 arrival date also entails, for the first year or so of the tour, a degradation in ring science similar to the last year of the baseline tour. This later arrival date would also entail programmatic impacts such as those mentioned in relation to the backup mission.

The delayed launch (more than three years) and greatly extended duration (10.4 years) of this mission alternative would have a significant impact on overall development and mission operations costs. Assuming that the spacecraft was developed on the established 1997 baseline schedule, it would then be placed in storage to wait until the 2001 launch opportunity, at a cost of \$2 M (FY 1993 dollars) per year, for a total cost of roughly \$6 M (FY 1993 dollars). Additional testing following removal from storage and preparation for launch would cost an estimated additional \$75 M (FY 1993 dollars).

2.2.2.2 Gravity-Assist Trajectories Using the Russian Energia

When examining non-U.S. launch vehicles, the Russian Energia, given the appropriate upper stages, appeared potentially capable of sending Cassini to Saturn on a Jupiter gravity-assist trajectory. Such a trajectory could provide several advantages over the baseline mission, such as eliminating an Earth swingby, reducing flight time, and decreasing cruise operations costs. However, detailed technical information on Energia is not yet available to accurately evaluate its feasibility as a Cassini launch vehicle. Energial's very brief flight history calls into question the long-term reliability and availability of this system. Only two Energia launch vehicles have flown, and the upper stage failed on one of them. There have been no Energia flights for nearly five years.

When considering the above-noted items, as well as existing U.S. policy concerning the use of Russian launch vehicles, too many questions remain unanswered about the Russian Energial's performance capabilities and reliability for it to be deemed a feasible Cassini mission launch vehicle option. Pending further developments, this launch system may become technically "potentially feasible". Accordingly, a detailed comparison with the baseline is currently not practical due to insufficient information.

2.2.3 Low-Thrust Trajectories

Systems capable of producing low-thrust trajectories (solar electric propulsion, nuclear electric propulsion, solar thermal propulsion, solar sails, etc.) have been extensively studied over the last 30 years, but have not yet been developed for interplanetary flight. Of these systems, solar electric propulsion (SEP) is the most mature and best understood. The development of SEP technologies does not conform to the baseline time frame. Moreover, the SEP option cannot satisfy all of the spacecraft's propulsion and power requirements at Saturn; because of Saturn's distance from the Sun, an SEP option would still require chemical propulsion and radioisotope power augmentation.

Insert for Cassini Program Environmental Impact Statement Supporting Study,
Executive Summary, after Section 2.2.2.1.2 (p. 2-4).

New Information Regarding The March 2001 VVVGA Trajectory

It has been determined that if Cassini were launched with the Titan IV (SRMU)/Centaur, then the March 2001 VVVGA trajectory would only meet project requirements if the spacecraft used the currently non-space qualified rhenium main engine. A non-Earth gravity assist backup trajectory to the March 2001 VVVGA could only be possible if Cassini used a more powerful launch system than the baseline. However, VEEGA trajectories periodically are available as backups to the March 2001 VVVGA. There are a number of concerns with respect to the March 2001 VVVGA, and these are discussed in Volume 2.

2.3 IDENTIFYING POWER ALTERNATIVES

To the extent that an environmentally meaningful alternative to Cassini's baseline power system is one that would reduce or eliminate the risk of plutonium release in the unlikely event of a severe accident, such reduction could be achieved by: 1) substituting another, less potentially hazardous substance for the plutonium in the RTGs, 2) developing designs using less plutonium, 3) using a nuclear reactor, or 4) using a nonnuclear power source.

2.3.1 Substituting for Plutonium

Two possible alternatives to plutonium-238 as a radioactive heat source for RTGs include strontium-90 and curium-244. A careful examination of each isotope's properties and production requirements revealed that neither constitutes an environmentally significant alternative. Both pose extensive gamma and/or neutron radiation hazards to the spacecraft and would require extensive shielding. In addition, neither can be produced with currently available facilities.

2.3.2 Using Less Plutonium

If a mission could be accomplished using less plutonium, the potential environmental hazard associated with an accident would be reduced. A variety of alternative static and dynamic power conversion systems using less plutonium to generate the same amount of electrical power have been examined (e.g., alkali metal thermoelectric conversion, thermophotovoltaics). All of these alternative power systems, however, manifest serious technology issues that cannot be resolved in time to benefit the Cassini mission.

