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CHAIRMANSHIP OF THE NEPTUNE/PLUTO OUTER PLANETS SCIENCE WORKING GROUP

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1.0 Introduction

The Outer Planets Science Working Group (OPSWG, formerly NPOPSWG) is the NASA Solar System Exploration Division (SSED) scientific steering committee for the Outer Solar System missions. OPSWG consists of 23 members and is chaired by Dr. S. Alan Stern.

This proposal summarizes the FY92 activities of OPSWG, describes a set of objectives for OPSWG over FY93, and outlines the SWG's activities for subsequent years.

As chair of OPSWG, Dr. Stern will be responsible for: (i) organizing priorities, setting agendas, conducting meetings of the Outer Planets SWG; (ii) reporting the results of OPSWG's work to SSED; (iii) supporting those activities relating to OPSWG work, such as briefings to SSAAC, SSES, COMPLEX, and OSSA; (iv) supporting the JPL/SAIC Pluto study team; and (v) other tasks requested by SSED.

As the Scientific Working Group (SWG) for Jupiter and the planets beyond, OPSWG is the SSED SWG chartered to study and develop mission plans for all missions to the giant planets, Pluto, and other distant objects in the remote outer solar system. In that role, OPSWG is responsible for: (i) defining and prioritizing scientific objectives for missions to these bodies; (ii) defining and documenting the scientific goals and rationale behind such missions; (iii) defining and prioritizing the datasets to be obtained in these missions; (iv) defining and prioritizing measurement objectives for these missions; (v) defining and documenting the scientific rationale for the strawman instrument payload; (vi) defining and prioritizing the scientific requirements for orbital tour and flyby encounter trajectories; (vii) defining cruise science opportunities plan; (viii) providing technical feedback to JPL and SSED on the scientific capabilities of engineering studies for these missions; (ix) providing documentation to SSED concerning the scientific goals, objectives, and rationale for the mission; (x) interfacing with other SSED and OSSA committees at the request of SSED's Director or those committee chairs; (xi) providing input to SSED concerning the structure and content of the Announcement of Opportunity for payload and scientific team selection for such missions; and (xii) providing other technical or programmatic inputs concerning outer solar system missions at the request of the Director of SSED.

2.0 OPSWG Activity Report: FY 1992

OPSWG was chartered as an SSED Science Working Group in March 1991. It's FY91 activities were summarized in a similar report to this one submitted to SSED (Stern 1991).

In 1992, OPSWG held three full-group meetings, two subgroup meetings, and organized a Workshop at the Munich DPS meeting. The full-group meetings were: (i) January 1992/Tucson, which had the main purpose of evaluating the Pluto 350 concept and re-evaluating the status of future Neptune missions in light of the CRAF cancellation; (ii) April 1992/Washington, which had the main purpose of evaluating the relative merits of the 'Pluto 350' and 'Pluto Fast Flyby' concepts; and (iii) July 1992/Carmel, which had the main purpose of selecting a strawman payload for the Pluto Fast Flyby mission, based on scientific measurement objectives prioritized in previous meetings.

The two sub-group meetings were: (i) March 1992/Schaumburg to evaluate SAIC studies on small mission concepts for Uranus and Neptune, and (ii) October 1992/JPL to evaluate SDIO payload technology.

From these meetings and the work done by the SWG, OPSWG produced the following products in 1992:

- Three post-Meeting letter reports to the Director of SSES (Dr. Huntress) and SSED's Advanced Study Chief (Dr. Pilcher) summarizing the progress and decisions made by the SWG;
- Two presentations to SSED describing the SWG's work on Neptune and Pluto mission studies.
- The Neptune/Pluto Scientific Mission Objectives Document (SMOD).
- A baseline Neptune-Pluto Tour/Encounter Scientific Requirements Document (T/ESRD).
- The baseline Pluto Flyby Science Objectives, Mission Requirements, and Scientific (SOMRS) Payload report.
- An improved set of Pluto system constants and parameters, which were delivered to JPL.
- Assessment of the science capabilities of the "Strawman" Pluto payload and how they match the stated objectives (with R. Terrile).
- A letter report to Dr. Brinton describing recommendations for near-term PIDDP development relating to Neptune and Pluto missions.

The SWG is presently completing:

- A report requested by Dr. Huntress evaluating the expected advances in groundbased and Earth-orbital capabilities for Pluto study between 1995 and 2010. And,
- A report for publication summarizing all Neptune-system mission studies to date; this report will also form the basis of an invited chapter in the University of Arizona Space Science Series volume, *Neptune and Triton*.

In addition to these activities, Dr. Stern also (i) made OPSWG presentations to (i) the February 1992 SSES meeting, (ii) OSSA's Space and Solar Physics Division (June 1992), (iii) supported weekly JPL Pluto Team study telecons throughout the year, (iv) provided various technical input to questions from the JPL and SAIC study teams, and (v) made the following presentations concerning Pluto mission studies:

- *The Neptune Orbiter Mission* (Invited Review), University of Arizona Book Series, Neptune/Triton Meeting, Tucson, January, 1992.
- *Something Lite: NASA's Mission to Pluto*. San Antonio Amateur Astronomical Association, June 1992.
- *The Neptune Orbiter and Pluto Flyby Missions*, COSPAR Invited Talk, Washington, D.C. September, 1992.
- *Pluto-Charon: A Trip to the Little Planet with the Big Moon*. Joint Institute for Laboratory Astrophysics and Department of Astrophysical, Planetary, and Atmospheric Science, University of Colorado. September, 1992.
- *The Pluto-Charon System*. Briefing to the JPL Pluto Spacecraft Team. JPL. Pasadena, October, 1992.
- *The Pluto-Charon System*. Review to the DPS Pluto Workshop. Munich, October, 1992.
- *Pluto and Charon: Hot Results on Cryogenic Worlds*. Physics and Astronomy Department Colloquium. Northwestern University, Evanston Illinois. November, 1992.

3.0 OPSWG FY93 Plan

In FY93 OPSWG's primary goal is to complete the definition of the science goals/measurement objectives, payload definition, and other Phase A work required for the Pluto Flyby mission. As a part of these Pluto mission activities, OPSWG will:

- Review and finalize the strawman payload selection for the mission.
- Set up and review the results of Instrument Definition Teams (IDTs) for each strawman payload experiment. These IDTs will be led by members of the SWG but include outside members to ensure fairness and maximum feedback to the community. IDTs will (i) conduct Phase A instrument definition work and (ii) design and/or build instrument prototypes as a part of the Pluto FY93 Advanced Technology Insertion (ATI) program.
- Review the evolving JPL spacecraft and encounter designs, and provide feedback on these to JPL and SSED with regard to its ability to accomplish the Class I scientific objectives described by OPSWG in FY92.
- Produce a Phase A study report summarizing the scientific rationale, scientific objectives, encounter requirements, and strawman payload requirements for the Pluto mission.
- Interact with SSED as required to prepare materials for the payload and IDS selection AO.
- Complete its report to SSED describing the present outlook for knowledge base enhancement about the Pluto system through 2010. This report will include a discussion of groundbased and spacebased observational advances, modelling advances. It will also define needs for datasets which could improve the conduct of the ongoing mission studies and the expected late-1990s Phase C/D development effort. The report will make recommendations for strategically improving the knowledge base through targeted research activities.
- Support JPL by providing technical inputs to and critique of the Phase A mission study.
- Support SSED in creating promotional materials describing the Pluto mission.
- Provide additional input and reporting to SSED itself, the SSES, COMPLEX, and SSAAC in 1993 at the request of the Division Director or the Advanced Studies Chief.

In addition to its Pluto mission development work, OPSWG is also charged with studying missions to the giant planets and other bodies of the distant outer solar system. As such, we plan to:

- Evaluate and then prepare a report to SSED describing additional intermediate mission opportunities for outer solar system exploration using the Pluto Flyby spacecraft.
- Initiate a major study, called MEASURE-Jupiter, of post-Galileo missions to Jupiter.
- Evaluate additional mission candidates as requested by SSED.

The above-given 1993 plan is open to modification at the request of SSED.

OPSWG FY93 Full-Group Meeting Plan

Meeting	Date	Location	SWG Milestones
OPSWG6	Jan '93	Boulder 2 Days	PF Payloads Work Evaluate CalTech Pluto Mission Organize PF IDTs Begin MEASURE-Jupiter Study
OPSWG7	May '93	DC 2 Days	Begin PF Phase A Rpt Evaluate MEASURE-Jupiter Concepts Complete PF Spacecraft Applications Report
OPSWG8	Jul '93	Flagstaff 3 Days	Review PF Phase A Rpt Review PF Payload Accommodations Evaluate MEASURE-Jupiter Implementation
OPSWG9	TBD (if req'd)	DC 2 Days	TBD TBD

¹ PF=Pluto Flyby

4.0 OPSWG Outlook: FY 1994

The specific plans for OPSWG for FY94 are obviously less mature than plans for FY93. This is natural, due to the fluid nature of the present studies and the branchpoints they contain. However, several objectives for FY94 are already clear. They are to (i) complete the development of the Pluto mission for new start; (ii) to support that new start with documentation and other activities as requested by SSED; (iii) to complete the MEASURE-Jupiter study; and (iv) to re-evaluate options for missions to Uranus and Neptune which could receive new stars in the late 1990s.

Future Neptune and Triton Missions

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Submitted: 24 September 1992

Future Missions to the Neptune/Triton System

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Abstract

Since the completion of the *Voyager 2* mission, NASA has undertaken several studies of future missions to the Neptune/Triton system. These studies have investigated flyby/probe, orbiters-only, and orbiter/probe missions in some detail. We examine scientific questions motivating renewed exploration of the Neptune/Triton system, and review the technical results of the mission studies completed to date.

