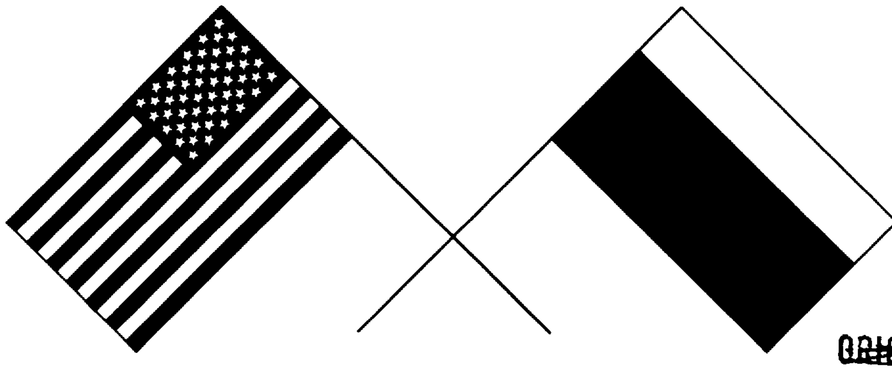
NASA-CR-198864



Mars Together and FIRE & ICE

Report of the Joint U.S./Russian Technical Working Groups

October 1994

Mars Together
and
FIRE & ICE

Report of the
Joint U.S./Russian
Technical Working Groups

October 1994

Table of Contents

Chapter Three: ICE: The Pluto Mission

Chapter Four: Launch Vehicles

Figures

Tables

SUMMARY

Introduction

The United States and the former Soviet Union have independently engaged in planetary exploration since the dawn of the space age. Both have flown many missions to the Moon, Mars, and Venus, and both continue to hold planetary science among the highest priorities within their space programs.

Some cooperation in planetary exploration between the US and the former USSR has been in place for many years. Although scientific data has been exchanged, and scientists from each side routinely have contributed to each other's projects, most of these interactions have been at a distance. Until recently, no truly joint undertaking, where each side was a full co-equal with the other, was possible in the climate that prevailed.

The end of the cold war opened up an exciting opportunity. Instead of independently pursuing a common goal, the mutual benefit of the US and Russia joining forces became obvious. Two phenomena prompted this joint venture. The change in the political climate allowed contacts and exchanges that had been prohibited for decades, and funding constraints on both sides prompted each to look at new ways of undertaking exploration at less cost.

It was against this background that a delegation of US space planners led by Dr. Wes Huntress, Associate Administrator for Space Science at the National Aeronautics and Space Administration (NASA), set off for Russia last spring to discuss possible joint missions to explore the solar system.

April 1994 Agreement

The Huntress-led delegation went to Moscow with the goal of reacquainting the Russians with NASA's interest in possible joint missions to Mars, Pluto, and the Sun and to see whether the Russians had similar interests. The US delegation was received warmly by the Russian representatives. The Russian side was as eager as the US to explore joint mission possibilities. The vision emerged of the US and Russia, long rivals in space, joining forces to explore both Mars and the inner and outermost extremities of the solar system. The two sides agreed to establish US/Russian technical study groups to investigate a cooperative solar system exploration program to the three bodies: Mars, Pluto, and the Sun. A protocol (see Study Group Results) executed by Huntress and Yuri Milov, Deputy Director of the Russian Space Agency (RAS), ratified this resolve.

Two groups were formed. The first, termed Mars Together, was co-chaired by Dr. Charles Elachi of the Jet Propulsion Laboratory (JPL) and Professor Vassili Moroz of the Institute for Space Research (IKI) in Moscow. The second, termed FIRE and ICE, was co-chaired by Elachi and Academician Albert Galeev, also of IKI. From the Russian side, Lavochkin Association representatives actively participated in both groups under the direction of Dr. R. Kremnev. The purpose of the technical groups was to study options that could accomplish both sides' highest priority space science goals more cost-effectively.

Some ground rules were established in the April agreement:

- These projects would be strictly cooperative, with no exchange of funds.
- The collaboration would advance the established national goals of each country.
- On the US side, the Mars Together activity must stay within the approved budget line item of the Mars Surveyor program.

With these guidelines, the study teams began their work in earnest shortly after the April meeting.

Study Group Results

Mars Together: The scientific goal of Mars Together is to investigate and further the understanding of the processes on the surface and in the atmosphere of Mars and to determine their evolution and current state. This is the cornerstone of the long-term national programs in both countries.

The Mars Together team developed a concept for a flight in 1998 that merged one of the US Mars Surveyor 98 missions with the former Russian Mars 96 mission. In this proposal, a US orbiter is mated with a Russian launch vehicle, propulsion module, and descent module (Figures S-1 and S-2). This plan satisfies the highest priority science objectives

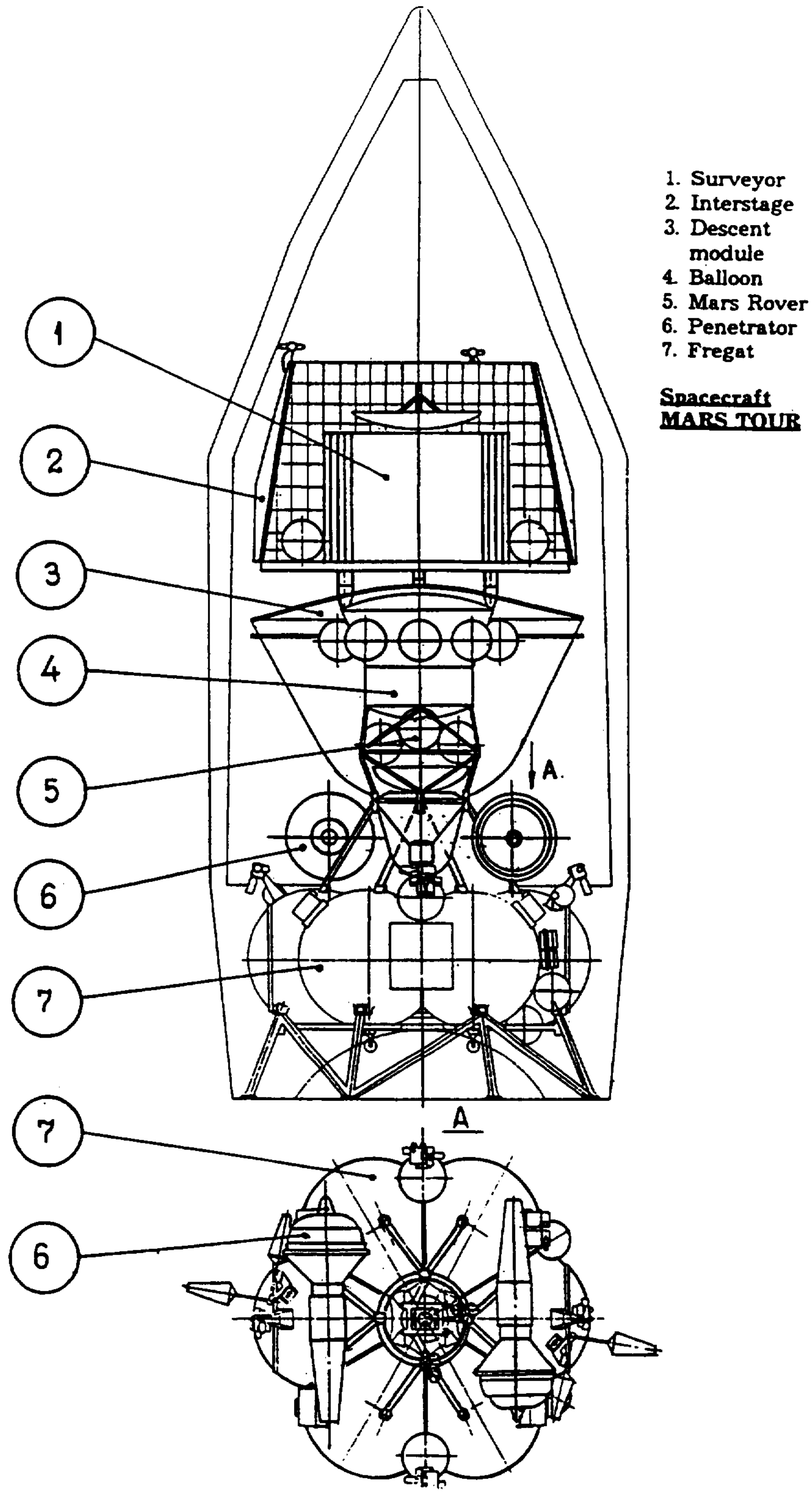


Figure S-1. Mars Together 1998 Stack

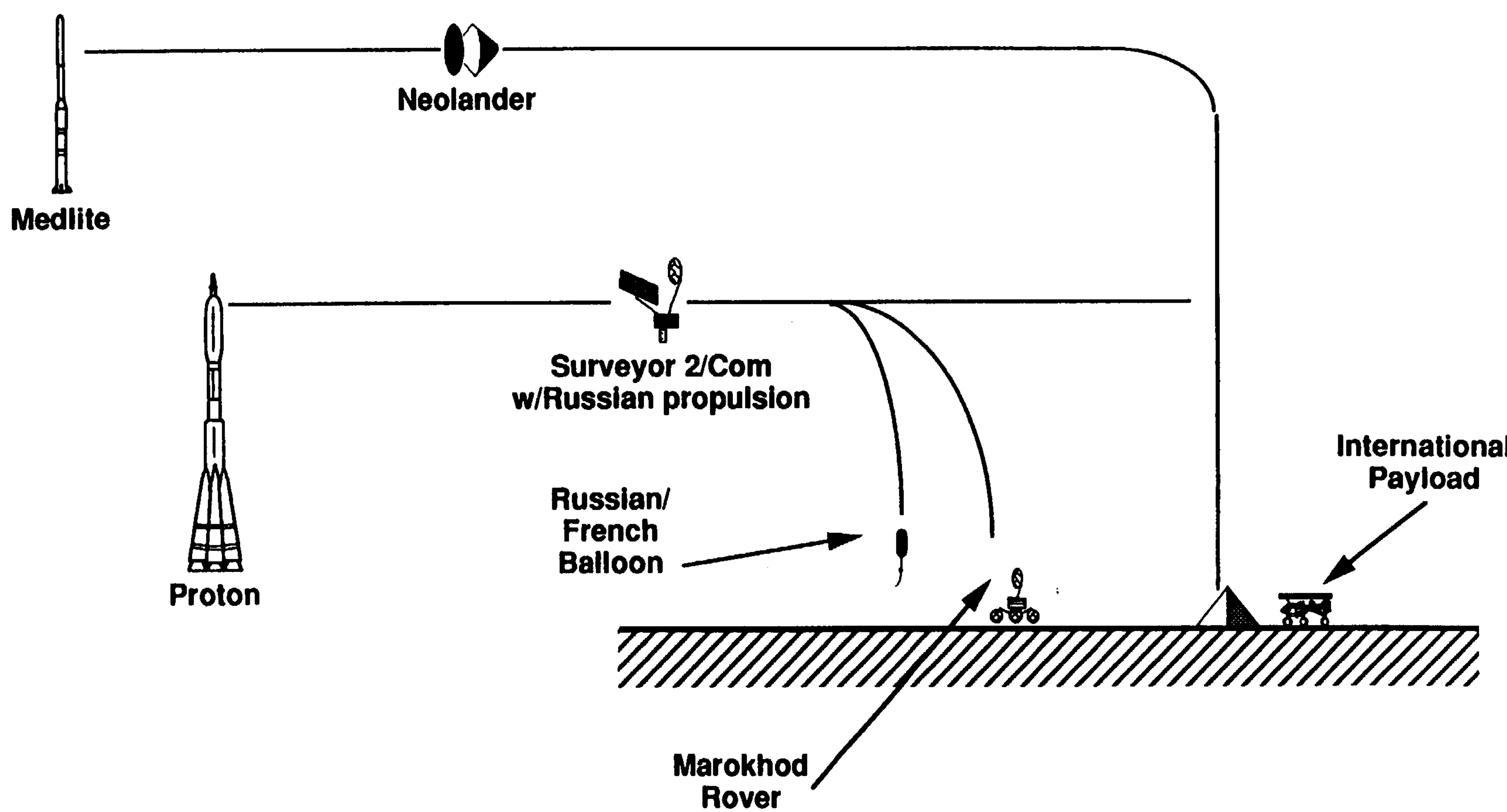


Figure S-2. Mars Together 1998 Mission of both countries while constraining costs for each. The US remote-sensing objectives that had been originally planned for Mars Observer can be largely achieved with this arrangement. In addition, the expense of a larger launch vehicle can be avoided. On the Russian side, the rover and balloon experiments, both previously scheduled for 1996, can be accomplished without incurring the expense of a Russian carrier/orbiter. To take advantage of the 1998 opportunity, this mission must start in earnest in 1995.