2.3.3 Using a Nuclear Reactor

From an environmental risk standpoint, nuclear reactors offer an advantage in that they can be launched "cold", or in a non-operating mode. Before activation, the inventory of environmentally detrimental fission by-products is very small. However, reactors of the size and operating lifetime suitable for Cassini do not exist and are not under development.

2.3.4 Using a Non-Nuclear Power Source

Fuel cells, the power source for the STS Orbiter, have never displayed the operational life needed for planetary missions. Also, the mass of storage batteries needed to power Cassini greatly exceeds current launch vehicle lift capabilities.

Only solar photovoltaic arrays exhibit potential compatibility with Cassini's power and operational needs. This compatibility is questionable because Cassini's period of largest power demand occurs when it is between 1.34 and 1.38 billion kilometers (between 9.0 and 9.3 AU, or 840 and 865 million miles) away from the Sun. At these great distances, sunlight intensity is only about one percent of what it is at the Earth. To the extent that new, gallium arsenide Advanced Photovoltaic Solar Array (APSA) technology might lead to arrays of a reasonable mass despite this

low sunlight intensity, all-solar spacecraft point designs incorporating the technology (described below) were carried out to investigate solar array compatibility with Cassini's power and operational needs.

2.4 ALL-SOLAR DESIGN INVESTIGATIONS

Because solar photovoltaic arrays exhibited a possible compatibility with Cassini's power and operational needs during the identification phase of the study, the characterization phase involved development of a detailed all-solar point design. The point design sought to retain as much science as possible, in accordance with this study's science objective satisfaction criterion. In keeping with this philosophy, the all-solar design was developed with turntables and scan platforms to offset the extremely long turn times that would result from the required array size. The design's solar arrays were determined to encompass 598 square meters (about 6430 square feet), with an associated spacecraft mass increase of over 1337 kg (2948 lb), greatly exceeding launch vehicle mass constraints. The all-solar Cassini would utilize four wings, each five times the size of a Hubble Space Telescope wing. The deployment of these large, massive spacecraft appendages adds considerable risk to the mission as compared to the baseline, for which deployment of the RTGs is not required. Even after incorporating this greatly increased mass and risk, the associated spacecraft design failed to manifest mission and performance characteristics capable of satisfying Cassini's minimum science objectives.

Several variations on this all-solar design were then developed with the goal of reducing the mass of the solar arrays. These variations included combining RTGs with solar arrays, using concentrators to focus sunlight on the arrays, and solar propulsion technologies. All of these options involved considerable technical complexity, increased cost, and elevated risk, as well as diminished science return.

Another point design aimed at mass reduction was then undertaken. In this version, instruments were fixed to the body of the spacecraft rather than being mounted on turntables and scan platforms, thereby reducing mass and required power at the expense of subjecting instrument observations to the constraint of array-induced, increased turn times. The resulting science impacts included:

- (1) increased times for image mosaics,
- (2) inadequate turn rates for fields and particles instruments,
- (3) reduced image resolution due to inadequate target motion compensation,
- (4) lose of instrument observation time during turns for communicating with Earth, and
- (5) insufficient turn rates to support radar observation of Titan's cloud-enshrouded surface.

To further reduce array size and corresponding spacecraft mass, power to the instrument complement was cut by 50 percent -- a reduction that leads to an even greater sacrifice of science return. Nevertheless, the total spacecraft mass, including the launch adapter and propellants, still exceeded launch vehicle mass constraints by about 59 kg (130 lb). Only by disregarding launch vehicle contingency margins and reserves was it possible to meet launch vehicle mass constraints. However, discounting launch vehicle contingency margins and reserves cannot realistically be done - past experience has repeatedly demonstrated that such margins and reserves are required for a successful mission. While methods for engineering around some of the above science difficulties may exist, these methods will severely exacerbate the mass problems just discussed.

A broad spectrum of mission opportunities and spacecraft configurations, yielding varying levels of science return, lies between the two design points just discussed. Many intermediate scenarios can be postulated that would increase science return at the expense of spacecraft mass. However, since the second design endpoint, with maximum mass reduction at the expense of science, is still at best marginal from a mass standpoint, any alternatives which provide more science at the expense of increased mass would prove even more implausible.

In summary, an all-solar Cassini must be considered infeasible at this time because:

- 1) No U.S. launch vehicles exist to launch the large mass of even the lightest solar configuration required, and
- 2) Even if a heavy-lift booster were used, there would still be severe limitations on spacecraft motion, instrument field-of-view, and programmatic risk that would make this option scientifically untenable.