I. Introduction

Planetary exploration proceeds in a fashion which can more or less be divided into three phases: reconnaissance, exploration, and in-depth study. The reconnaissance phase, exemplified by the *Voyager* project, involves flybys making a limited suite of remote sensing measurements. The exploration phase generally involves a spacecraft in orbit about a body, allowing repeated measurements, extended time-base studies, and observations with experiments not suited to flybys. *In situ* probe measurements of planetary atmospheres have also become a routine part of exploration missions. In depth study involves landing spacecraft on a planet or its satellites, the utilization of very powerful on-orbit experiments to conduct detailed investigations, and sample return.

With the glaring exception of the Pluto-Charon system, the *Pioneer 10/11* and *Voyager 1/2* missions have propelled outer planets studies to the exploration stage.

In this chapter we review studies of future Neptune mission planning. Our discussion is restricted to studies and developments since the *Voyager 2* Neptune flyby in 1989. The chapter is organized as follows: in §II we review programmatic context and prospects for Neptune missions; in §III we examine the kinds of scientific questions that future Neptune exploration should address; in §IV we review the technical studies of Neptune probes, orbiters, second-generation flybys, and Triton landers; finally, in §V we briefly examine the prospects for such missions.

II. Background and Programmatic Context

A. Present Outer Solar System Exploration Plans

The outer solar system is of profound scientific interest for two key reasons. First, each of the giant planets is a planetary system unto itself, with uniquely individual magnetospheres and plasmaspheres, distinct ring systems, satellites of many sizes and unique properties, and atmospheres exhibiting different dynamical regimes. Second, the chemical and physical record of solar system formation contained in these objects is distinct from

that of the inner solar system because the abundances of volatile species contained in these cold objects can be better connected to gas and grain abundances in presently-observed interstellar clouds.

For the giant planets, a set of missions corresponding to the exploration stage has been initiated. The first among these, *Galileo*, is now en route to Jupiter. It will enter orbit in December 1995, drop a probe into the Jovian atmosphere to make *in situ* measurements of extraordinary value to dynamical and cosmogonic studies, and make a nine-or-more petal orbital tour to study Jupiter's atmosphere, magnetosphere, satellites, and dust ring. The *Cassini* mission now being built will involve a comparable orbital tour of Saturn beginning in 2006. The presence of a thick atmosphere and the potential for extensive surface volatile deposits on the Saturn's satellite Titan create a unique emphasis for this mission. With the cancellation of CRAF in 1992, these two missions at present (late-1992) represent the only outer solar system exploration efforts firmly underway.

Beyond Jupiter and Saturn lies a change in the nature of the outer planets. The gas giants Jupiter and Saturn give way to Uranus and Neptune, which have more ice- and rock-forming material than hydrogen-helium gas, and may represent objects whose accumulation of gas was arrested. Further, a suite of cold, volatile-rich bodies of moderate size in this region, most particularly, Triton, Chiron, and Pluto, are believed to contain clues to the chemistry of the pre-solar nebula at locations where the molecular cloud mix was only incompletely altered.

The United States is the only nation that has demonstrated the capability to conduct planetary missions in the outer solar system. This was first accomplished with the successful flybys of Jupiter by Pioneers 10 and 11 in 1973 and 1974, and the 1979 Pioneer 11 flyby of Saturn. These missions made measurements of the Jovian magnetospheric particle population which were critically important to the subsequent success of the *Voyager* missions. Additionally, Pioneer 11 data led to the discovery of the F-ring of Saturn and inference of the E-ring. Subsequently, from 1979-1989, the two *Voyager* spacecraft made major reconnaissance flybys of all four giant planets.

The *Voyager* 1 and 2 encounters with the Jupiter, Saturn, Uranus, and Neptune systems fulfilled many of the science goals of the grand tour mission as conceived in the late 1960's. After the *Galileo*/Jupiter and *Cassini*/Saturn missions, the next appropriate step in the reconnaissance phase of outer solar system study is a Pluto flyby. The next logical step in the transition from reconnaissance to exploration of the outer solar system lies in missions ice giant systems at Uranus and Neptune. In response to this realization and recommendations by the Solar System Exploration Subcommittee (SSES), NASA's Solar

System Exploration Division charted a new working group, the Outer Planets Science Working Group (OPSWG) in 1991 to study missions to Uranus, Neptune, and Pluto.

B. Uranus and Neptune

Prior to the formation of OPSWG, the issue of which of the ice giants to target first in planetary exploration was deliberated during SSES workshops in 1989 and early 1991. The following rationale were cited at those workshops in placing preference for Neptune over Uranus:

- The bland appearance of Uranus' atmosphere makes meteorological imaging more difficult and arguably less productive at Uranus than Neptune.
- The lack of a large, volatile-rich satellite around Uranus, such as Triton, was considered a key weakness of a Uranus mission. Unlike Triton, none of the Uranian satellites shows evidence of an atmosphere, substantial volatile deposits, or active geology. The detailed exploration of Triton offers strong aspects of comparative study with Pluto and Titan, which is of high importance to comparative cosmochemical, atmospheric, and volatile transport studies. The lack of a massive, Triton-class, satellite around Uranus also severely limits the capability to change orbits and thereby undertake a comprehensive orbital tour.
- Although the extreme rotational axial tilt of Uranus creates magnetospheric effects of high interest, this was not considered sufficient to outweigh the other limitations of the Uranus system.

Based on these rationale, OPSWG, JPL, and SAIC have begun studying Neptune missions. We now examine some of the scientific questions which such missions are designed to address.

III. Scientific Questions

This book is a testament to the scientific richness of the Neptune system. The range of scientific questions which future Neptune/Triton missions can address certainly beyond the space limitations of this chapter. In what follows we present a sampling of the outstanding questions identified by OPSWG for Neptune/Triton system missions to address. In doing so we begin with Neptune itself, then proceeding to its complex (and very likely captured) satellite Triton, its other satellites, its complex rings, and finally its magnetosphere.

- *Why are the wind and temperature structures of Neptune's atmosphere so similar to those of Uranus, despite widely different conditions of solar and internal heat input? Why are there significant differences from those of Jupiter and Saturn? Why are equatorial winds at Uranus and Neptune retrograde while those at Jupiter and Saturn are not? Indeed, how deep into the atmosphere do the east-west winds persist, and what accounts for the vertical decay of these winds with altitude above the tropopause?*
- *What accounts for the extended vertical coherence of the meridional temperature structure on Neptune and Uranus (over ten or more scale heights), compared with Jupiter and Saturn? Why do Neptune and Uranus exhibit almost no meridional temperature contrast except for mid-latitude minima?*
- *What are the vertical and horizontal variations of atmospheric composition and temperature in Neptune's upper atmosphere, and what species form aerosols at what levels? Photochemical processes acting on H₂ and CH₄ create a host of constituents, altering the atmospheric composition and critically affecting the thermal structure and dynamics of the upper atmosphere. The high altitude hazes are probably condensed photochemical species. What are the physical properties of these aerosols? To what degree is stratospheric methane oversaturated, and why is Neptune so different from the other giant planets in this regard?*
- *How can Neptune's internal heat flux be so different from that of Uranus, when the internal structures and magnetic fields of these planets are apparently so similar? Why does Uranus have such a small internal heat flux compared to all the other giant planets? Might we be observing snapshots in cyclic processes?*
- *What is the deep compositional and rotational structure of Neptune's atmosphere? What magnitude are the planet's higher gravitational moments? How did these ice-giants form, and over what timescales? Why are Uranus and Neptune ice-giants, rather than gas-giants?*
- *What do the isotopic, elemental, and chemical abundance differences between "gas giants" (Jupiter/Saturn) and "ice giants" (Uranus/Neptune) reveal about conditions in the primitive solar nebula, and are there systematic trends in noble gas and heavy element abundances of the giant planets?*
- *What is the surface magnetic field configuration at Neptune, and why is it so much more asymmetric in the ice giants than the gas giants?*

- *How do magnetospheric inputs, such as auroral and Joule heating of Neptune's upper atmosphere, affect the thermospheric circulation and the global distribution of heat and minor species such as H?*
- *Is Triton a captured satellite, and how do its dynamical and impact histories compare with those of other icy bodies in the outer solar system, particularly Pluto and Charon? Did Triton form close to Neptune or far away, and if so where? Was Triton strongly heated during the course of its evolution? Does Triton preserve any impact record that reflects the reservoir of cometary bodies believed to exist in the outer solar system? Was Triton's formation unique?*
- *How do the volatile inventories and compositions of Triton, Titan, Pluto, and Charon compare with each other and with comets? In the outer solar nebula, where Triton and Pluto presumably formed, infalling interstellar matter may have undergone relatively modest processing, owing to a low infall velocity and mild shock heating. The volatile inventories of Triton and Pluto may preserve information on planetary formation processes in the outer solar nebula.*
- *What is the abundance of CO in Triton's atmosphere? What hydrocarbons, nitriles, and noble gases are present? What is the distribution and source of Triton's aerosols? What is the escape rate of hydrogen from Triton's thermosphere?*
- *What processes drive exchange of volatiles between Triton's atmosphere and surface, and how does it compare with Pluto and Mars? What are the wind speeds and how do they vary with altitude, latitude and season? How are the winds related to the temperature structure of the atmosphere?*
- *What is the distribution of the various ices on Triton's surface, particularly N₂, CO, CO₂, and CH₄? Where (or how deep) is Triton's water ice, and in what phases does it occur? Are there clathrates?*
- *What are the processes affecting the physical nature of Triton's surface? Why is Triton's winter hemisphere relatively dark, at least at the moment? Why is the southern polar cap so large, and what is the composition of the bright material there? How should seasonal changes affect the distribution and nature of surface condensates? What causes long-term color and albedo changes? What are the implications for the latitudinal and thermal structures of the atmosphere?*
- *What processes drive Triton's plumes? How long are plumes active and how much do they vary in strength? What is the spatial distribution and the lifetime of the plumes,*

and what is the composition of the dark material in the plumes? Is there any ongoing deep-seated volcanism?