The team also considered various options beyond 1998 leading to a Mars and/or Phobos sample return mission by the year 2005. A joint sample return mission would be the culmination of the Mars Together partnership, occurring within 10 years of the start of this joint activity.

While some outstanding issues remain, the team concluded that there are no insurmountable technical barriers to the joint mission under consideration. The US element of the proposed program is feasible within the approved budget for the Mars Surveyor in the 1995–1999 period. The Russian funding needs to be approved by RSA early in 1995 for detailed design and by late 1995 for implementation. This requires agreement by the leadership of NASA and RSA to proceed with the design phase of this joint effort by early 1995 and with the implementation phase by summer of 1995.

FIRE and ICE: The FIRE and ICE missions will for the first time explore the two extremities of the solar system. The dual-spacecraft FIRE mission to the Sun (the Solar Probe) will determine why the one-million degree solar corona exists. The ICE mission to Pluto will explore the last unexplored planet at the outer limit of the solar system.

Solar Probe: The scientific goal of the Solar Probe is to investigate the origin of both the solar corona and the solar wind. The solar wind flowing out from the corona creates the heliosphere (the sphere of influence of the Sun) and generates effects throughout the entire solar system, including on and around the Earth. It is not possible to understand the processes of solar coronal heating and solar wind acceleration by taking remotely sensed observations. Only direct *in-situ* measurements of the plasma characteristics of the corona, taken close to the Sun, can help researchers solve these fundamental problems.

To identify the specific physical mechanisms underlying these questions, measurements should be taken at two different distances from the Sun: near 4 solar radii (Rs), where the solar wind becomes supersonic, and near 10 Rs, where the extended acceleration is still taking place and optical observations of the solar disc can be performed. Two separate spacecraft will simultaneously fly by the Sun at these distances and through different latitude regions in the solar corona. This will permit researchers to determine for the first time the three-dimensional structure of the corona and to identify the solar regions responsible for generating the various types of solar wind.

The FIRE mission study considered several different spacecraft/launch vehicle options. The most attractive includes two spacecraft, one Russian and one US, launched by a single Russian Proton with a US Star 48 final stage (Figure S-3). The spacecraft separate after launch and independently swing by Jupiter on their course to the Sun (Figure S-4). The US spacecraft travels to a 4 Rs perihelion while the Russian spacecraft passes the Sun at 10 Rs. The US payload emphasizes *in-situ* plasma measurements while the Russian mission incorporates both *in-situ* plasma and remote optical observations, which provide a global context for the two-level *in-situ* measurements.

Pluto Mission: The scientific objective of this mission is to conduct the first detailed exploration of the outermost planet in our solar system, Pluto, and to investigate the basic global characteristics of the surface and atmosphere of Pluto and its satellite Charon.

The ICE, or Pluto, mission team adopted a concept comprising two US Pluto spacecraft, each launched on a Proton and each carrying a Russian separated probe, or Drop Zond (Figure S-5). Each identical Zond leaves its parent spacecraft one month before encounter and is placed on an impact trajectory toward Pluto or Pluto's satellite, Charon (Figure S-6). The Zonds carry a mass spectrometer, a camera, and an accelerometer. Each Zond acquires *in-situ* atmospheric composition and structure data that will be complementary to the remote-sensing information obtained by the flyby spacecraft. Data is relayed to the US spacecraft and from there returned to the Earth.