Insert for Cassini Program Environmental Impact Statement Supporting Study, Executive Summary, after Section 2.4 (p. 2-7).

PURPOSE

This insert is to update the November 1993 Cassini Program Environmental Impact Statement Supporting Study Executive Summary. In 1994, the June 1993 version of Volume 2 of the Cassini Supporting Studies was updated. This current version of Volume 2 addresses a number of additional potential launch system alternatives. The Office of Science and Technology Policy (OSTP) and the Office of Management and Budget (OMB) requested that NASA investigate for the Cassini mission additional potential launch system alternatives, and the possibility of reducing mission operations and data analysis costs. To comply with this request, early in 1994 the Jet Propulsion Laboratory (JPL) and Lewis Research Center (LeRC) provided NASA with feasibility evaluations of a number of additional potential launch system alternatives for the Cassini mission. The potential launch system alternatives that were investigated included:

- Two launches of the Space Transportation System (STS) with-an upper stage and spacecraft/upper stage assembly on-orbit.
- Ariane 5 with Centaur I IA upper stage.
- Proton-M with Block 'D' + Star 63F upper stages.
- Split mission using two Proton launches, sending two smaller orbiters (one carrying the Huygens probe) to Saturn.

In addition to the information addressed in the June 1993 version, this version addresses the above mentioned potential launch system alternatives, as well as updating information on the Russian Energia launch vehicle.

SCOPE OF LAUNCH SYSTEMS DISCUSSION

Volume 2 describes the above mentioned potential launch system alternatives: the boosters and upper stages; the enabled trajectories to Saturn; the technical feasibility; the expected science return; and the concerns that surround using each launch system for the Cassini mission.

SECTION 3

SUPPORTING STUDIES VOLUME 3: EARTH SWINGBY PLAN

3.1 INTRODUCTION

In order to minimize the risk of a release of radioactive material from the spacecraft's RTGs, precautions must be taken to ensure that an inadvertent reentry into the Earth's atmosphere, defined for this report as Earth impact, does not occur in the course of performing an Earth gravity assist (i.e., Earth swingby). The situation is analogous to previous missions where navigation techniques and mission operations were designed to ensure either Earth impact avoidance (Galileo mission to Jupiter) or Mars protection from microbiological contamination (Mariner and Viking missions to Mars).

Design precautions must also be taken to preclude Earth impact resulting from loss of control of the spacecraft during interplanetary cruise. If the spacecraft were to drift in its orbit around the Sun, Earth impact could result decades to millennia later, after many spacecraft revolutions around the Sun.

In order that an accidental Earth impact not be a credible event, the Cassini Project has levied the following design requirement in its Project Policies and Requirements Document:

"Following injection, the probability of Earth impact by the spacecraft shall not exceed 10^{-6} taking into account potential failures."

To satisfy this requirement, an assessment of the Earth impact probability has been performed. The probability of Earth impact is presented as a probability density function (PDF) over the model uncertainty rather than as a worst-case value. The advantage of such an approach is to provide information about the uncertainty of the estimation of an Earth impact probability. The above requirement is interpreted to be that the expected value of the Earth impact probability, from injection to 100 years beyond the nominal Saturn encounter date, shall not exceed 10^{-6} .

Volume 3: Cassini Earth Swingby Plan documents a study that has been performed to determine the necessary actions --- in spacecraft, ground system, and navigation design --- to ensure that the probability of Earth impact satisfies the design requirement. Also included is a quantitative assessment of the probability of Earth impact, including uncertainties in the assessment process. The report serves several useful purposes. First, it develops and exercises the approach to be used in the Earth swingby strategy. This provides an early understanding of the Earth impact probability and enables identification of possible failure modes specific to the baseline spacecraft design. Second, it allows the Project to conduct trades among possible measures that reduce Earth impact probability early in the spacecraft and navigation design process. Third, it demonstrates that the navigation strategy will result in a probability of Earth impact that meets the Project's requirement.

3.2 METHODOLOGY

The Earth impact probability is composed of short-term and long-term components. The short-term component is the contribution resulting from the navigation of the Earth swingbys for a given trajectory; the long-term component is the contribution due to a disabled spacecraft drifting in orbit about the Sun that could reencounter the Earth sometime beyond the nominal Saturn encounter date. For this analysis, the possibility of impact during the first 100 years is considered.