- *Is dark material on Triton's surface of photochemical origin?*
- *What is the composition of the ionosphere? What species escape Triton's upper atmosphere to enter the magnetosphere and at what rates?*
- *How does chemical processing of Triton's atmosphere, initiated by the absorption of solar radiation and magnetospheric charged particles, affect the atmospheric composition and thermal structure. How do these affect the composition and structure of Neptune's plasmasphere?*
- *What is the density and composition of Neptune's small satellites? Are these small satellites icy? Is the dark material silicious or carbonaceous? Is it primordial or was it produced by radiation processing of organic ices?*
- *What is the collisional history of satellites in the Neptune system? Are some of the small inner satellites collisional fragments? Do their surfaces preserve records of the cometary population in the outer solar system? How do these satellites relate to the generation and dynamical maintenance of Neptune's rings?*
- *How are azimuthal asymmetries such as kinks and arcs produced and maintained? How are ring structures driven by dynamical interactions with small satellites? Are the ring arcs long-lived? How important are electrodynamic interactions between dust and plasma?*
- *What is the composition of the rings? Are they primarily icy or refractory?*
- *How old are Neptune's rings, how rapidly do they evolve, and why? What is the role of collisions and impacts on ring structure? Why do Neptune's rings have a high dust fraction similar to the dusty F ring of Saturn? How did the rings form?*
- *What are the sources of plasma energy input to the magnetosphere? Do the observed plasmas originate from the solar wind, Neptune's atmosphere, or Triton's upper atmosphere, and what are their relative source strengths? How are the plasmas energized? Is the ultimate energy source the solar wind or the rotation of Neptune? Is Neptune's magnetosphere more like that of Earth or more like that of Jupiter in these respects?*
- *Does Neptune's magnetosphere undergo a global configuration change once every rotation period, when Neptune's magnetic pole faces the solar wind? Why was no evidence*

of magnetospheric activity observed? Is magnetospheric activity truly absent, and if so, why?

- *What are the processes responsible for auroral emissions from Neptune and Triton, and how do these compare with those from other giant planets and Titan? What is the global distribution of aurora relative to the surface magnetic field structures on the giant planets?*

Going beyond these kinds of general questions, any return to the Neptune/Triton system also affords important opportunities for studies of comparative cosmogony and planetary evolution. In this regard, the reader is referred to chapters by Cruikshank, Richardson, et al., Hubbard, et al., and Porco, et al.

IV. Mission Concepts

A. Overview

The formal process for achieving a new start for a NASA mission is not always well-defined and is often subject to considerable delays. In 1991, the advisory committee for NASA's solar system exploration program, the Solar System Exploration Subcommittee (SSES), endorsed a strategic plan which included Mariner Mark II-derived Pluto flyby and Neptune orbiter/probe missions to be started in FY96. Subsequently, the parent advisory committee to SSES, the Space Science and Applications Advisory Committee (SSAAC), recommended to NASA the inclusion of one or both of these missions for an FY97 New Start in revision to the Strategic Plan of the Office of Space Science and Applications, depending on funding prospects. These recommendations led to the Mariner Mark II Neptune Orbiter/Probe study we discuss below.

Before the new Strategic Plan could be published, however, external events forced further revision to Neptune exploration plans. For planetary exploration, the cancellation of the Comet Rendezvous Asteroid Flyby (CRAF) mission in FY92 left the comet community with no mission, and virtually invalidated the concept of a Mariner Mark II "production line." This led the SSES and SSAAC to endorse a revised plan in which a comet nucleus mission, possibly with international cooperation, could be started in the 1997 time-frame instead of the Mariner Mark II Neptune mission. Under the revised plan, the Pluto flyby and comet missions would be in competition.

As a result of these events and NASA's present budget constraints, a set of less expensive, more focused, and in some cases quicker missions to the Neptune/Triton system have been examined. These include a smaller orbiter mission without a probe and a flyby/probe

mission concentrating on atmospheric studies at Neptune and seasonal change on Triton. In this section we review the results of the original Mariner Mark II Orbiter/Probe study, as well as other post-*Voyager* Neptune mission studies that have been undertaken. All the missions under study rely on the use of existing or near-term technology, conventional chemical propulsion systems, and spacecraft elements derived from previous or current flight programs. We begin with the most ambitious mission, and work on to the more focused concepts now under study. Before describing these missions, however, we first review the launch opportunities and trajectory requirements for Neptune missions in the 2000-2020 timeframe.

B. Launch Opportunities and Trajectory Requirements

The great distance of Neptune's orbit requires very energetic launches from Earth, unless planetary gravity-assist techniques are utilized. Another hallmark of all trajectories to Neptune is their long flight times; until advanced propulsion techniques are developed, this will remain the case.

Fortunately, with respect to launch energy, several trajectory opportunities become available just after the turn of the century to utilize a Jupiter swingby for comparatively fast (14-19 year) transits to Neptune. In addition, gravity assists by Venus and/or Earth may be included en route to Jupiter in order to enhance the injection mass performance of existing launch vehicles. Jupiter swingby to Neptune opportunities only occur in 3-year windows every 12 years.

Table 1 lists the best launch years for several different trajectory types and indicates the corresponding range of flight parameters for these trajectories, namely, flight time, specific injection energy (C_3), Jupiter swingby distance, Neptune approach velocity, and spacecraft ΔV . These launch opportunities span the years 2001 to 2007. The indirect modes (i.e., those using Venus and Earth gravity assists) occur early, and the Jupiter direct mode occur several years later. Flight times to Neptune range between 9 and 20 years for orbiter and flyby/probe missions, with the corresponding trajectory parameters that determine both launch vehicle and spacecraft propellant requirements varying over a wide set of choices. Indirect transfers to Jupiter, particularly using Venus, have the lowest launch energy requirements and are the most attractive for either heavy spacecraft (Mariner Mark II) missions launched on a Titan/Centaur, or lighter spacecraft launched by Delta or Atlas-class vehicles. Launch vehicle performance is shown in Figure 1. Direct launches to Jupiter are found applicable only to lightweight spacecraft.

One of the key trajectory characteristics indicated by Table 1 is that faster flights al-

ways necessitate closer Jupiter swingby distance and therefore a higher approach velocity at Neptune. This trade is important because it affects the Jovian radiation dose on spacecraft electronics. Mariner Mark II component limitations dictate a safe distance of about $15 R_J$ (Jupiter radii), but possibly can be reduced to $10 R_J$ at greater risk. Alternative spacecraft designs using radiation-resistant or radiation-hardened electronics might allow much closer Jupiter swingby, perhaps as low as $6 R_J$ (comparable to the *Pioneer 10* and *Ulysses* closest approach distances).

The approach velocity characteristic (V_∞) is also important for orbiter missions because the propellant capacity carried for orbit insertion dictates as low an approach velocity as possible, certainly less than 10 km/sec. Approach velocity limits also affect atmospheric entry probe heating and g-loading. Clearly, these constraints imply the need for a compromise between short transit time to the target and low V_∞ at arrival: this unfortunate 'Catch-22' will remain with us until much higher performance deep space propulsion systems are available.

C. The Mariner Mark II Orbiter/Probe Mission

The first Neptune mission concept studied was a comprehensive orbital tour and entry probe mission to be conducted with a CRAF/Cassini Mariner Mark II clone. CRAF has since been cancelled and Cassini's Mariner Mark II capabilities decreased (e.g., by the deletion of instrument scan platforms), making the Cassini Mariner a mission-unique spacecraft. Because no studies of the use of the rescoped Cassini-orbiter for future outer planet orbiter missions have been made, we present the Mariner Mark II study results here.

The Mariner Mark II is a highly capable interplanetary spacecraft designed for outer solar system missions with its first application being the *Cassini* Saturn Orbiter/Titan Probe. Key attributes of this spacecraft are long life, large propellant capacity for orbit insertion, high data rate communications, accurate pointing and stability for scientific observations, redundant and fault-tolerant avionics, and support of entry probe berthing, deployment, and radio relay link. JPL design studies have shown that only modest changes in the *Cassini* subsystems are required to carry out the Neptune Orbiter/Probe mission. These are increased data storage, higher power transmitters, an extra RTG or the addition of batteries, and a higher thrust engine for orbit insertion. Entry probe studies by SAIC have shown that direct heritage of the *Galileo* probe for Jupiter can be applied with only modest design changes in thermal control and battery power to accommodate the longer cruise and atmospheric descent time at Neptune; the desire to reach depths below 15 bars

requires a more pressure-tolerant internal structure, but surprisingly, no increase in rf communications power (Swenson 1991).

Candidate science payloads for both the Mariner Mark II (MMII) orbiter and Neptune entry probe were selected by OPSWG and reviewed by the JPL design study team to assess their accommodation ability on this mission. These instruments are listed in Table 2; in many cases the instrument capabilities and requirements were derived from the *Cassini* orbiter and *Galileo* probe payloads.

The favored MMII Neptune Orbiter/Probe mission (Kerridge 1992) employs a VVE-JGA trajectory launched on a Titan IV/Centaur in July 2002. This trajectory and launch vehicle combination is capable of injecting 6700 kg toward Neptune (60% of which is on-board propellant for orbit insertion and other maneuvers). An ecliptic-pole view of this trajectory is shown in Figure 2 for the selected 18.8 year trip to Neptune. Arrival occurs in May 2021. At that time, a 4-year orbital tour begins. The estimated cost of this mission is \$1.2-1.5B (FY92 dollars).