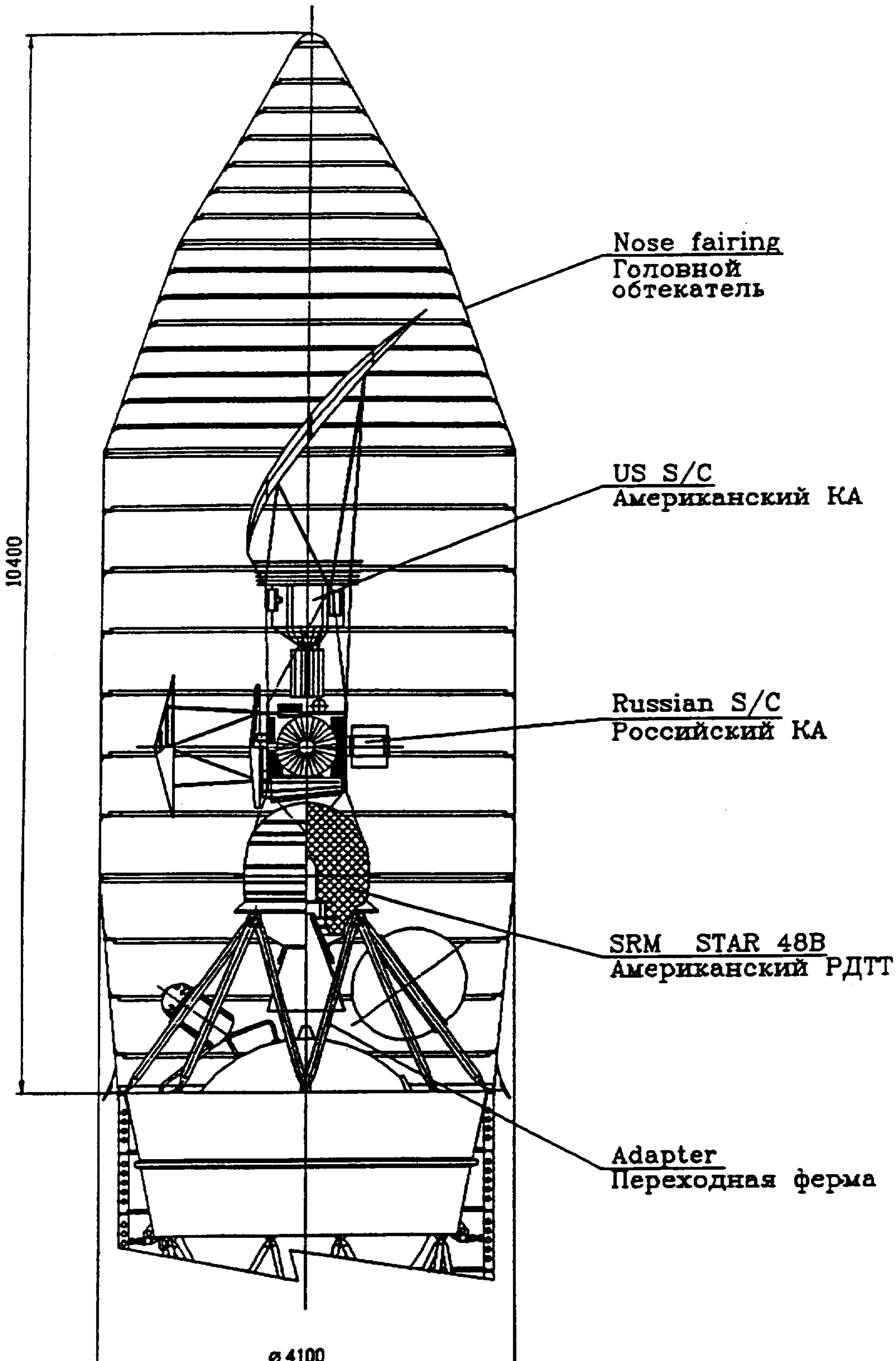


Figure S-3. FIRE Launch Stack

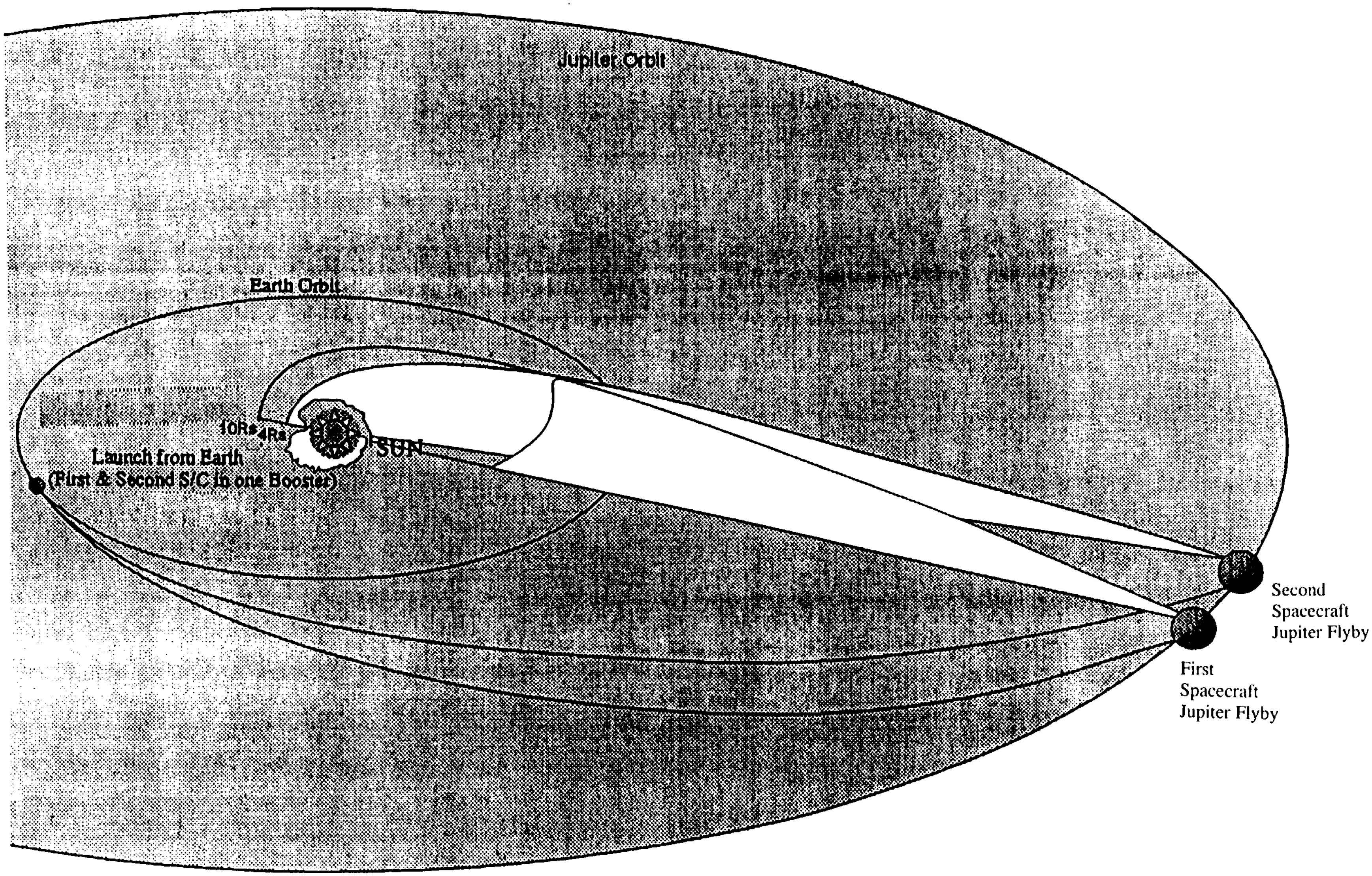


Figure S-4. FIRE Trajectories

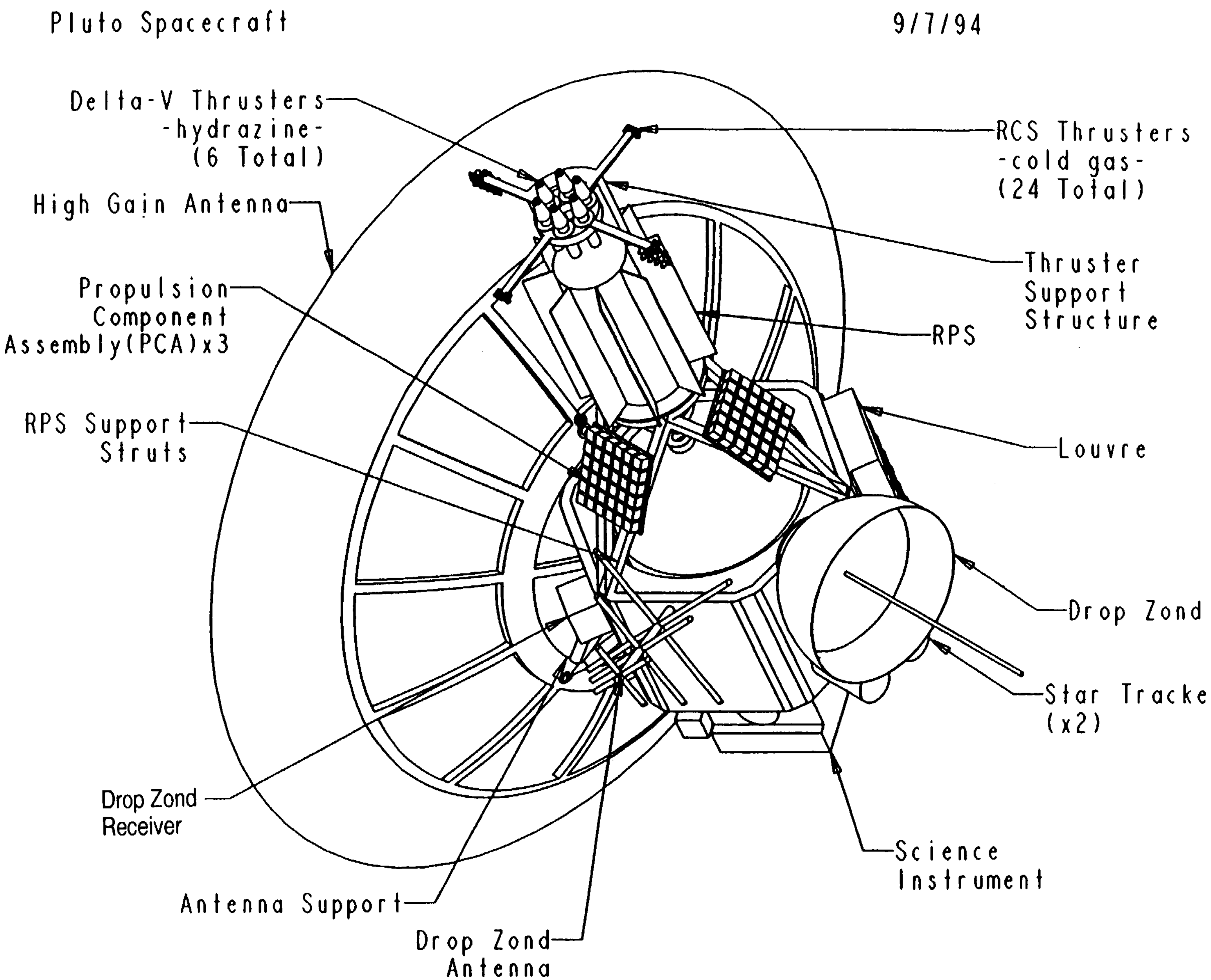


Figure S-5. Pluto Spacecraft with Zond

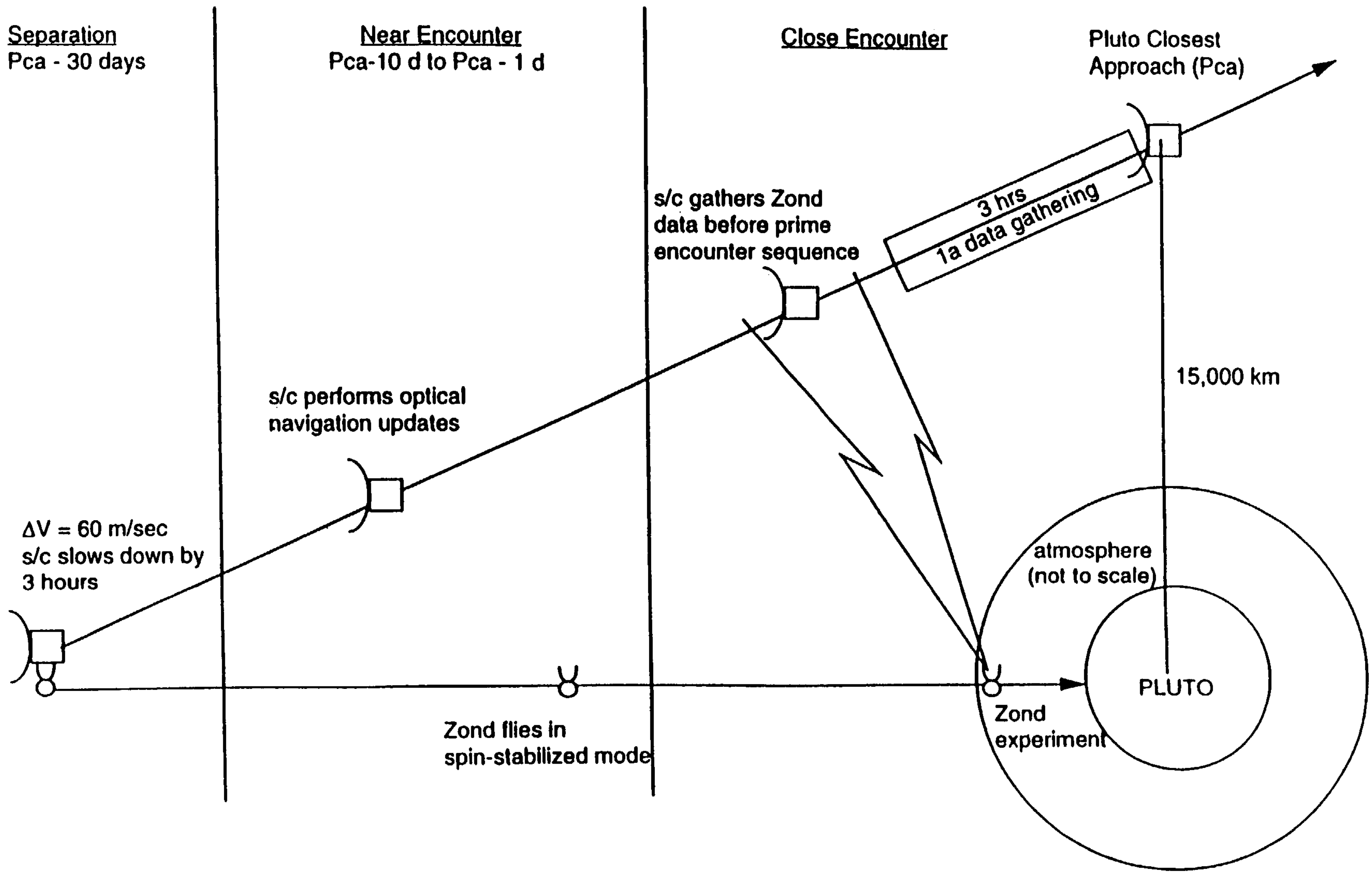


Figure S-6. Drop Zond Sequence of Events

The launch of US spacecraft from Kazakhstan using Russian launch vehicles will be a new experience for all. An area identified in the study that will require attention is the presence of a radioisotope thermoelectric generator (RTG) in each of the launch stacks. In the case of the ICE mission, the RTG powers the US spacecraft; in the FIRE mission, it powers the Russian spacecraft; and in Mars Together, it powers the Russian rover contained in the descent module. US law requires that consideration be given to the prospect of nuclear material release. The US government must also grant an export license before the US can ship its hardware to Russia for integration and launch. The process to secure these licenses was an outstanding issue at the close of the study. However, preliminary indications lead the team to believe that such a license can be granted.

Conclusions

During all three mission studies, the Russian and US representatives developed a positive, professional, and mutually supportive relationship at the working level. Each side has been very responsive to the needs of the other. Even with different traditions and work styles, the two teams feel that carefully structured, close cooperation can be successful and mutually beneficial. Nevertheless, it will be a challenge. It will require very strong discipline to make sure that interfaces, schedules, and agreements are well defined, well understood, and adhered to on both sides. These challenges, notwithstanding, the technical team recommends that all three programs go forward, bringing the two countries together in the exploration of the solar system.

Recommendations

The team believes that a joint program can be developed that is publicly engaging, scientifically excellent, technically and managerially realistic, and affordable by both sides. To achieve this, the study team recommends that

- Approval is sought from the responsible agencies in each country to proceed with these joint missions.
- The design phase of a 1998 Mars Together project (phase A/B in American terminology, "teknicheskoe predlozhenie" and "eskiznyi project" in Russian) should begin in January 1995 and the implementation phase in the fall of 1995.

- A mechanism is established to finalize the payload for the US and Russian Mars 98 elements.
- The study of a joint Pluto mission is continued with phase A in 1995 and phase B in 1996/97. The US focus will be on a low-mass spacecraft that will capitalize on advanced spacecraft technology under development by NASA. The Russian focus will be on a low-weight Zond. A Joint Science Definition Team should proceed to recommend a science payload and to constrain Pluto atmospheric models in 1995. RTG safety issues must be addressed.
- The study of a joint Solar Probe mission should be continued. In particular, instrument concept/feasibility studies, an environmental workshop, and a joint FIRE study development group should proceed. The focus in the US will be on a high-technology, low-mass solar-powered spacecraft that will be as similar as possible to the Pluto spacecraft.

SUMMARY OF DISCUSSION
US/RUSSIA SPACE SCIENCE MEETING
MOSCOW, RUSSIA
APRIL 7–9, 1994

A delegation of the National Aeronautics and Space Administration (NASA) visited Moscow, Russia, April 7–9, 1994, at the invitation of the Russian Space Agency (RSA) in order to explore potential areas of cooperation in space science. The delegation met with representatives of the RSA, the Russian Academy of Sciences (RAS) and Lavochkin NPO. Following their talks, both sides agreed to focus studies, under the auspices of the Joint Working Groups, on the following specific mission opportunities.

FIRE and ICE

Both sides agreed to study a concept in which the US and Russia together would explore the extreme ends of the solar system: the Sun at the center and Pluto at the outer boundary. An American solar probe spacecraft carrying a Russian optical module would fly by the Sun at a very close distance. Near the Sun, the Russian optical module would be separated from the main spacecraft to obtain global information on the surface and atmosphere of the Sun. Another American spacecraft would fly by the Pluto–Charon system to examine the last planet not yet visited by planetary spacecraft, where a Russian Drop Zond would be separated to impact either Pluto or Charon.

Solar Probe: Over the past decade, the US and Russian sides have conducted independent studies of a reconnaissance mission of exploration and discovery to the center of our solar system. This "Solar Probe" would address outstanding, fundamental questions that bear on the structure and dynamics of the outer solar atmosphere by making *in-situ* measurements of coronal particles and fields in a near-Sun region that has not previously been investigated. It is now apparent that a Solar Probe mission has broad scientific support, especially in the US and Russia, and the complementary capabilities of these two countries could lead to a highly promising mission that neither country at this time is prepared to pursue on its own. The Solar Probe mission would be an exciting joint program to explore one of the last frontiers of the solar system: the close environment of the Sun.