There are a number of failure modes that contribute to Earth impact probability. One objective is to identify these failure modes. Not all failures place the spacecraft on an impacting trajectory nor affect the capability to achieve a successful and safe Earth swingby, and this is taken into account in the probability assessment. An example is the Galileo high gain antenna anomaly that resulted in only a partial deployment of the antenna. This failure did not prevent the precise delivery of the Galileo spacecraft at the second Earth swingby.

In order to keep the short-term impact probability low, a trajectory-biasing strategy is used. During most of Cassini's inner solar system journey, the spacecraft is on a trajectory that, without further maneuvers, would miss the Earth by tens of thousands of kilometers. The spacecraft is not placed on a trajectory passing through the actual Earth swingby point, as close as 500 km, until 10 days prior to the encounter.

A trajectory-biasing strategy selected to control the short-term probability, while affecting the long-term probability, cannot be used to control the long-term probability. Over a long time scale, the impact probability is dominated by third-body perturbations to the spacecraft trajectory and by accidental planetary gravity-assist swingbys. Therefore, the long-term Earth impact probability is controlled by designing the spacecraft and mission operations such that the failure probabilities are low.

Also taken into account is the spacecraft's ability to recover and successfully apply a corrective maneuver after a failure. If a failure does not completely incapacitate the spacecraft, then the normal course of action is to accurately determine the spacecraft trajectory and, if required, command a recovery sequence to modify the trajectory and avoid Earth impact.

The Earth impact probability is evaluated for two trajectories. The first trajectory is the primary VVEJGA trajectory. The second trajectory considered in this study is the backup Venus-Earth-EarthGravity-Assist (VEEGA) trajectory. The launch period for this trajectory is in March/April 1999.

3.3 FAILURE MODE ANALYSIS

In general, all failures can be classified into three categories: environmentally-induced failures, internal spacecraft failures, and ground-induced failures. These types of failures can result in an anomalous AV (spacecraft velocity change) that could place the spacecraft on an Earth impacting trajectory, and a subset of these failures could prevent the spacecraft from being recovered after being placed on an Earth impact trajectory.

Of all the failure modes identified in this study, only micrometeoroid-induced tank rupture is a significant contributor to the short-term Earth impact probability. The spacecraft design does include components to provide protection from micrometeoroids, but there are particles with sufficiently high energies to damage the spacecraft. The rupture of a propellant or pressurant tank will cause an anomalous AV and may cause loss of spacecraft commandability. The contribution to Earth impact probability from all other failure modes is more than one order of magnitude less than that from micrometeoroid-induced failures.

Loss due to spacecraft system internal failures is the dominant failure mode for the long-term Earth impact probability. These failures include design and implementation errors (including common mode failures), electronic parts failures, hardware failures, and software errors.

Ground-induced errors are errors made on the ground by the spacecraft controllers, which are then sent to the spacecraft and executed. Two categories of ground-induced errors are erroneous ground commands and navigation design errors. These potential errors are insignificant contributors to Earth impact probability.

In addition to the potential failures described above that could place the spacecraft on an Earth impacting trajectory, the failures which could prevent the spacecraft from being recovered once it is on an Earth impacting trajectory must be considered. In some cases the same failure that puts the spacecraft on an impacting trajectory also prevents recovery.

For those failures that do not completely disable the spacecraft, additional failures are required to prevent recovery. Until the spacecraft is close to Earth swingby, only new failures that completely disable the spacecraft need to be considered; other failures can be diagnosed and corrected with sufficient time remaining to make another recovery attempt. The primary spacecraft-disabling failures are micrometeoroid hits and spacecraft system internal failures. For initial failures that occur very close to swingby, there is not enough time to detect the failure and take corrective action. Between these two periods, there is an interval before the Earth swingby when there is only time to make one recovery attempt; any subsequent failure is conservatively assumed to abort recovery attempts. The major contributors during this period are ground failures preventing successful execution of a recovery maneuver and a spacecraft failure requiring ground intervention.