En route to Neptune, the spacecraft would conduct intensive cruise science investigations. Highlights of the cruise mission include close swingby encounters of Venus, Earth, and Jupiter, with the possibility of targeting one or two close flybys of Ganymede or Callisto and observation of Io volcanic activity. The Jupiter passage also allows an unprecedented two year traverse through the Jovian magnetotail, an unexplored region of high interest to plasma physics investigations. Cruise encounter opportunities have been identified for one or more asteroid encounters and distant "observatory phase" observations of Chiron. The MMII's capabilities for a large payload also present opportunities for studies of the solar wind and outer heliosphere. Further, unique astrophysical investigations requiring large heliocentric distance, such as very long baseline gamma ray burst triangulation and IR sky surveys beyond the foreground clutter of the zodiacal light, would naturally compliment such a mission.

The Neptune encounter would begin with a nearly year-long observatory phase during which approach images and spectra of Neptune and Triton would be taken. For example, it is estimated that a *Cassini*-like imaging system would provide better resolution on Neptune than the repaired Hubble Space Telescope, beginning as much as 18 months before the encounter. Such data would extend the time base of meteorological information on Neptune and seasonal monitoring of Triton to a full 5 years by the end of the planned 4-year orbital tour.

Approximately 10 days before closest approach and orbit insertion, the atmospheric entry probe would be released and the spacecraft carrier would be retargeted to both

optimize the line-of-sight communications link with the probe and to avoid the ring plane hazard. Analysis shows the probe must be targeted for a narrow band of latitudes north of 30 deg N or to near-equatorial latitudes in the southern hemisphere. Atmospheric entry occurs at a moderately steep inertial flight path angle of -45 deg resulting in a peak aerodynamic load of 400 g's, which is slightly less than the *Galileo* probe deceleration at Jupiter. Peak aerothermodynamic heating rates for Neptune entry are well below those the *Galileo* probe will encounter at Jupiter, thereby allowing a less massive heat shield for entry thermal protection.

Approximately 30 minutes prior to entry, the probe instruments would be activated and begin measurements of the ionosphere and charged particle environment (if the pre-entry science option is provided). During entry, when ionization blackout occurs, the probe would record data on upper atmosphere structure. The heat shield would be jettisoned after peak heating and a parachute deployed to slow the probe's descent (Swenson 1991). Instruments in the descent module would begin data taking ~35 km above the cloud tops, at a pressure of 100-150 millibars. The example entry/descent profile illustrated in Figure 3 indicates that the probe should encounter clouds of the major condensables in Neptune's atmosphere. *In situ* sampling includes determination of H/D and other isotopic ratios, noble gas abundances, the bulk C, N, and O abundances, measurements of the rotational, pressure, and temperature structure below 2 bars, and determination of the thermal balance and cloud particle properties and structure below the highest cloud deck. Probe tracking by the Mariner spacecraft would yield wind profile information.

A descent time of 90 minutes appears feasible on the basis of available battery capacity (cf., Swenson 1991). Relay communications is supportable by the spacecraft for this period prior to the orbit insertion maneuver timed to occur about 10 minutes after the probe mission completion. Note that all probe data acquired after entry would be relayed to the overflying spacecraft in real time. Entry science objectives require that the probe be capable of reaching at least 15 bars depth, although it is desirable to continue measurements down to the 75-100 bar region.

The deep entry objectives can be achieved within the 90 minute probe lifetime and communications constraint by jettisoning the parachute at between 7 and 4 bars and then allowing a more rapid free-fall to higher pressures. Deep penetration raises two concerns. First, there is less time for sampling measurements than might be desired; second, there is an additional 6 db radio signal attenuation due to atmospheric absorption. As we describe below, each of these concerns can be accommodated.

After the probe mission is completed, the orbiter would be inserted into an initial

prograde orbit of 200 days period. This initial, prograde orbit is a necessary result of *probe* mission requirements. At apoapsis of the first Neptune orbit, however, a second propulsive maneuver would nominally flip the orbit plane orientation to allow slow flybys of the retrograde satellite Triton. The first Triton swingby then reduces the orbit period to 80 days, improving the mission science return through more frequent Triton close encounters.

During the 4-year tour (Figure 4), observation of Neptune's atmosphere would include imaging studies to track winds and determine details of the planet's meteorology, IR studies of atmospheric composition and dynamics, studies of the atmospheric thermal balance, and measurements of aurora and airglow phenomena. Imaging, dust studies, and stellar occultations would be used to study the tenuous ring system. Finally, throughout the 40 orbits, measurements would be made of the planet's magnetosphere and particle environment over a wide range of magnetic field distances, latitudes, longitudes, and solar wind/magnetosphere geometries.

Perhaps the most exciting aspect of such a Neptune tour, however, would be the dozens of close flybys of Triton itself. These encounters would permit the mapping of Triton at a resolution 20-50x that achieved by Voyager (and over the entire satellite, rather than about half), study the atmosphere through repeated solar/UV and earth/radio occultations, probe the ionosphere and exosphere using *in situ* ion and neutral mass spectroscopy, map the composition of volatile ices and involatile photochemical and radiolysis products on the surface, study the meteorology and active geyser/plume discovered by Voyager, probe Triton's internal structure by deriving its higher-order gravitational harmonics and determining its precise moment of inertia, and search for evidence of an intrinsic magnetic field. Importantly, these studies of Triton would take place during a substantially different epoch from Voyager in Triton's complex, three-harmonic seasonal cycle. Post-Voyager volatile-transport models predict Triton's surface frost covering and atmospheric bulk in 2020 to be very different from the 1989 epoch which Voyager briefly sampled. Indeed, some models predict that during the period 2015-2025, the changing subsolar latitude on Triton will force detectable, year-to-year atmospheric changes.

D. Triton Probe/Lander

Landing on Triton's surface is an intriguing idea with intrinsically high scientific merit. Unfortunately, it is not easily accomplished. Because Triton lacks a sufficiently dense atmosphere to substantially slow descent, any landing system must rely on propulsive energy dissipation.

Relative velocity limits at Triton have been studied as part of the orbital tour calcula-

tions described earlier. It was shown that multiple swingbys of Triton in a retrograde orbit can reduce the approach velocity to about 3.5 km/sec after many several tens of orbital encounters \approx 1 year of elapsed time. A two-stage retropropulsion system providing a total ΔV of 4 km/sec yields a ratio of lander "wet" mass to lander mass of approximately 5. Thus, if the net lander mass is 50 kg, the total lander system mass is 250 kg, about the same as an entry probe. Unlike the flyby/probe mission concept, however, any Triton lander must be carried by the spacecraft through the large orbit insertion maneuver and subsequent orbit change maneuvers before it can be deployed (otherwise, the landing ΔV would be several times higher). This places a significant burden on MMII propellant requirements (like in the Mariner Mark II orbiter/probe concept), in turn greatly increasing the launch-injected mass necessary to accomplish this mission, or severely restricting the MMII orbital payload. Based on these ramifications, an estimated Triton lander development cost is likely well above \$500M. and the perceived risk of designing a lander with only *Voyager* data on hand, caused this mission option to be tabled by OPSWG.

E. Lightweight Orbiter Mission

The Lightweight Neptune Orbiter (LNO) concept was studied to investigate a minimum cost Neptune orbiter mission. The spacecraft concept used is the intermediate, "Pluto 350," 3 axis-stabilized spacecraft (cf., Collins, 1992; Friedlander & Swenson 1992). Although not designed for orbital operations, the substantial investment in this spacecraft design and cost estimates made it the most attractive option for the LNO study.

Figure 5 describes the LNO performance trades involving flight time, trajectory type, launch date, Jupiter swingby distance, and launch vehicle capability. The direct flight mode to Jupiter was ruled out because it requires a Titan/Centaur launcher and a late launch date, which place the mission outside the moderate cost category. The selected reference mission employs an Atlas IIAS/Star 48 ELV to inject the NLO spacecraft on a 2002 VVEJGA trajectory. This trajectory and launch vehicle yields a minimum flight time of just over 16 years for Jupiter swingby distance just under $14 R_J$. If the Star 48 kick stage is deleted, the flight time increases to 16.5 years (still 2.3 years less than the Mariner Mark II mission). Injected mass margin for the Atlas IIAS is a comfortable 170 kg, equivalent to a 50% margin on spacecraft dry mass.

A mass statement for the Pluto 350/LNO mission is shown in Table 3. The net spacecraft dry mass estimate is 345 kg (compared to the Pluto flyby reference mass of 316 kg). All LNO ΔV maneuvers, including the large orbit insertion and adjustment requirements, were assumed performed by a bipropellant propulsion system operating at

308 sec I_{sp} (specific impulse) with inert mass scaled to 15% of the propellant load plus 50 kg. Such a propulsion system is much larger than required for the Pluto 350 mission, and would therefore require substantial modifications to the spacecraft design. The preferred implementation for this modification was the addition of a discrete propulsion module.

Since this mission does not carry a probe, the orbiter is *initially* inserted into a retrograde orbit. Because there are no probe-entry ring plane constraints to consider, a more efficient periapsis insertion is possible than for probe deployment missions. The total LNO spacecraft ΔV requirement is 3250 m/sec, which includes 440 m/sec for cruise trajectory adjustments and 500 m/sec for post-insertion orbit tour maneuvers; this budget would allow an ≈ 23 orbit tour. This implies a propellant load 1079 kg added to the net spacecraft; propulsion inerts and launch vehicle adapter upgrades over the Pluto 350 mission brings the total injected mass to 1703 kg.

The LNO orbital mission is essentially the same as described for the MMII. However, the available payload mass and power resources are factors of 3-4x smaller. The data transmission rate provided by this spacecraft is also much lower (~ 500 bps), severely constraining encounter sequences and data volume. The estimated cost estimate to develop this mission, is \$470M, or about 1/3 the cost of the MMII orbiter.