A complementary science payload has been proposed. The US could develop a miniaturized scientific payload to study the *in-situ* plasma and particle environments, while Russia could develop an optical instrument module that could remotely observe more global phenomena. There are also complementary engineering interests. The US could capitalize on its extensive design experience in developing the spacecraft and *in-situ* instrument concepts, while Russia could contribute the high performance and reliable launch vehicle (Proton), as well as the optical instrument module.

The mission scenario would include the launch of the combined spacecraft and solar optical module on the Proton, heading directly to Jupiter where a gravity-assist maneuver will place the spacecraft on a trajectory to the Sun. The unshielded optical module would observe the Sun until the heat from the Sun exceeds the module's thermal design tolerance. At that time, the module will be separated from the shielded Solar Probe, which will proceed to its perihelion encounter destiny at a distance of three solar radii from the Sun's surface.

As part of the FIRE and ICE Program, the Solar Probe spacecraft will be a near-duplicate of most of the major systems of the Pluto flyby spacecraft. Because of the high-energy trajectory requirements, both vehicles must utilize the highest performance and lowest mass technology. Russia could provide the high energy booster, as well as the additional separable modules for each mission, including the Drop Zond for the Pluto mission and the optical module for the Solar Probe.

Pluto Flyby: Russian and American spacecraft have visited all the major planets of the solar system except for Pluto–Charon. The US planetary community has placed a high priority on a Pluto Flyby mission to characterize the global geology and morphology, map the surface composition, and characterize the atmosphere of the Pluto–Charon system. Two flyby spacecraft are being considered for launch at the beginning of the next century. Because of the great distance to Pluto, a combination of light-weight spacecraft and a high-performance launch vehicle is required to reach Pluto in a reasonable time (less than 10 years). Russia and the US each have capabilities that complement one another very well for a joint, cooperative mission to the last frontier of our solar system. The concept proposed for the Pluto flyby includes the use of US miniaturized spacecraft with new instrument technology, together with Russian launch vehicle capability and a Russian-developed drop-sonde for *in-situ* atmospheric measurement and possibly for high-resolution surface imaging. The US flyby spacecraft would transport the Russian surface probes to Pluto–Charon and relay their data to Earth.

The two sides have agreed to form a technical team to study and define this joint program, focusing on the commonality in the spacecraft design and subsystems for the Pluto Flyby and the Solar Probe missions. A preliminary report was prepared in August 1994 and a final plan was prepared in November 1994 for consideration by the US and Russian space agencies. The US lead will be Dr. Charles Elachi; the Russian lead will be Academician Albert Galeev.

Mars Together

Recalling with satisfaction the highly successful cooperation between the US and Russia in solar system exploration over the past two decades, the two sides agreed that progress on currently agreed Mars cooperative activities, namely the US provision of an experiment for flight on the Mars-94 landed station, was satisfactory and that the highest priority should be given to successful completion of the Mars-94 mission. The sides agreed that since both the US and Russia have a strong, continuing interest in Mars exploration with each intending to independently fly several missions to Mars in the next decade, it would be mutually beneficial to the US and Russia to study options to initiate a new level of cooperation in the planning and implementation of Mars exploration activities. Cooperation would strengthen both programs scientifically, technically, and programmatically, would provide increased levels of program and technical resilience through exchanges of launch and instrument flight opportunities, and would facilitate the transition to a completely international Mars exploration program.

It is envisioned that a cooperative Mars exploration program could consist of two launches, one US and one Russian, at each opportunity, with the payloads consisting of both US and Russian spacecraft and instruments.

The two sides agreed to establish an American/Russian technical study group to investigate a cooperative Mars exploration program with emphasis on the 1998 and 2001 launch opportunities. This joint technical study group reports to the Solar System Exploration Joint Working Group (JWG). The US Lead is Dr. Charles Elachi, and the Russian lead is Dr. Vassili Moroz. The first meeting of the study group took place in the US in June, followed by a meeting in Russia in July. A preliminary report to the JWG was made in October, and a final report is being submitted in December 1994.

Cooperation in the Spectrum Series of Astrophysical Observations

Both sides have agreed that the highest priority should be placed on accomplishing the currently agreed program of joint missions. In astronomy and astrophysics, US participation in the Russian Spectrum series of three great observatories is the dominant portion of currently active US–Russia cooperation. The Spectrum collaborations have been studied thoroughly and endorsed by the Russian Academy of Sciences and the US astronomy community.

Spectrum-X-Gamma, the first in development, will be a world-class observatory for the study of some of the most exciting cosmic riddles of today: black holes, active galaxies, novae and supernovae, neutron stars, pulsars and the Universe as a whole. RadioAstron will extend the ground-based network of radio telescopes to space for high spatial resolution radio mapping through interferometry, permitting study of the structure lying at the core of powerful cosmic energy sources. A third mission in this series, Spectrum-UV, also has high interest on both sides, and we encourage its further definition.

Both sides determined that they have already made large investments in these joint programs and have made good progress in their development. Both sides reaffirmed their commitment to continue development and flight of the Spectrum missions on the agreed schedule. The cooperation on the Spectrum Series will continue through the Astronomy and Astrophysics JWG, co-chaired by Dr. Dan Weedman and Academician Rashid Sunyaev.

Joint Statement Preparation for the Gore–Chernomyrdin Commission

The two sides also agreed to draft a joint statement for submission to the Gore–Chernomyrdin Commission (GCC). NASA will initiate a draft statement based on the agreements from this meeting to document our joint conclusions. NASA will fax this working draft to the RSA for additional comments and inputs. Following agreement on this draft, NASA will prepare a final document for signature of both sides to be submitted to the GCC.

The NASA delegation expressed its appreciation to the RSA, RAS, and Lavochkin NPO for their hospitality during these meetings.

Dr. W. T. Huntress,
NASA Associate Administrator
for Space Science

Mr. Y. G. Milov,
Deputy General Director, RSA

CHAPTER ONE

Mars Together

1.1 Introduction and Background

The Mars Together joint US–Russian study was established on April 9, 1994, by US and Russian scientific delegations meeting in Moscow. The delegations included representatives from the US National Aeronautics and Space Administration (NASA), the Russian Space Agency (RSA), and the Russian Academy of Sciences (RAS). At the Moscow meeting, an agreement was forged to investigate cooperation in Mars exploration "with emphasis on the 1998 and 2001 launch opportunities." While the US and USSR had previously collaborated in human space flight and Earth application missions, this was the first time in the history of cultural relations between the two countries that US and Russian specialists had been authorized to work together on a joint space science mission. The Jet Propulsion Laboratory (JPL) is the principal contributor on the US side, while the Lavochkin Association and Institutes of the Academy of Sciences (IKI, Izmiran, and Vernadsky Institute) are the principal contributors on the Russian side.

The basic concept of a joint mission in 1998 (known as MT-98) was quickly formulated. The mission would comprise a US orbiter, a Russian descent module, an Autonomous Propulsion System (APS), and a Proton launch vehicle (Figure 1-1). The rationale for this arrangement is described in Section 1.3. Implementation of this concept will be a challenge. Never before have US and Russian engineers involved in space science worked together as closely as will be necessary for such a project to succeed. However, the joint study team is fully confident that this challenge can be met, if senior management decisions are made in a timely fashion. In the few months since April, the joint team has established an effective and productive working relationship. It has met three times, has held video conferences, and has effectively exchanged information in the interim. Extensive use of electronic mail has been vital to the study team's productivity and will be critical in continuing this work. Summaries of meetings held in June, July, and August are available.

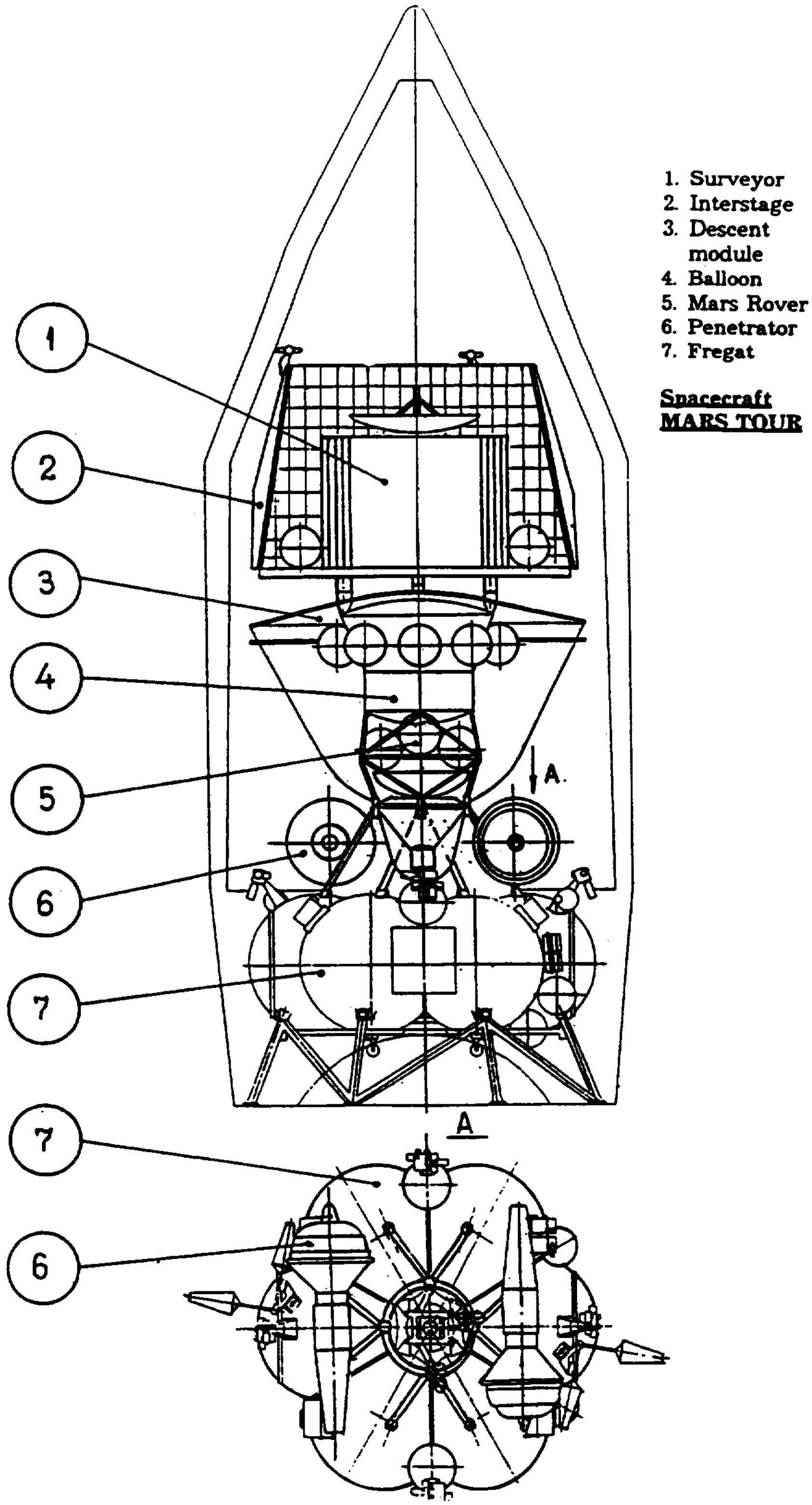


Figure 1-1. Mars Together 1998 Basic Configuration

In accordance with the April agreement, the team has been led by Dr. Charles Elachi for the US and by Dr. Vassili Moroz for Russia. Midway into the study, the Russian team was subdivided into two subgroups: a technical team under the leadership of G. Rogovsky and a scientific team led by Dr. Moroz (Moroz is also responsible for coordination functions).

1.2 The US and Russian National Programs

Goals: The exploration of Mars was selected as a baseline Russian goal some years ago and has long been an important element of the US solar system exploration program. Basic science objectives for both Mars programs include the global mapping of the surface, long-term meteorological surveys, and the first studies of the planet's interior. Both programs emphasize understanding the evolution of Martian volatiles and climate as a key endeavor. Scientific topics of interest include

- Studies of the surface: tectonic and volcanic processes and products, crustal formation, weathering, ancient aqueous sediments, fluvial processes, eolian processes, hydrothermal systems, and polar deposits
- Studies of subsurface material: ground ice, composition of bedrock, possible subsurface organics, soil oxidation processes, and structure of the crust, mantle, and core
- Atmospheric studies: present and past climate, trace gas abundances, stable isotopes, atmospheric escape rates, and global circulation and the forces that drive it.