3.4 SHORT-TERM EARTH IMPACT PROBABILITY

The primary objective of the navigation strategy between launch and the Earth swingby is to satisfy the Earth impact probability requirement while delivering the spacecraft to the necessary Earth swingby aimpoint. To calculate the probability of Earth impact requires a knowledge of three factors: 1) the failure probabilities and associated AVs, 2) the uncertainties in the navigation process, and 3) the characteristics of the spacecraft trajectory. For the purpose of defining an Earth swingby navigation strategy, steps have been taken to minimize the effect of both failures and navigation uncertainties. The navigation strategy focuses on specifying and controlling the spacecraft trajectory conditions given the failure probabilities and navigation uncertainties.

In general, the impact probability decreases as the swingby altitude increases, so that impact avoidance requirements could be satisfied by simply raising the swingby altitude. However, specific swingby conditions are needed to shape the trajectory and the spacecraft cannot carry sufficient propellant to replace this effect (except possibly for a very small bias). Fortunately, there would be enough propellant to bring the trajectory in towards the Earth in several steps before the swingby.

In order to calculate a PDF for the short-term Earth impact probability it was necessary to perform a Monte Carlo simulation for both the primary and backup mission trajectories. The mean values for the resulting distributions are 2.0×10^{-7} and 6.1×10^{-7} , respectively.

3.5 LONG-TERM EARTH IMPACT PROBABILITY

Short-term impact analysis establishes that the probability of Earth impact during a targeted Earth swingby is extremely small. However, if the spacecraft becomes uncommandable before SOI and does not impact the Earth during a targeted swingby, there is still a remote possibility that long-term perturbations to the orbit could cause the spacecraft to eventually reencounter the Earth. The long-term analysis computes the probability of Earth impact at a non-targeted swingby from the time of spacecraft failure to 100 years beyond the planned SOI date.

The number of torus crossings for all Monte Carlo cases were computed by propagating the initial conditions for each case using a highprecision numerical integration program, and then counting each passage through the Earth torus. For a given torus crossing, Earth-crossing asteroid theory was used to analytically compute the probability of the Earth being in the position required for Earth impact. An uncertainty analysis was performed to yield probability distributions for both the number of torus crossings per case and the probability of Earth impact given a torus crossing. These distributions were combined with the spacecraft failure distribution to yield a PDF for the long-term Earth impact probability.

The mean long-term Earth impact probability for 100 years is 3.7×10^{-8} for the primary mission and 3.6×10^{-7} for the backup. The impact probability is larger for the backup mission due to the longer cruise duration and different interplanetary trajectory characteristics. An important result is that for failures occurring during the latter half of interplanetary cruise on both missions, in nearly all cases, the spacecraft is quickly ejected from the solar system by a strong Saturn gravity assist, thus precluding any possibility of Earth impact.

3.6 EARTH IMPACT PROBABILITY ASSESSMENT

The total Earth impact probability distribution is the probabilistic sum of the short- and long-term Earth impact probability distributions. The expected mean values of these distributions are 2.4×10^{-7} for the primary trajectory and 9.7×10^{-7} for the backup trajectory. Since the mean of both distributions is less than 10^{-6} , the Project's Earth swingby requirement is satisfied for both missions.

Insert for Cassini Program Environmental Impact Statement Supporting Study, Executive Summary, after Section 3.6 (p. 3-5).

The Earth impact probability functions for the baseline and backup missions have been recalculated (see Table 3-1) to account for:

- analyses that could not be completed, by the time Volume 3 (Cassini Earth Swingby Plan) was issued in November 1993, due to insufficient information regarding the Perseid's meteoroid shower. Appendix D in Volume 3 mentions that JPL would complete the Perseid's analyses and incorporate them in the micrometeoroid model.
- modifications and refinements of the models used to predict the velocity increment resulting from one or both bipropellant tanks failing due to a micrometeoroid impact
- a more accurate reliability model that accounts for common and noncommon mode failures

Details concerning the recalculated values can be found in the Cassini Program Environmental Impact Statement Supporting Study, Volume 3.

Table 3-1. Recalculated Earth Impact Probability Density Function Mean Values

Mission	Short-Term	Long-Term	Total
Primary	0.76 x 10 ⁻⁶	0.06 x 10 ⁻⁶	0.82 x 10 ⁻⁶
Backup	0.47 x 10 ⁻⁶	0.40 x 10 ⁻⁶	0.87 x 10 ⁻⁶

Cassini Environmental Impact Statement Supporting Studies

Executive Summary

Volume 1 - Program Description

Volume 2 - Alternate Mission and Power Study

Volume 3 - Earth Swingby Plan

Earth Swingby Plan Supplement