F. Flyby/Probe Mission

The final return-to-Neptune study we review is the Neptune Flyby/Probe (NF/P) concept. The primary objectives of this mission are *in situ* atmospheric Neptune science, second-generation magnetospheric reconnaissance, and a Triton revisit. The entry probe is delivered by a carrier spacecraft that does not capture into Neptune orbit, but does support all of the necessary functions of cruise, targeting, and relay communications. The carrier vehicle includes a small science payload which could be devoted to cruise and magnetospheric studies, or second-generation reconnaissance in the Neptune system. We note that because Neptune will remain in the general direction of the solar apex where the heliopause distance is minimized, post-flyby heliospheric studies could be particularly valuable. For the purpose of this study, a hybrid space physics/planetary science payload was adopted.

Two carrier options were examined within this concept; these were a carrier derived from the Pluto 350 study and a spin-stabilized, Pioneer 10/11-like carrier. Mass statements for each are given in Table 3. The Pluto 350-derived mission has a dry mass of 377 kg including a 50 kg science payload.

The reference science payload for this mission study was comprised of an imaging

system. a UV imaging spectrometer, a plasma wave spectrometer, electron spectrometer, a magnetometer, and an ultrastable oscillator. Because the data transmission capability of the Pluto 350's 1.5m diameter high gain antenna (10.6 w RF X-band power) is only 200-600 bits/sec at Neptune (assuming a 70 m receiving station), flyby and probe data would have to be stored and played back after the encounter.

As noted above, the spin-stabilized carrier was derived from a TRW design concept that adapted the Pioneer 10/11 spacecraft as a probe carrier. The estimated dry mass is substantially lighter than the Pluto-350 carrier, at 242 kg. However, this carrier only allows a 25 kg flyby science payload, and supports data rates of not more than 100-200 bps at Neptune.

For both of these two carrier concepts, a monopropellant hydrazine system was assumed for ΔV maneuvers after launch. The propulsion subsystem mass (propellant and inerts) was calculated from the mission ΔV requirement which varies with trajectory type, launch year, and flight time.

Three different atmospheric probe options representing a range of scientific objectives and capabilities were considered. A comparative mass statement is given in Table 4. The first and most capable of these probes includes the full (33.5 kg) complement of 7 instruments from the Mariner Mark II probe. This entry probe was designed to nominally reach the 20 bar pressure level; however, with parachute jettison, and some structural modification, it could descend to the 75 bar level in 90 minutes of operation. The second probe design studied was an atmosphere structure/composition probe with a reduced science payload (18.1 kg) consisting of only 3 instruments. The dimensions and equipment layout of this reduced-capability probe are illustrated in Figure 6. Note that the structure/composition probe requires one less battery module because of the reduced power requirements of the smaller payload; its total mass (185-195 kg) is about 25% lighter than the fully instrumented probe. Backing off even further in science capability, the third probe concept examined is a tenuous atmosphere (TA) probe designed to only obtain composition and state data from a 4-instrument payload (11.9 kg) to a pressure level of 1 micro-bar. The TA probe's mission lasts only 10 minutes before it reaches a radiation equilibrium temperature above 600 K and burns up. This "minimalist" probe weighs only 60 kg; either carrier spacecraft could carry two or three.

For the purpose of spanning the performance/cost space of flyby/probe concepts, a logical mix and match of spacecraft and probe designs were studied. These were (1) fully instrumented deep entry probe carried by the axis-stabilized spacecraft, (2) a structure/composition (S&C) probe carried by the spin-stabilized spacecraft, and (3) two ten-

uous atmosphere probes on the lighter carrier.

Figure 7 illustrates the mass performance trade against flight time option (1). A lower limit to flight time was determined by setting a minimum margin on injected mass for a given launch vehicle of 20% of the flight system dry mass, and a minimum swingby distance of $10 R_J$. Although option (i) could be launched on a direct (JGA) flight in 2006 and achieves a relatively fast 10.5-year trip, this was considered a poor choice because of high Titan/Centaur costs, and the late launch and arrival dates. At 30% of the Titan launch service cost, the Atlas IIAS is a preferable choice. A $3+\Delta$ VEJGA flight launched in late 2002 can reach Neptune in 13.5 years, and its low ΔV requirement (470 m/sec) places minimal burden on the carrier's monopropellant system. Table 5 describes the Neptune encounter profile for this mission, which includes a magnetic pole latitude overflight, Earth and Sun occultation, and a close flyby of Triton, all occurring after the entry probe's end-of-mission.

Parametric performance data of the type shown in Figure 7 was generated for the other two flyby/probe concepts as well. As shown there, it is possible to capture the lightweight, spin-stabilized spacecraft/probe missions using a Delta II (7925) launch vehicle, at the expense of somewhat longer flight times and larger propellant loading. For example, a Delta II launch of the spin-stabilized carrier with an atmospheric S&C probe can be carried out in a flight time of 14.4 years, and a Neptune arrival in late 2016.

For the third mission concept, the best choice seems to be a $3+\Delta$ VEJGA trajectory launched by an Atlas IIAS with a flight time to Neptune of only 11.8 years, with an arrival in 2014.

As shown in Table 6, an estimate of project development cost, was made for each flyby/probe concept. The cost range is \$465 to \$820 million (FY 92). Probe development costs alone account for 38-53% of total project costs. The conclusion of this study is that Neptune flyby/probe missions, though 30-50% less expensive than MMII missions, are several hundred million dollars more expensive than the lightweight (no-probe) orbiter concepts.

V. Outlook

The opportunity to undertake any new mission to the Neptune/Triton system must be viewed against the backdrop of new realities for all programs within OSSA. Given the federal budget climate in the United States, the salability of missions which are in the billion dollar cost class is presently becoming very difficult. It is therefore likely that "smaller, more focused" missions are more likely to succeed. Innovative, intermediate-

sized missions in the \$400-600M category which avoid large funding peaks in any given year appear most attractive. The studies reviewed above indicate that only the Lightweight Neptune Orbiter and Flyby/TA probe concepts fall into this cost category.

Programmatic attributes which would enhance the opportunity for a return to the Neptune/Triton system are international cooperation and reduced flight times. At the moment it appears that flight times in excess of a decade are rejected by those to whom such missions must be proposed (senior NASA officials, Congress, and large segments of the US planetary community). This implies either (i) restricting interest to flyby probe missions or (ii) developing new propulsion systems (e.g., nuclear propulsion (NEP) which enable decade-or-shorter flight times for orbiter missions. Of course, the expense and time required to develop new deep space propulsion systems themselves present severe obstacles to Neptune orbiter missions. Clearly, the present US Federal budget climate (at best) severely restricts the options and opportunities for the detailed exploration of Neptune.

Around the time that this book is published (1993), the Space Studies Board's Committee for Lunar and Planetary Exploration (COMPLEX) will issue a new science strategy for solar system exploration, encompassing the inner planets, small bodies, and the outer solar system. This strategy will be used to reassess and possibly revise the plan for planetary exploration in time for the next major reexamination of the OSSA strategic plan, scheduled for summer 1994.

Before that time, we recommend more intensive studies of the LNO and flyby/probe concepts, as well as a serious investigation into less conventional mission development architectures (like the Pluto Very Small mission under study; Staehle, et al. 1992). Although one wishes the scientific community and NASA were not forced to make compromises in space exploration, reality intrudes. Given that future Galileo and CRAF/Cassini class missions are *not presently* programmatically realizable, our choice is to either find ways of doing exciting, constrained missions that fit in present-day budget envelopes, or abdicate exploration of the outer solar system.

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Table 1
Neptune Trajectory Requirements

Trajectory	Launch Year	Flight (years)	C_3 (km/s) ²	JGA (R_J)	Nep V_∞ (km/s)	F/P ΔV (km/s)	O/P ΔV (km/s)
VVEJGA	2002	12.4 - 20.0	12.8 - 13.0	06.0 - 19.6	16.5 - 06.8	1.5 - 0.4	8.0 - 2.0
VEJGA	2002	16.3 - 19.3	14.9 - 15.0	06.3 - 09.9	09.9 - 07.3	1.2 - 1.0	4.0 - 2.8
	2004	12.5 - 14.6	19.6 - 19.8	10.2 - 15.2	13.1 - 10.1	1.9 - 1.7	6.4 - 4.6
3+ Δ VEJGA	2001	15.9 - 19.8	47.9 - 48.0	06.0 - 11.6	10.9 - 07.3	0.4 - 0.4	3.7 - 2.1
	2002	11.8 - 19.8	47.6 - 48.1	06.0 - 22.3	16.9 - 06.7	0.5 - 0.4	7.3 - 2.0
	2004	14.6 - 19.7	47.8 - 48.2	24.5 - 35.6	10.6 - 06.3	0.6 - 0.5	3.7 - 2.0
2+ Δ VEJGA	2002	15.0 - 19.9	27.4 - 27.7	06.0 - 12.7	10.9 - 06.6	0.8	4.1 - 2.3
	2003	10.9 - 19.8	27.5 - 28.4	06.0 - 23.3	16.9 - 06.1	1.6 - 0.8	8.3 - 2.2
	2005	13.7 - 19.7	27.5 - 27.8	24.4 - 36.2	10.6 - 05.8	1.8 - 1.4	4.9 - 2.7
DIRECT JGA	2004	12.0 - 17.8	83.1 - 87.3	04.7 - 12.7	12.1 - 06.6	0.2	4.0 - 1.7
	2006	08.7 - 16.7	86.3 - 104.3	06.0 - 22.3	16.9 - 06.7	0.2	6.9 - 1.7
	2007	09.0 - 13.6	104.8 - 121.1	15.5 - 30.2	14.7 - 08.4	0.2	5.5 - 2.4

¹F/P=Flyby/Probe Mission; O/P=Orbiter/Probe Mission; ΔV 's are *spacecraft* mission profile requirements.