Current US Program: An initial goal of the US Mars program was the recovery of the science lost by the loss of Mars Observer. Now, however, the US is adopting a fresh approach to Mars exploration by embarking on a new series of focused, low-cost missions known collectively as Mars Surveyor. The first element is the Mars Global Surveyor (MGS) orbiter which, along with the Mars Pathfinder lander, is to be launched in 1996. The Mars Surveyor program was introduced in February 1994 and authorized by the US Congress in the succeeding months.

The Mars Surveyor sequence (Figure 1-2) presumes two launches to Mars every 26 months from 1996 through 2005. New technology will be exploited for orbiters, landers, rovers, and instruments. The main features are low cost, fixed annual budgets, short development

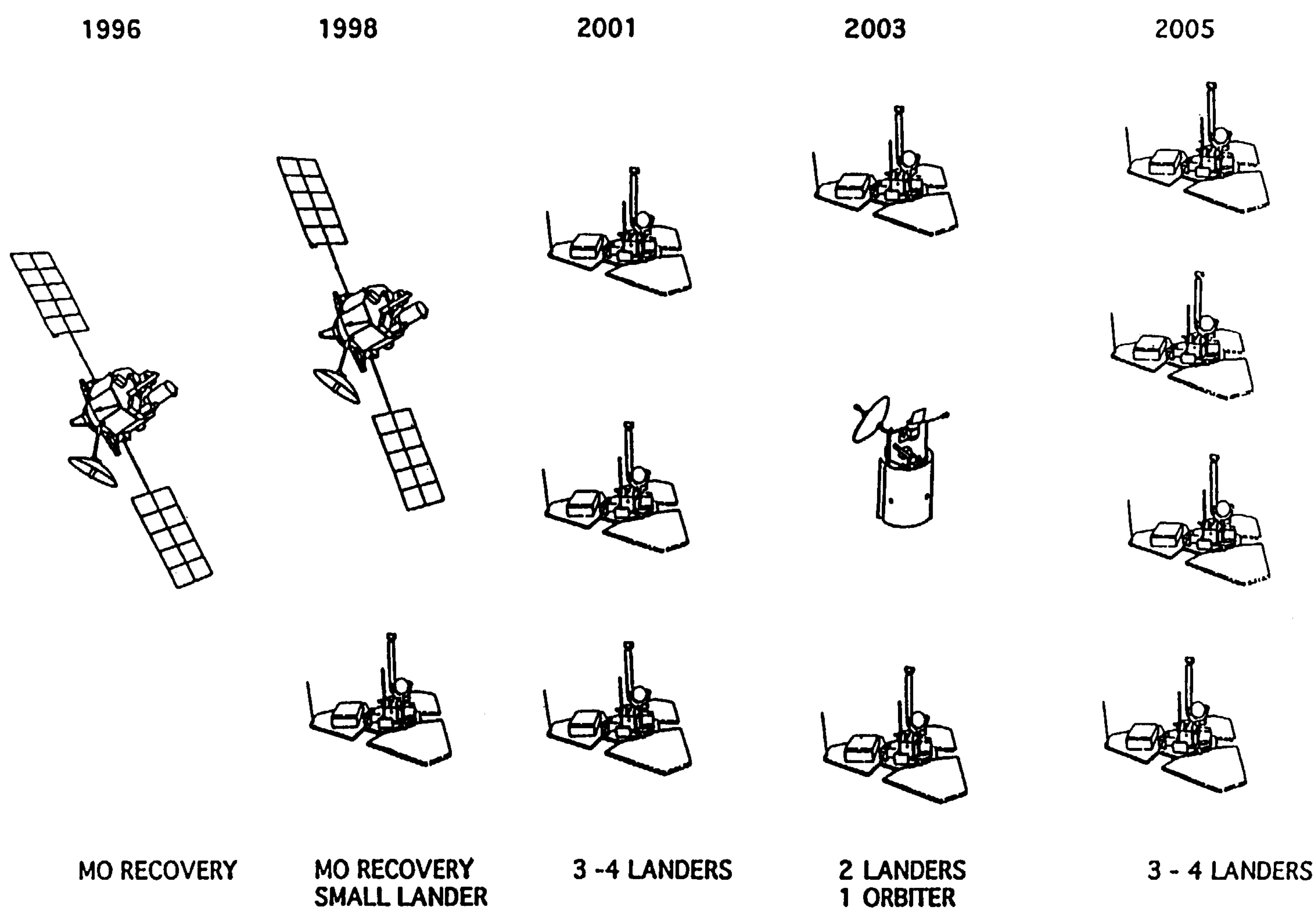


Figure 1-2. Mars Surveyor Program Elements

times, and small launch vehicles. Beginning in 1998, all US launches will be accomplished with the Medlite launcher.

The second Surveyor orbiter (MS-2) and first Surveyor small lander will be launched in 1998. MGS and MS-2 are intended to achieve most of Mars Observer's global science objectives. In 2001 and beyond, the Surveyor program continues with a series of small landers, with support orbiters as necessary. The goals of the US Surveyor program may be accomplished by joining forces with international partners, the Mars Together concept being a prime example.

After completion of the Surveyor sequence, a Mars Sample Return mission is the long-range goal of the US Mars science program. This would most likely be conducted in cooperation with other countries.

Current Russian Program: The Russian government has approved a Russian program of fundamental scientific research in space, comprised of two missions for solar system exploration. The Mars-94 mission, recently postponed to 1996, includes an orbiter, two small landing stations and two penetrators. The Mars-96 mission, recently postponed to 1998, consists of an orbiter, rover, and balloon station although the possibility of adding two penetrators to this mission is under study. Both these missions have the status of national projects but involve very broad international cooperation, mainly with European countries.

The Mars-94 mission has been delayed because of well-known economic difficulties in Russia and the inability of governmental bodies to provide sufficient and timely financial support. Much of the industrial infrastructure important to space activity is currently in poor condition as a result of the transitional events occurring in Russian economic and political life. Nevertheless, RSA hopes to complete this project in 1996.

The next Mars mission (1998) is in a more tenuous position, and RSA has recognized that stronger support from foreign partners will be necessary to complete it on time. This project needs foreign partners, not only as participants in experiments but also as investors of funds or hardware in spacecraft systems. As yet, there has been no positive response from any of the European agencies.

Beyond 1998, the Russian Mars exploration program is still being defined. A few options are under study, such as a Phobos Sample Return mission; a Mars Global lander network, termed Mars Glob; a Mars Aster mission (landers on Mars together with an asteroids/ comets flyby); and a Mars Sample Return as a final step.

1.3 Rationale for Mars Together 1998 Mission

The concept for the Mars Together 1998 Mission (MT-98), shown in Figure 1-1, combines two missions into one. A US spacecraft (in principle, either an orbiter or a lander—see Section 1.4) from the Surveyor family is launched together with a Russian descent module from the prior Mars-96 mission (now postponed to 1998). The Russian descent module contains a balloon, which is partly a French responsibility, and a rover. These two devices are the most important elements in the original Russian mission. However, while the orbiter in the original all-Russian mission was designed primarily as a relay, in MT-98 this function will be provided by the US Mars Global Surveyor and the '98 US orbiter.

Scientific Rationale: The main elements of the MT-98 mission have been developed as a result of years of scientific planning. The orbiter payload includes a pressure-modulated infrared radiometer (PMIRR) and a gamma-ray spectrometer (GRS) used to complete the synoptic survey of the Martian surface, originally planned for Mars Observer. A similar payload planning process on the Russian side has determined the payloads and missions for both the rover and balloon. In addition to their own intrinsic scientific merit, joint development of Mars Together is advantageous because scientific experiments on the Russian rover and balloon and the US orbiter will provide complementary research to resolve common scientific problems pertaining to the Martian environment. Furthermore, both elements of the mission may be reinforced scientifically by a possible exchange of experiments between the US and Russia.

Programmatic Rationale and Cost: The MT-98 will achieve both Russian and US scientific objectives at lower cost to both countries. For a fixed total cost, the US can build a more sophisticated orbiter than could be prepared for a separate launch. Russia, on the other hand, can avoid the necessity of designing and producing a new orbiter. (The classic Phobos orbiter cannot be used in the 1998 opportunity.)

MT-98 will therefore be a combined international planetary mission, bringing together the very effective and reliable Russian Proton with a high-technology US spacecraft. MT-98 will also provide the first opportunity for highly qualified US and Russian specialists in space science and technology to work together, which will give both a better perspective for developing more challenging future projects, such as Mars Sample Return.

The Political and Public Relations Effects: This joining of US and Russian efforts in a peaceful and scientifically important field will be a new step in the development of good relations between the two countries. It is likely to stimulate a positive public response in the US where many people have a deep interest in planetary exploration. For people in Russia, such a joint project would be appreciated as an indication of the firm intellectual and technological place Russia enjoys in the post-Cold War world.

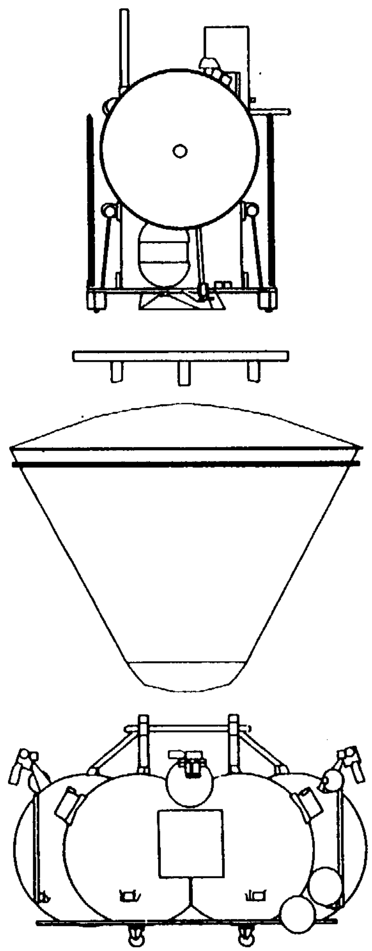
1.4 Technical Options for MT-98

A set of options was studied for different parts of MT-98. The following questions were raised:

- Should a Phobos or Fregat APS be used?
- Should there be a single descent module, as in the former Russian Mars 96/98 missions, or two separate ones?
- What US spacecraft should be provided: a Surveyor 2 orbiter with one lander or two smaller landers?

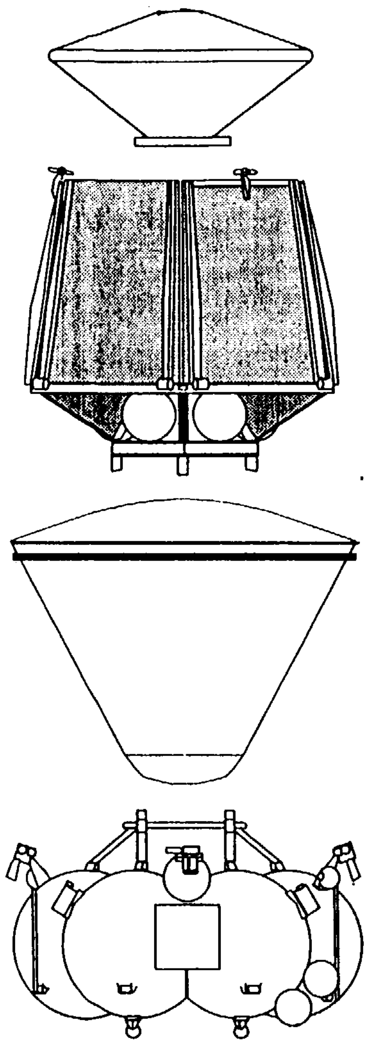
Some of these options are shown in Figures 1-3 and 1-4.