Table 2
Neptune Orbiter/Probe Science Payload (Mariner Mark II Concept)¹

Orbiter Payload (219 kg)	Entry Probe Payload (34 kg)	Probe Pre-Entry Payload (23 kg)
Imaging Subsystem	Atmospheric Structure Instrument	Neutral Mass Spectrometer
UV Spectrometer/Photometer	Neutral Mass Spectrometer	Ion Mass Spectrometer
Visible/IR Mapping Spectrometer	Helium Abundance Detector	Retarding Potential Analyzer
IR Spectrometer/Radiometer	Gas Chromatograph	Electron Temperature Probe
Ion/Neutral Mass Spectrometer	Nephelometer	
Microwave Radiometer/Sounder	Net Flux Radiometer	
Cosmic Dust Analyzer	Lightning Radio Detector/	
Radio Plasma Wave Spectrometer	Energetic Particle	
Plasma Spectrometer		
Magnetometer		
Radio Science Subsystem		
Gamma-Burst Detector		

¹OPSWG Baseline Payload, Not Prioritized.

Table 3
Neptune Flyby/Probe Carrier Options Mass Statement (kg)

Carrier Subsystem	3-Axis Stabilized (Pluto 350-Derived) ¹	Spin-Stabilized (Pioneer-Derived)
Telecommunications	053.9	031.8
Power/Pyro	049.2	036.7
Attitude Control	048.3	006.8
Command and Data	016.0	008.6
Structure/Cabling/Devices	096.4	100.4
Thermal Control	014.0	010.4
Science Payload	050.0	025.0
Contingency	049.2	022.3
Total Dry Mass ²	377.0	242.0

¹When configured as a no-probe, lightweight orbiter, this spacecraft has a dry mass of 345 kg.

²Excludes propellant and propulsion pressurants.

Table 4a
Neptune Probe Options Studied - Mass Statement (kg)

	FI (20 bars)	FI (75 bars)	S&C (20 bars)	S&C (75 bars)	TA (μ bars)
Deceleration Module	112.4	118.1	085.9	087.8	
Descent Module	095.3	117.0	081.4	089.0	
Science Payload	033.5	033.5	018.1	018.1	011.9
Total Probe	241.2	268.6	185.4	194.9	059.7

¹ FI=Fully Instrumented; S&C=Structure and Composition Only; TA=Tenuous Atmosphere.

Table 4b
Neptune Probe Options Studied - Payloads

Fully Instrumented	Structure & Composition	Tenuous Atmosphere Probe
Atmospheric Structure	Atmospheric Structure	Neutral Mass Spec
Ion/Neutral Mass Spec	Neutral Mass Spec	Ion Mass Spec
Helium Abundance	Helium Abundance	Retarding Potential Analyzer
Gas Chromatograph		Electron Temp Probe
Nephelometer		
Net Flux Radiometer		
Lightning/Energetic Particles		

Table 5

ENCOUNTER EVENTS ON NEPTUNE FLYBY/ENTRY PROBE MISSION

Neptune Periapsis Time (TCA) = 2016 Jun 7.922 (1.75 RN)

Triton Close Approach Targeting

KEY EVENT		T-TCA (minutes)	DISTANCE (RN)	RESOLUTION* (km/pixel)	LAT.	E. LONG.	SUB-SPACECRAFT ANGLES (deg) SUN ELEV.
Ascending Node	N	-109	4.97		0	201	65
Triton Full Disk		-95	18.72	2.6	7	354	48
Positive MP Lat.	N	-19	1.95		48	206	9
Periapsis	N	0	1.75		64	250	-22
Positive MP Lat.	N	22	2.02		48	305	-58
Enter Occultation	N	26	2.10		44	308	-63
Exit Occultation	N	85	4.07		10	313	-76
Descending Node	N	137	6.01		0	301	-54
Triton CA		374	5600 km	0.02	-----	Selectable	-----

* Cassini NA Camera, 0.34 deg FOV, 1024 pixels/line, 7.5 microradian resolution

Table 6
Neptune Flyby/Probe Mission Concept Profiles

Carrier S/C: Probe:	3 Axis-Stabilized Full Entry Probe	Spin-Stabilized S&C Entry Probe	Spin-Stabilized TA Probes (2)
Trajectory Type	3+ Δ VEJGA	VVEJGA	3+ Δ VEJGA
Launch Date	DEC 2002	JUL 2002	DEC 2002
Arrival Date	JUN 2016	NOV 2016	OCT 2014
Flight Time (yrs)	13.5	14.4	11.8
Launch C_3 (km/s) ²	47.8	12.8	48.0
Spacecraft ΔV (m/s)	468	834	625
Jupiter Swingby (R_J)	10	10	6
Neptune V_∞ (km/s)	13.4	12.6	16.9
Total Science Payload (kg)	84	43	37 (49)
Total Flight System Mass (kg)	600	489	409
Monopropellant (kg)	167	231	138
Total Injected Mass (kg)	891	749	569
Launch Vehicle	Atlas IAS/S-48	Delta II (7925)	Atlas IAS
Injected Mass Margin	24%	24%	27%
Development Cost Estimate ¹	\$20 M	615 M	465 M

¹In FY 92 dollars, for one flight unit plus full spares, with 30% reserve, through launch +30 days, excluding launch vehicle and mission operations costs.

Figure Captions

Figure 1. Launch vehicle performance as a function of specific launch energy (C_3). Comparison of these data to the C_3 requirements shown in Table 1 together specify which launch vehicles are capable of lifting given launch masses on given Neptune mission types. Figure 5 depicts the results of such a comparison for the Atlas IIAS and Titan launch vehicles.

Figure 2. The 2002 VVEJGA Orbiter/Probe mission trajectory, with arrival in May 2021.

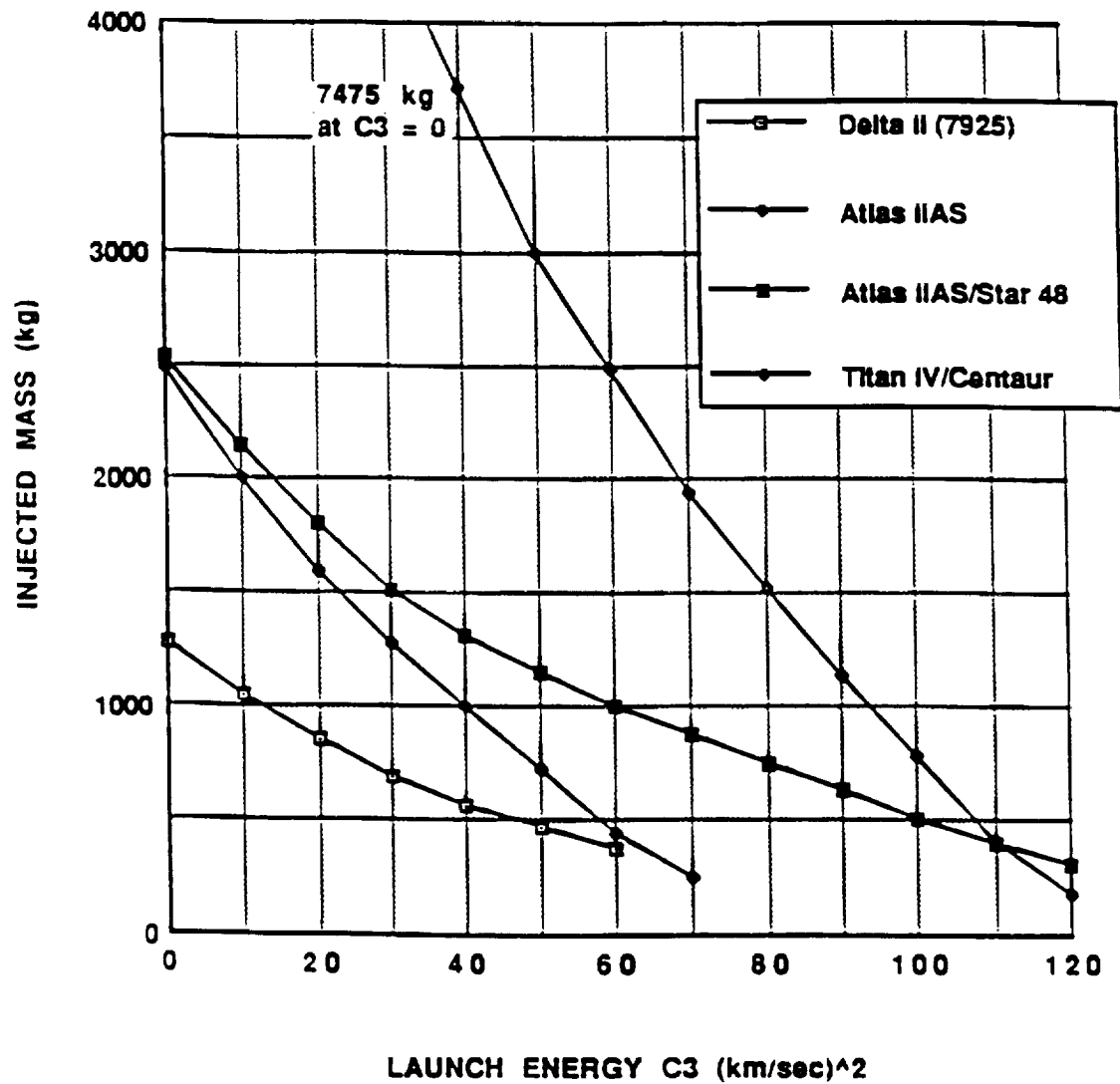
Figure 3. Schematic diagram showing the descent times, pressure regimes, and instruments to be used during each phase of a typical Neptune entry probe mission.

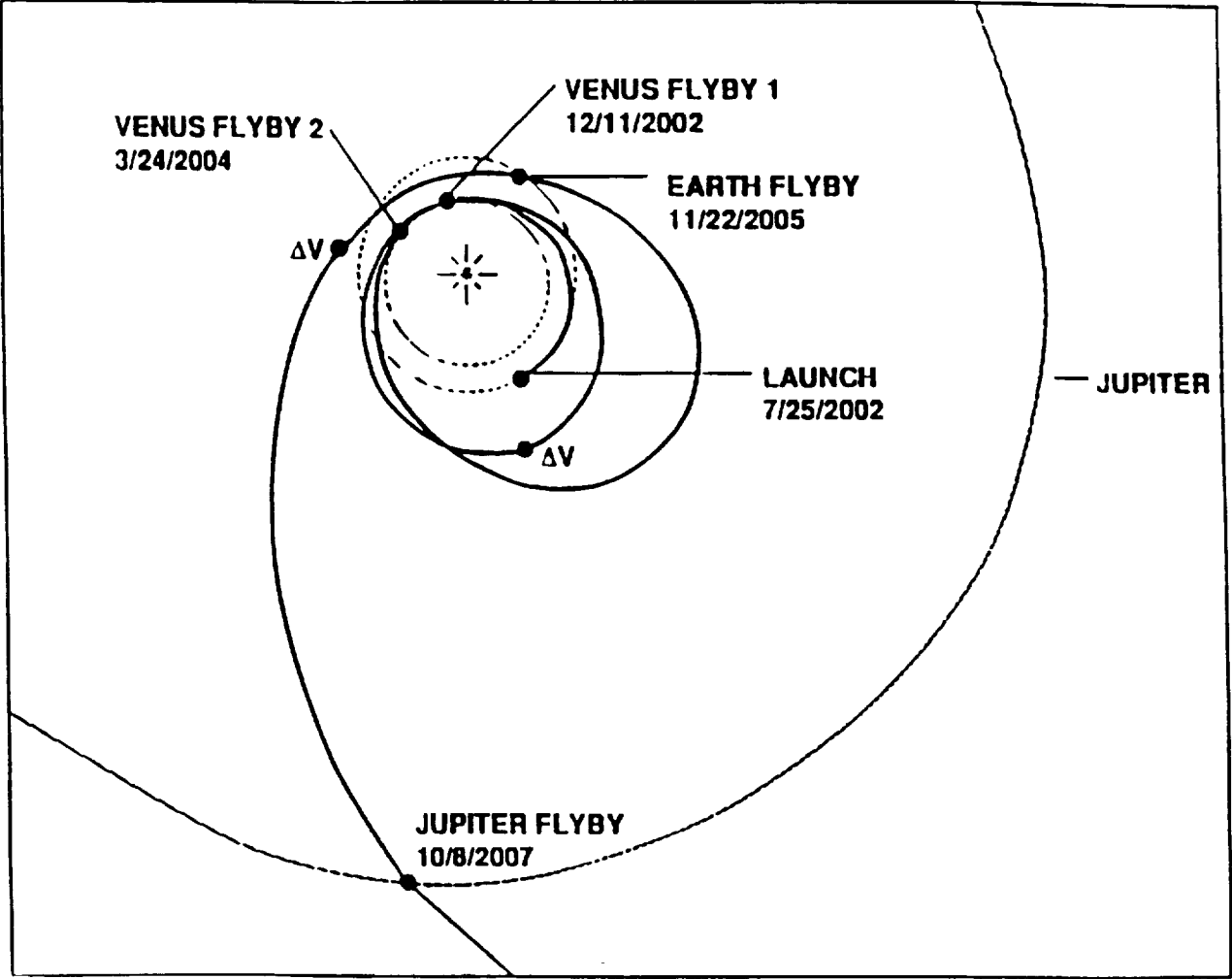
Figure 4. Neptune orbiter mission arrival and orbital tour. Top panel shows arrival geometry and the orbit reversal maneuver needed to achieve slow flybys of Triton. The lower two panels depict the orbital tour in two orthogonal planes. At left, looking down on Neptune's orbital plane; at right, showing the evolution of the orbiter's orbital plane.

Figure 5. This figure depicts the LNO mission launch mass margin for various Atlas IIAS/Star 48 and Titan/Centaur trajectories. Mass margins are shown as a function of launch date, trajectory type, and Jupiter closest approach distance (R_J). Injected mass margin refers to the available, *excess* launch mass above that of the fueled orbiter and its launch adapter. For the LNO mission, this is 400 kg; a 20% safety factor is represented by the dashed horizontal line shown across the bottom of the plot. The total launch mass for any given trajectory and flight time is simply the mass margin plus the 400 kg spacecraft plus adapter mass.

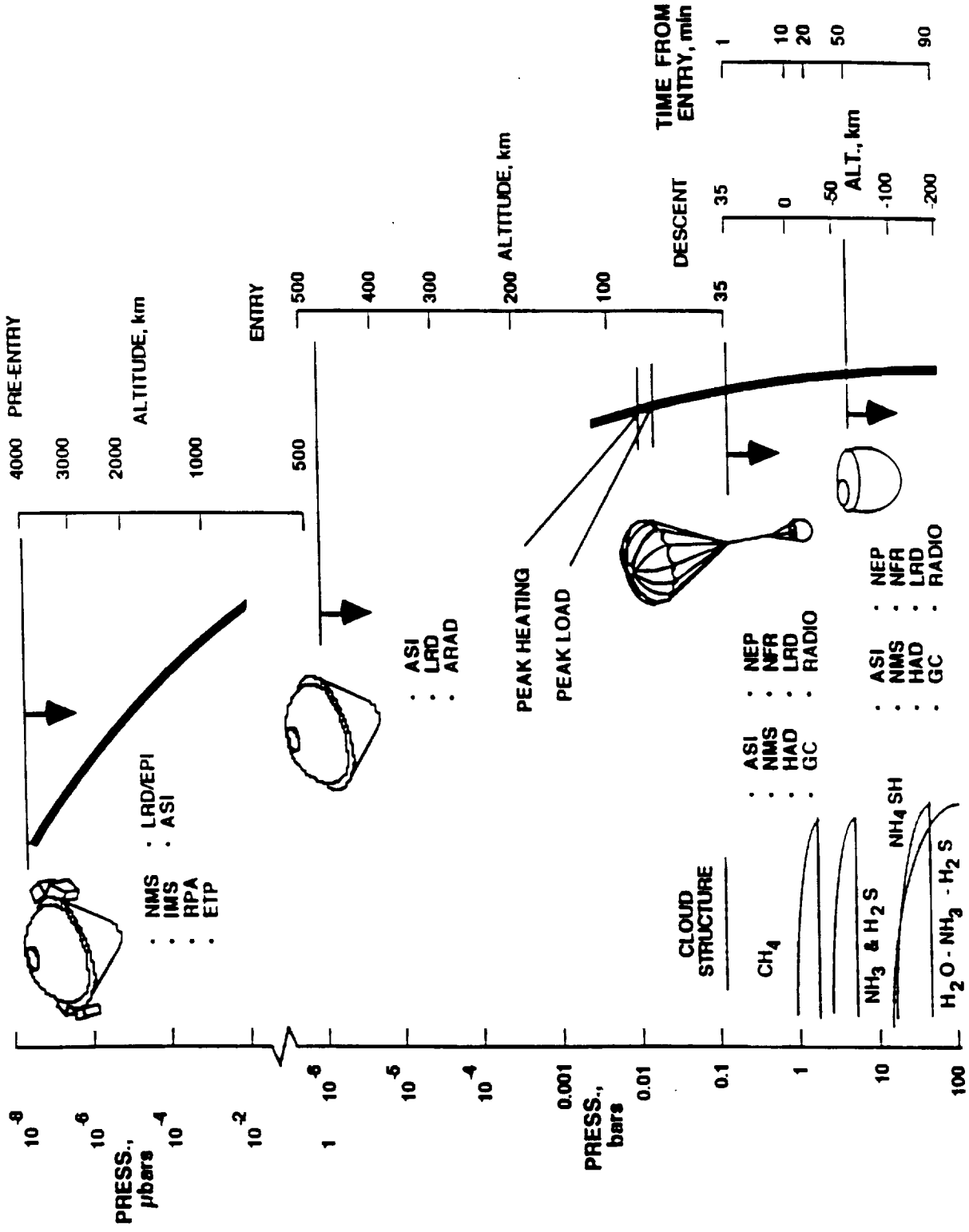
Figure 6. Conceptual design of the Neptune entry probe. This kind of large probe was studied both for the Mariner Orbiter/Probe mission and the smaller, flyby/probe mission.

Figure 7. This figure depicts the Neptune flyby/probe mission launch mass margin for various Atlas IIAS/Star 48 and Titan/Centaur trajectories. Mass margins are shown as a function of launch date, trajectory type, and Jupiter closest approach distance (R_J). Injected mass margin refers to the available, *excess* launch mass above that of the fueled orbiter and its launch adapter. For the flyby/probe mission, this is 800 kg; a 20% safety factor is represented by the dashed horizontal line shown across the bottom of the plot. The total launch mass for any given trajectory and flight time is simply the mass margin plus the 800 kg spacecraft plus adapter mass.