The team discussed the differences between the Phobos and the Fregat APS systems. Phobos has no control subsystem, as Fregat has, but Phobos has been built and flight tested, unlike Fregat. The Phobos option is cheaper for Russia, as it involves no new design work, but is more expensive for the US because of the complexity of interfaces and the imposition of APS control functions on the US spacecraft. Also, Phobos requires the US spacecraft to perform a risky sequence of maneuvers that puts it temporarily on an impact trajectory at a critical time in the mission. Both sides agreed the Fregat option was preferable. The Russian side has been informed that Fregat should be designed and produced in time, independent of efforts on MT-98, as there are plans for its use elsewhere.



	Supplier	ACS Reqts	ΔV Reqts	Power Reqts	Mass	Payload
Orbiter	US	Cruise: Att. Determination & Control Maneuvers: Att. Determination Commanding	Circularize Orbit: ΔV = 1045 m/s Orbit Control: 40 m/s Propellant Load: 360 kg	~ 350 watts ave. Generates Power for all Systems	~1040 kg (wet) ~680 kg (dry) ~360 kg (propellant)	PMIRR. GRS USO, Relay +30 kg
Interstage	US	Cruise: Control Authority Maneuvers: None	Cruise ACS: 30 m/s Coast/Sep ACS: 30 m/s	Interface to Russian Spacecraft	~100 kg	none
					US Total: 1258 kg US Margin: 118 kg	
Descent Module	Russia	Spin Up Prior to Aeroentry Passive afterwards	Ballistic Aeroentry	Negligible	~710 kg	Russian Rover (w/ Potential US Instruments) French Balloon
Fregat	Russia	Cruise: Large Turns Maneuvers: Attitude Control Authority Post-Separation: Turns & Burns Autonomously	TMI Completion: 1110 m/s Midcourses: 50 m/s MOI: 1650 m/s Orbit Trim: 50 m/s Deorbit/Reorbit: 110 m/s	~200 watts ave.	~5800 kg (wet) ~1050 kg (dry) (incl adaptors)	none

Figure 1-3. Option 98A Configuration Description



	Supplier	ACS Reqts	ΔV Reqts	Power Reqts	Mass	Payload
Lander	US	Cruise: Determination & Control Maneuvers: Determination, Commanding	Ballistic Aeroentry From Orbit	~350 watts ave.	~450 kg (dry)	Potential polar science payload
Interstage	US	Cruise: Control Authority Maneuvers: Att. Determination	Cruise ACS: 30 m/s; Adjust for Drift 700 m/s; Deorbit/Reorbit: 100 m/s	Generates Power for All Systems ~700 watts (at Mars)	~800 kg (wet) ~475 kg (dry) US Total: 1250 kg US Margin: 0 kg	None
Descent Module	Russia	Spin Up Prior to Aeroentry Passive afterwards	Ballistic Aeroentry	Negligible	~710 kg	Russian Rover (w/ Potential US Instruments) French Balloon
Fregat	Russia	Cruise: Large Turns Maneuvers: Attitude Control Authority Post Separation: Auto. Turns & Burns	TMI Completion: 1110 m/s Midcourses: 50 m/s MOI: 1650 m/s Orbit Trim: 50 m/s Deorbit/Reorbit: 110 m/s	~200 watts ave.	~5800 kg (wet) ~1050 kg (dry) (incl adaptors)	None

Figure 1-4. Option 98B Configuration Description

Both sides agreed that a single descent module was preferable. The single normal-sized descent module is a current design prepared for the Russian-only mission. A smaller module would require new design work with the attendant increase in cost and risk. Also, it would be necessary to de-orbit both descent modules at the same time, so there is little operational advantage in having two.

The baseline US national program calls for two Surveyor spacecraft to be launched in 1998—one orbiter and one small lander. In principle, MT-98 could be stacked with the Russian descent module while the other is launched separately. If both launches were successful, any combination would work in achieving the US goals for the 1998 opportunity.

Having the orbiter in the stack with the descent module offers two clear advantages. This configuration will deliver to Mars a self-contained complex of elements. No external element is necessary to ensure the success of the mission. In the alternative case, the destiny of descent module science would depend on the result of the second launch (or availability of MGS at that time). Also, the US orbiter can carry both PMIRR and GRS, thus achieving the science objectives of Mars Observer.

The fact that the Proton could provide delivery of the Polar Pathfinder Mission to the Martian south pole in late 1999 was also considered. All other polar lander mission options incur either a large mass or flight time penalty. This was an attractive argument for a US lander in the MT-98 stack, but the consensus of the study team was that the arguments for the orbiter were stronger.

1.5 Recommended Option

Two options, 98A (Fregat/descent module/orbiter) and 98B (Fregat/descent module/lander) were studied in detail. While both options were found technically reasonable, the 98A option was chosen to minimize overall mission risk. Various issues of risk and interfaces were considered, including telecommunications, attitude control, command data handling, power, and mechanics. The primary factors in favor of 98A were that it is self-contained and includes both GRS and PMIRR. At the August meeting, option 98B was excluded from further consideration for the 1998 opportunity. (However, this concept could be attractive for the 2001 opportunity (see Section 1.9.)) Only the Fregat/descent module/orbiter is now recommended for further work for 1998.

1.6 Scientific Payload for MT-98 Mission

Descent Module: The descent module will deliver the rover and balloon station to the surface of Mars. Russia has technical responsibility for the rover; the responsibility for the balloon station is shared by France's Centre National d'Etudes Spatiales (CNES) and Russia.

Scientific experiments and instruments for the rover and the balloon were selected by the International Scientific Committee of the Mars-94/96 Project. Design and, in some cases, production has started. Some changes are still possible. For example, new experiments from the US could be included in the rover payload, although restrictions in mass, volume, and power are severe. The existing rover concept presumes a full mass of about 100 kg, with a scientific payload of about 14 kg.

Two potential US experiments, an imaging spectrometer and a mini-met station, were presented at the August meeting. Technical accommodation issues will be studied by the Russians. Both sides recognize that these are not the only possible instruments and that should the opportunity arise for US participation in rover science, a free and open process would be initiated in the US to solicit additional ideas. Following this process, a final recommendation would be agreed upon by both sides.

Orbiter: The Surveyor 2 orbiter spacecraft is currently in the conceptual design phase at JPL and will be procured from a US industrial partner to be named in 1995. The Surveyor 2 will be ready in time.

The baseline US national program plan is for this orbiter to be launched by a Medlite, probably carrying only one instrument. However, the Mars Together opportunity increases the payload mass available, offering the possibility of an expanded payload, to complete the Mars Observer mission objectives. The combined orbiter and interstage mass will be less than 1050 kg. It is still not known how much weight will be allocated for the scientific payload. This payload (funds permitting) should contain a US PMIRR experiment, a US gamma-ray spectrometer, a wide-angle camera (development source is still to be determined) and a radio relay for communication with descent module elements, potentially to be provided by France.

Some changes are possible. Additional Russian experiments such as those presented at the August meeting could be included in the Surveyor 2 scientific payload. Technical accommodation issues on these proposals will be studied by the US. Priorities and final recommendations will be made by mutual agreement.

Penetrators: At the August meeting, the Russian side proposed inclusion of one or two penetrators in the MT-98 scientific payload. A design already exists, and the first set of devices will be tested during the Mars-94 (now 96) mission. Penetrators could be attached to the Russian APS system without imposing any additional requirements on the US orbiter, although this could constrain orbiter mass.

The US response was generally positive. It was noted that this new element would not have any impact on the US spacecraft and that it was important to broaden Russian science support by involving the Vernadsky Institute. The only concern was the increased cost to RSA of the MT-98 mission. However, it was fully recognized that in the context of a cooperative mission, this is exclusively a Russian issue.

1.7 Schedule for MT-98

The current schedule proposes launch in December 1998 and arrival at Mars in September 1999. Predicted strong seasonal winds in the Northern Hemisphere at the time of arrival pose a potential problem. Current estimates of wind velocities are incompatible with the technical restrictions on Marsokhod and balloon descent operations. The following solutions will be studied:

- Changes in the design of the descent elements and operation sequence
- Possible earlier arrival using mass reserve
- A delay in orbit to the end of the strong wind period (6–8 months) before releasing the descent module
- Adjustment to the descent time to correspond to the predicted daily minimum wind velocity

A flexible approach should be taken to descent time selection, as in the Viking mission where a flexible strategy of landing-site selection was successfully implemented.

1.8 Open Issues on MT-98

A mutual understanding must exist regarding decision-making processes in both countries. Work should start at the beginning of 1995 with adequate financial support on both sides. A final US agency decision on US participation is expected early in 1995. An important step will be the endorsement by the Gore–Chernomyrdin Commission, based on a summary report and other materials. The first phase of work (phase A/B in American terminology, "teknicheskoe predlozhenie" and "eskiznyi project" in Russian) should be completed by June 1995. It could be started immediately in January 1995 if the MT-98 project is endorsed by the Gore–Chernomyrdin Commission.

Drawings of the US spacecraft and interstage are needed by the Lavochkin Association for the technical work of accommodating the combined spacecraft. The US side agreed to provide these drawings no later than 1 October 1995.

Drawings of the orbiter scientific instrument platform are needed for both sides to study the accommodation possibilities for potential Russian instruments. The US side promised to provide these drawings no later than 1 October 1995.

A mission time line that effectively deals with possible adverse winds needs attention.

US Launch Approval: All space transportation elements for the Mars Together are Russian: the first three stages of Proton, the Block D fourth stage, and a Russian fifth stage. The payload consists of Russian and US spacecraft. Only the Russian spacecraft carries an RTG, which contains a smaller amount of plutonium than that carried by Voyager, Galileo, or Cassini. The US spacecraft carries no nuclear materials. Discussions over the last three months reveal that the Russian planetary program has used RTGs and a launch approval process exists that appears to parallel the US process in many respects. Discussions on the Russian process continue. From the information available, it appears that any US launch approval requirements for this mission may be largely or totally satisfied by the Russian process. A better understanding of the Russian launch approval process is expected to reinforce this conclusion. It is recommended that substantive discussions between the US and Russia on launch approval proceed as rapidly as possible.

1.9 Beyond 1998

A plan to discuss possible future cooperative projects after MT-98 was accepted by the study team in June. These possibilities include additional flights of the basic configuration planned for 1998. In particular, the 98B option (see Figure 1-4) should be considered for 2001 or later. In addition, a Phobos Sample Return Mission (SRM), a Network mission (Mars Glob), and a Mars Sample Return mission are possibilities.

Both sides agree that sample return of extraterrestrial material has high scientific significance. Initial discussions of possible joint Phobos and Mars sample return missions beyond 2000 were started in July.

Phobos SRM is one of the probable options for the Russian national program beyond 2000. The US position is that only a small US participation in the Russian Phobos SRM could be assumed at the moment.

The US side proposed a possible joint Mars SRM as an extension of the Mars Together concept. Russian specialists think that a Phobos SRM could be a useful precursor to the Mars Sample Return mission. Both sides plan to proceed with further option studies for both kinds of potential joint sample return missions, Phobos and Mars.

1.10 Conclusion

The first joint study results confirm that MT-98 can be accomplished by the US and Russia as a joint mission if a decision process is started in December 1994 and completed in June 1995. Phase A/B of the MT-98 project should be conducted in the first half of 1995.