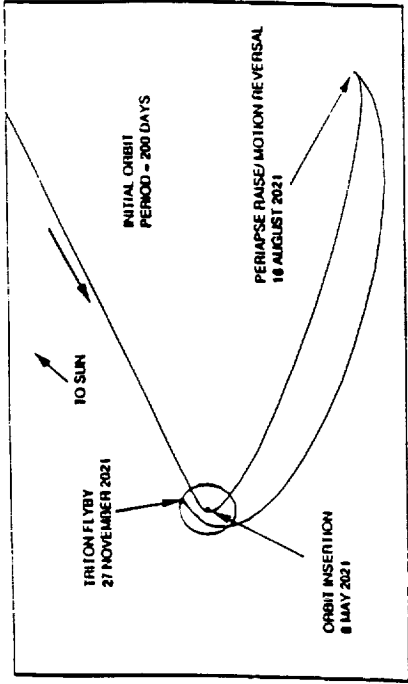




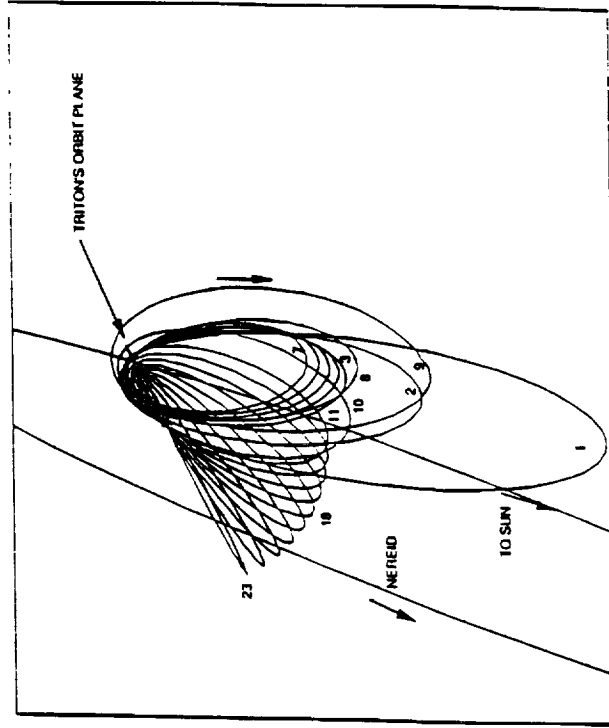
TO NEPTUNE ARRIVAL 5/13/2021



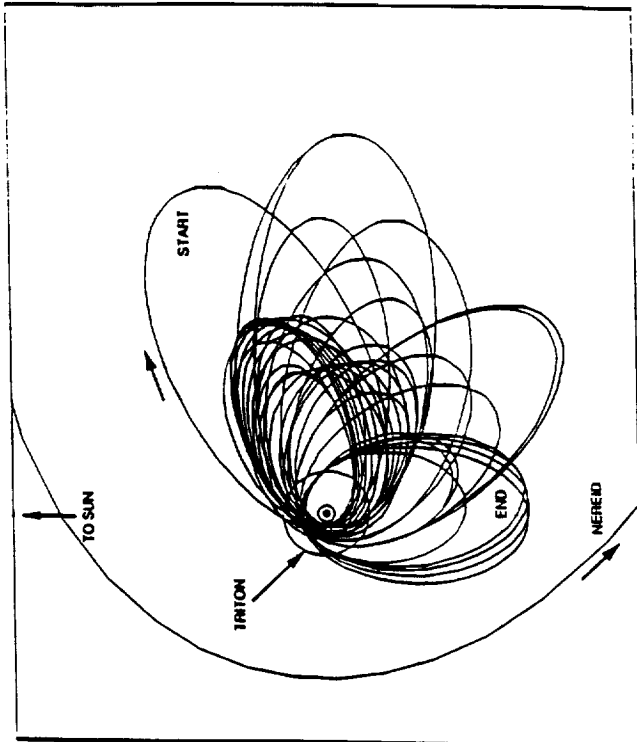
NEPTUNE ARRIVAL AND INITIAL ORBIT

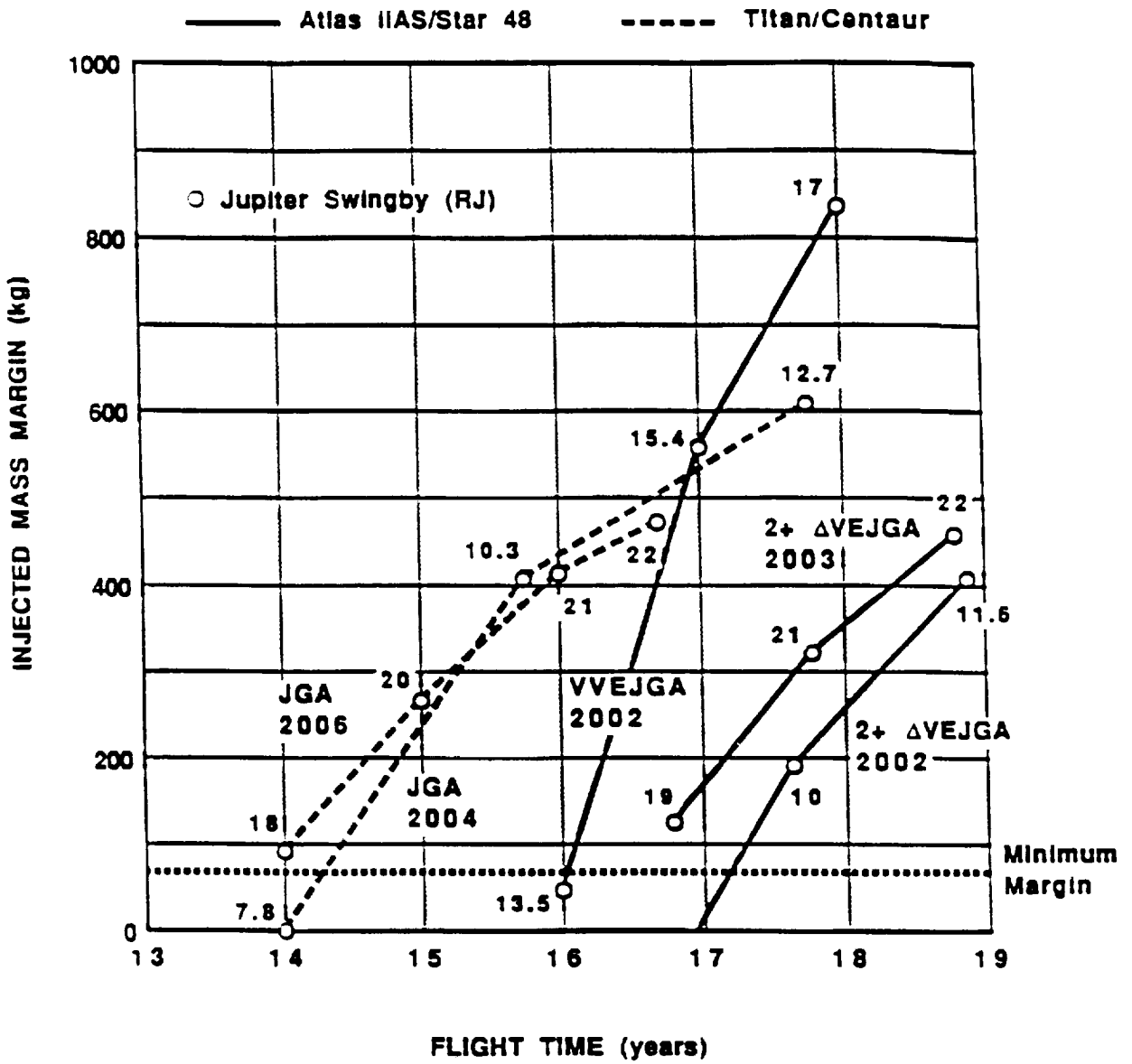


VIEW FROM EQUATOR

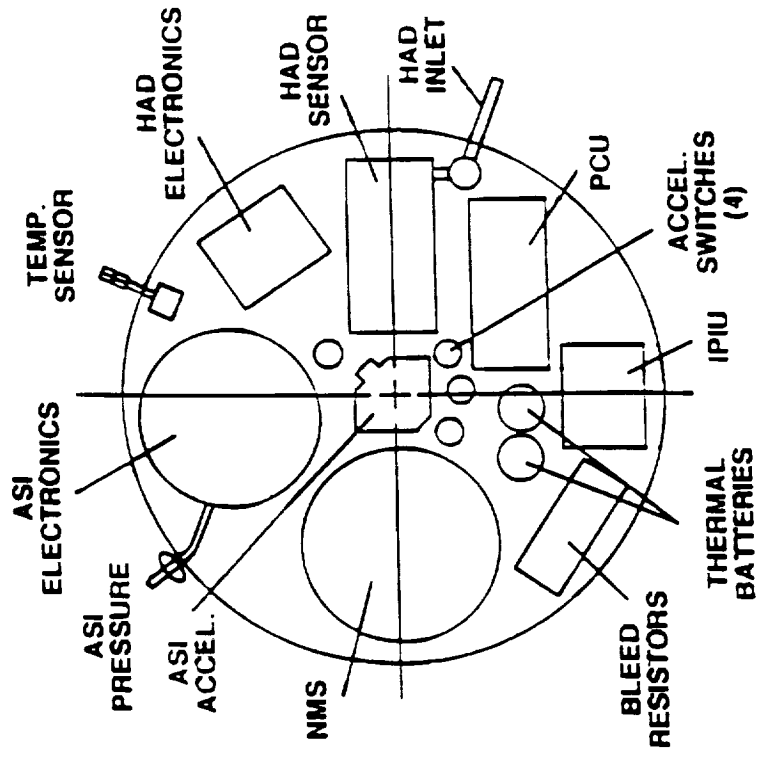


VIEW FROM POLE





FORWARD SHELF LAYOUT
55 cm DIAMETER



PROBE CROSS-SECTION
106 CM OVERALL DIAMETER