1.11 List of Supplements

A series of supplements to this chapter is available:

1. Summary of Discussion: US/Russian Space Sciences Meeting, Moscow, Russia, April 7–9, 1994 (incorporated in the Summary to this report).
2. Summary of June 6–9 Meeting (2 volumes)
3. Summary of July 14–16 Meeting
4. Summary of August 29–31 Meeting (3 volumes)
5. List of Recommended Experiments on Rover
6. List of Recommended Experiments on Balloon
7. Preliminary time line for MT-98 A
8. List of Potential Russian Proposals for US Orbiter
9. Summary for senior management officials (draft)

1.12 Membership

The members of the Mars Together Joint US-Russian Team are listed below:

R. Bourke	R. Kremnev
J. Boyce	V. Linkin
C. Elachi	B. Martynov
D. McCleese	V. Moroz
J. McNamee	O. Papkov
D. Murrow	K. Pichhadze
D. Shirley	G. Rogovsky
S. Squyres	Y. Surkov

CHAPTER TWO

FIRE: The Solar Probe

2.1 Introduction and Background

One of the fundamental mysteries in the universe is why ordinary stars like the Sun have extremely hot outer atmospheres (approximately one million degrees), while their surface temperatures are only thousands of degrees. To understand the existence of this outer atmosphere—the corona—the physical processes that occur there must be understood. Although both ground-based and satellite-borne remote-sensing observations have provided important clues, they have failed to provide answers to fundamental questions about this extreme heating.

Near-Earth observations have provided data on the thermodynamics and flows of the solar corona. However, all of the important physical processes thought to be the source of the heating involve small-scale phenomena that cannot be determined from line-of-sight integrated observations. Only *in-situ* measurements taken from inside the corona, combined with imaging of these extremely fine structures undertaken by a satellite traveling very close to the Sun, will provide the data to help researchers understand what makes the corona so very hot. The FIRE mission proposes first-time measurements from a point much closer to the Sun than any other satellite has ever approached. (Helios traveled only to 60 Rs, or 42 million kilometers, and only in the ecliptic plane.)

The processes that heat the solar corona, and thus provide the energy and momentum that accelerate the solar wind, occur over an extended radial distance, from tenths of a solar radius above its surface to about 30 Rs above (almost 21 million kilometers). In addition, these processes may be quite different over the polar and the equatorial regions, partly due to the different local magnetic field characteristics in the two regions. It is also highly probable that the heating and expansion of the solar corona are dynamic processes, continuously changing with time and space. Therefore, in order to understand these processes at different solar latitudes and to understand how the dynamics of the corona change with time and location, researchers need *in-situ* measurements taken at a variety of altitudes above the surface of the Sun and at different latitudes.

The FIRE mission consists of two spacecraft—one US and one Russian—synchronously traveling along polar trajectories close to the Sun. The US inner spacecraft will travel from 8 Rs (almost 6 million kilometers) over the poles to a 4 Rs perihelion at the equator, where the solar wind becomes supersonic. This is the closest approach that current technology will allow. The Russian outer spacecraft will travel from 20 Rs over the poles to a 10 Rs perihelion at the equator. Thus the FIRE mission, for the first time, will achieve simultaneous measurements from this range of altitudes and latitudes in the solar corona and will also provide imaging of both the underlying coronal region and the surrounding corona. This will enable researchers to determine the 3-dimensional coronal structure, so as to identify the regions of the Sun that are responsible for particular solar wind flows and the mechanisms that generate coronal heating and solar wind acceleration, thus answering the question of why the solar corona exists. Additionally, solar observations from Earth will help put *in-situ* FIRE measurements into context with large-scale coronal structures.

Both FIRE spacecraft will be launched with a single Russian Proton rocket on a trajectory that will take them first to Jupiter and then to the Sun. The Jupiter encounter is needed to remove orbital angular momentum, allowing close approaches to the Sun. Flyby of the Sun occurs 3.7 years after launch. The selected inclination of the orbit is 90°, providing a passage over both solar poles. This trajectory design maximizes the types of known coronal structures that can be studied by the probes, allows continuous communication with the Earth (because there are no solar occultations), and also allows a simultaneous orthogonal view of the Sun and its corona by ground-based and space-borne context observations.

2.2 Science Objectives and Payloads for Joint Mission

The primary focus of the FIRE mission is to study outstanding fundamental scientific questions about the last unexplored region of the inner solar system. FIRE will help determine the origin of the solar corona, and its structure and dynamics.

Science Objectives: The major scientific objectives of the mission are summarized below in the context of current knowledge of the Sun's corona. To date, this is based only on remote observations from Earth and some radio penetration measurements.

Why Does a Corona Exist Around Our Sun? The defining characteristic of the solar corona that sets it apart from the lower layers of the Sun's atmosphere is its million degree temperature. This unusual property was first recognized in the early 1940's and remains unexplained today. This temperature is much higher than that of the dense photospheric gas below (6000 K), so that radiative and conductive losses from the corona must be balanced by some non-radiative energy source.

Initial theories to explain the corona suggested that waves generated by convective turbulence just below the photosphere might be the source of mechanical heating. Observations of the scintillation of radio signals that have passed through the solar corona indicate that there is strong plasma turbulence at distances of less than 30 Rs. However, after nearly 50 years of research, there is still no experimental confirmation that turbulent heating is the dominant mechanism. Some more recent ideas suggest that the energy input is due to micro-activity at much lower altitudes. Unfortunately, remote measurements cannot test this theory because line-of-sight observations are biased to favor the lowest, densest layers at a given temperature. Remote measurements of the outer corona also integrate over a very large volume, thus preventing resolution of individual, small-scale structures. Only *in-situ* observations by the FIRE mission can provide definitive data to answer these questions.

Alternative means of energy input may also be possible. Examples that have been suggested include jets of upward-moving gas accelerated at lower altitudes by flare-like processes, and the incremental addition of momentum through secondary, jet-driven magnetohydrodynamic waves and diamagnetic forces. Solar wind acceleration can be directly inferred from comparisons between the measured flow states along two coplanar trajectories having different perihelia, which will be accomplished with the dual-spacecraft FIRE mission.

Where Are the Regions Near the Sun That Create the Solar Wind? All observations of the solar wind have been obtained from distances beyond the orbit of Mercury, 80 Rs. The observed flows are classified into two major categories: high-speed and low-speed solar winds. Attempts to locate the origins of these flows in the low corona have failed because little is known about the evolving bulk speed as a function of height above the coronal base. The possibility of time-dependent acceleration, non-radial flows as seen in eclipse photographs, and the Sun's rotation, all combine to provide considerable complexity and uncertainty in the coronal sources of measured solar winds.

The simplest and best understood case of solar wind flow suggests the expansion from a coronal hole becomes a high-speed wind observed near Earth. Density decreases with increasing radial distance and causes a pressure gradient that accelerates the flow upwards. The flow is subsonic near the Sun, but it becomes supersonic with increasing distance. However, if one uses measured conditions at the base of the corona to calculate expected flows at 1 AU, the calculated flows are far less than the measured values. Theoretical models indicate that additional heat and/or momentum must be added to the outflowing plasma over an extended region.

A potential source for the slow solar wind is the magnetic sector boundary within the helmet streamer belt that encircles the Sun. However, several other coronal structures, such as the general quiet corona and regions of magnetic activity, may also contribute to the slow speed solar wind.

What Mechanisms Accelerate, Store, and Transport Energetic Particles Near the Sun? Past studies of particle acceleration mechanisms in interplanetary space and within planetary magnetospheres have identified three general classes of processes:

- Acceleration by shock waves through a Fermi process
- Acceleration due to plasma turbulence
- Acceleration by inductive electric fields, as is predicted to occur at sites of magnetic reconnection

Acceleration of electrons to hundreds of MeV and protons to several GeV occurs in a matter of seconds (as inferred from gamma-ray flares). These flares and the events that yield anomalously high abundances of ^{3}He and other heavy ions are mysterious. Some proposed mechanisms can be determined by observing particle properties at energies below about 1 MeV. Near-solar observations are required because at 1 AU the observed properties are obscured by velocity dispersion and energy diffusion as the particles pass through overlying, strongly turbulent coronal layers. Instrumentation on the FIRE mission will directly measure the effects of strong plasma turbulence on energetic particle transport.

The same problem applies to attempts to observe the time-dependent fluxes of suprathermal electrons generated by the ensemble of small (nano- or granular-scale) impulsive events thought to contribute to general coronal heating. Such fluxes from larger flare-like solar outbursts are believed to be remnants of the magnetic annihilation process. From remote-sensing observations, it is known that the electrons carry a major fraction of the total energy released in these events. However, if intense suprathermal electron fluxes are produced episodically on granule-size scales, they must coalesce spatially before reaching the orbit of Mercury because they have yet to be positively identified using particle and field sensors aboard all previously flown missions. This issue can be resolved in one perihelion passage by *in-situ* observations aboard the FIRE spacecraft.

Solar-Terrestrial Connections: The solar wind is responsible for the formation and the existence of the heliosphere (the sphere of influence of the Sun), a region that extends well beyond the distance of the known planets. The state of the Earth's magnetosphere is also controlled and perturbed by the variations in the solar wind. This variability leads to complex magnetospheric dynamics including magnetic storms and intense aurora, enhanced radiation belts, and ionospheric and radio disturbances. Technological systems such as Earth-orbiting spacecraft and ground-based power systems are susceptible, as are human beings, to the increased radiation and the extreme currents associated with geomagnetic storm activity that is a product of solar wind variability.

The FIRE mission will significantly contribute to understanding of the solar-terrestrial connection by establishing the association between specific solar wind flows and the magnetic field structures in the lower solar atmosphere. This knowledge will contribute to the possibility of forecasting geomagnetic disturbances such as magnetic storms and large auroral displays.

Measurement Objectives and Payloads: The near-Sun scientific objectives require two generic classes of measurements:

- Coordinated *in-situ* observations using a complement of particle and field experiments on both FIRE spacecraft
- Imaging experiments, consisting of coronal imaging on the inner spacecraft and disc imaging on the outer spacecraft

The range of scientific objectives and the instrument payloads for each FIRE spacecraft are shown in Figure 2-1. Here each major objective is identified as a horizontal line plotted on a scale of distance from the Sun in solar radii. Note that the US mission travels to a perihelion of 4 Rs and the Russian mission travels to 10 Rs. This can be compared to the only other "Solar Probe" mission, Helios, which reached 60 Rs, as shown in Figure 2-1. The specific set of measurement objectives of FIRE is summarized below.

FIRE Particles and Fields *(In-Situ)* Measurement Objectives:

- Determine the characteristics of the magnetized plasma of the solar wind in the lower and upper corona
- Characterize plasma dynamics in the context of large-scale magnetic structures in the coronal-source regions of the solar wind
- Determine the nature of the waves and plasma turbulence in the corona and inner heliosphere, as well as their role in solar-wind dynamics
- Characterize the magnetic fields, temperatures, and morphology of the underlying coronal structures
- Measure the spectrum and determine the origin of energetic particles in the corona and inner heliosphere

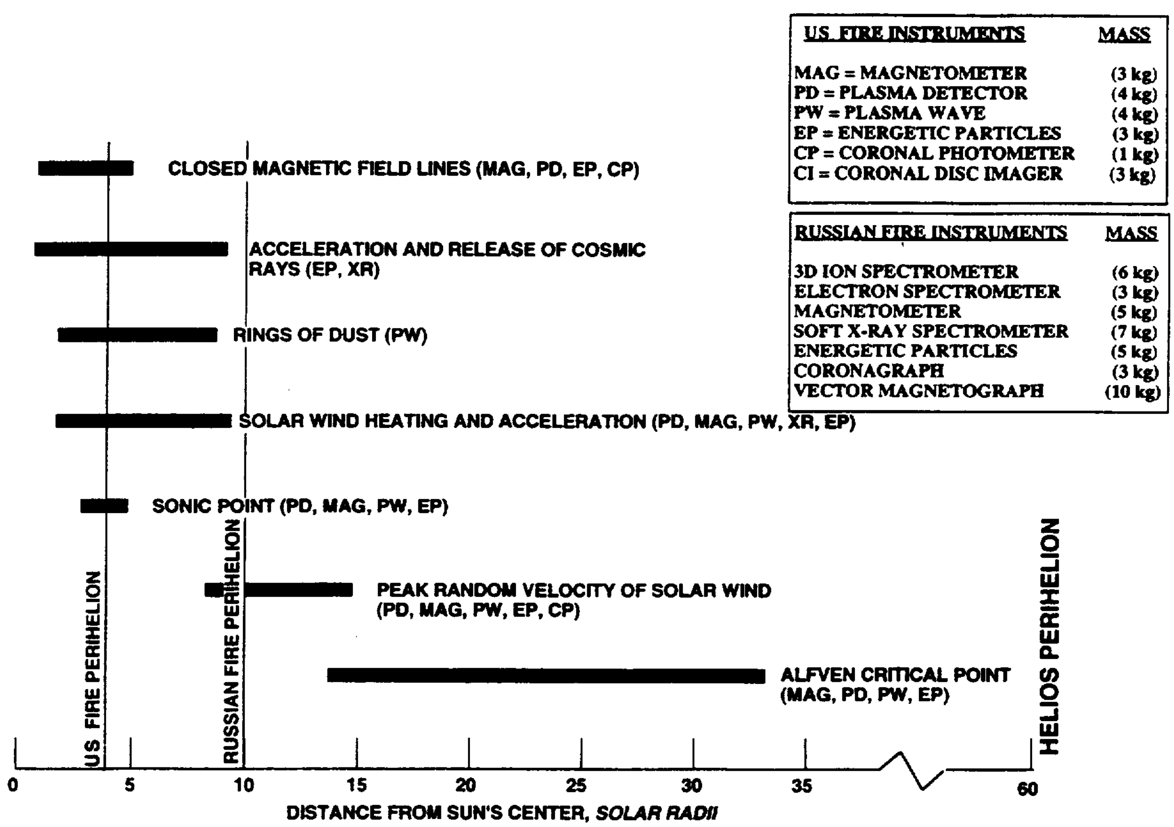


Figure 2-1. FIRE Near-Solar Objectives and US & Russian Instruments

FIRE Imaging Measurement Objectives:

- Obtain the 3-D structure of the large-scale corona for the first time by utilizing the view from polar trajectories provided by FIRE
- Infer the coronal properties below the regions sampled by the *in-situ* FIRE experiments
- Obtain high-resolution images (<70 km on the Sun) of coronal structures that are impossible to resolve from the Earth
- Measure and characterize the polar magnetic fields

It is expected that the FIRE mission will be complemented by a suite of remote-sensing experiments operating from near-Earth orbit satellites, balloons, and rockets or from ground observations taken during the time of perihelion passage. These observations will determine the solar global-to-medium scale structures of the Sun's corona and provide other context observations during the FIRE encounter.

2.3 Mission Options

Many mission design options exist to accomplish the FIRE mission. The joint study team considered various combinations possible for mission implementation; these included launch vehicles, upper stages, and spacecraft implementation modes. Four of the options are summarized in this section. All of the options studied employ launch on a direct trajectory to Jupiter for a gravity-assist maneuver leading to a trajectory toward the Sun. By consensus, the recommended option employs a four-stage Proton launch vehicle, a US-built Star 48 upper stage, a Russian-built spacecraft, a US-built spacecraft, and cooperative payloads on both spacecraft.

The four major options considered are illustrated in Figure 2-2, which shows their launch configurations.

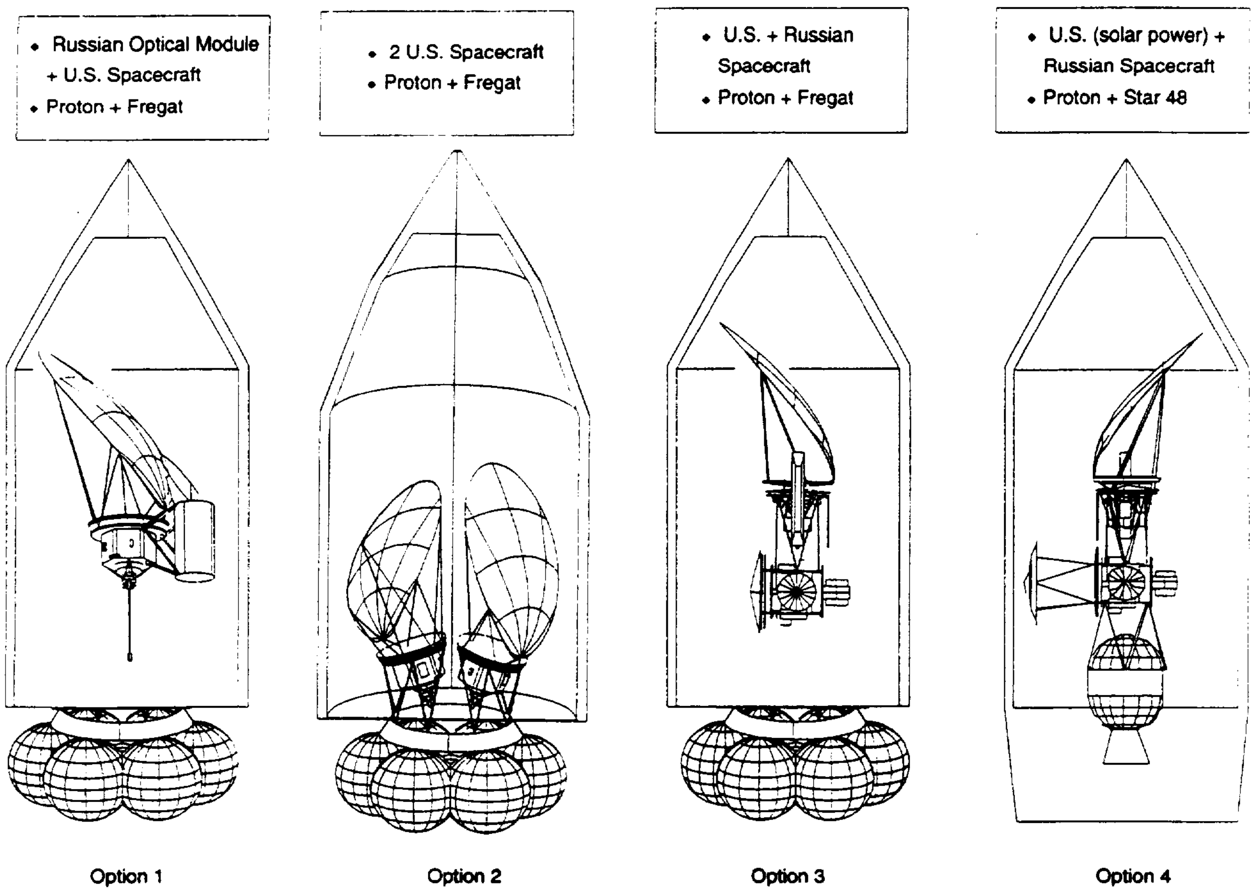


Figure 2-2. Evolution of FIRE Spacecraft Options

Option 1: Optical Module with a Proton-Fregat Launch Vehicle. The first option considered is a single US-built spacecraft, launched by a Proton-Fregat vehicle and targeted for a 4 Rs flyby of the Sun. The science payload would consist of fields and particles instruments along with a Russian-built optical module to provide direct imaging of the Sun to within about 30 Rs, at which point the optical module would be separated prior to the perihelion passage.

This was not an acceptable option for the Russians, who felt that the merits of a separable module were few and would, therefore, not be supported by the Russian scientific community. In addition, this mode was not favored by the spacecraft design and manufacturing community within Russia as their role in the mission would be diminished.

Option 2: Two US-Built Spacecraft with a Proton-Fregat Launch Vehicle. This option comprises a single launch of two US-built spacecraft by a Proton-Fregat vehicle. The two spacecraft would be separately targeted for 4 Rs and 10 Rs perihelia, with the payloads on each spacecraft tailored for the different destinations. Disk imaging would be emphasized with the 10 Rs-targeted spacecraft, while coronal imaging and fields and particles data could be acquired with the 4 Rs spacecraft. This option was unattractive to the spacecraft design and manufacturing community within Russia as it offered them only minimal participation.

Option 3: One US-Built Spacecraft and One Russian-Built Spacecraft with a Proton-Fregat Launch Vehicle. It became clear that an active role by the Russian spacecraft design and manufacturing community was essential to the success of this cooperative program. This led to a third option consisting of a single launch of two spacecraft with a Proton-Fregat vehicle. This option introduced a 10 Rs spacecraft that would be totally designed and manufactured within Russia. The 4 Rs spacecraft would still be designed and built in the US. Scientific payloads would again be tailored for their respective perihelia with joint participation encouraged in both payload sets.

This option was attractive to both sides and offered the necessary Russian participation. In particular, it provided the impetus for the development of Russia's next generation planetary spacecraft. New technology would need to be introduced into the Russian spacecraft to meet the mass allocation allowable with the launch vehicle.

A concern is that Option 3 requires the Fregat upper stage for the launch vehicle, thus increasing the cost to the Russian side. Nevertheless, this option may be viable and is considered a backup for the preferred Option 4.

Option 4: One US-Built Spacecraft and One Russian-Built Spacecraft with a Proton-Star 48 Launch Vehicle. The fourth, preferred, option implements a single launch of two spacecraft with a Proton-Star 48 vehicle injecting two spacecraft toward 4 Rs and 10 Rs encounters (US and Russian spacecraft, respectively). Each spacecraft would carry cooperative payloads optimized for their respective missions.

This recommended option is attractive to both sides because it makes possible the participation of Russia's engineering community and provides the impetus for the development of Russia's next generation planetary spacecraft. Furthermore, it utilizes the US-built Star 48 upper stage and does not require the Russian upper stage (Fregat). This is perceived as a more cost-balanced solution on both sides. The preferred option, option 4, is illustrated in Figure 2-2. Details of the spacecraft designs for both sides can be found in Sections 2.6 and 2.7.

2.4 Selected Mission Design and Rationale

The FIRE concept represents the first mission to combine out-of-the-ecliptic scientific coverage with dual, close solar encounters. A US and a Russian spacecraft will be launched on a journey to the Sun, where the spacecraft will fly by the Sun at minimum distances of 4 Rs and 10 Rs, respectively. The two spacecraft will be launched from the Baikonur Cosmodrome aboard a single Russian Proton launch vehicle. They will be injected onto an Earth-Jupiter-Sun trajectory that employs a Jupiter gravity-assist swingby for retargeting back to the Sun.

The mission design for both spacecraft includes the following sequence of operations:

- Insertion of the Proton payload or Space Head (composed of the Proton 4th-Stage D, the Star 48 Upper Stage plus the US and Russian spacecraft) into a low Earth-parking orbit using the first three stages of the Proton launch vehicle.
- Injection of the Space Head from the low Earth-parking orbit, using the Proton 4th-Stage D and the Star 48 upper stage, onto an interplanetary trajectory optimized for a 4 Rs perihelion.
- Separation of the US and Russian spacecraft from the Star 48 upper stage in preparation for independent flight trajectories.
- Execution of three trajectory correction maneuvers (TCMs) during the trans-Jupiter cruise. Transfer of the Russian spacecraft onto a trajectory with a perihelion radius of 10 Rs (after Jupiter flyby), achieved during the execution of its first correction maneuver approximately 30–40 days after launch. The magnitude of this maneuver is not to exceed 25 m/s.
- A gravity-assist swingby of Jupiter retargeting both spacecraft onto heliocentric trajectories with inclinations of 90° relative to the ecliptic plane and perihelion radii of 4 and 10 Rs, respectively.

- Execution of TCMs during the Jupiter–Sun trajectory to provide simultaneous perihelion passes by both spacecraft.
- Simultaneous exploration of the Sun and near-Sun environment by two vehicles during the approach and encounter phases of the mission.

The trajectories of the US and Russian spacecraft are illustrated in Figure 2-3. Note that the 10 Rs spacecraft arrives first at Jupiter because its orbital period is slightly larger than the spacecraft traveling to 4 Rs. Not shown in the figure is the quadrature alignment required at perihelion where the plane of the 4 Rs orbit is required to be perpendicular to the spacecraft–Earth line.

The characteristics of the Earth-Jupiter-Sun trajectories for perihelia of 4 Rs and 10 Rs (launch window in 2001) is shown in Table 2.1. Note that the Sun-spacecraft-Earth angle at perihelion must be slightly modified to be exactly 90° satisfying the quadrature requirement of the 4 Rs spacecraft.

2.5 Selected Launch Configuration

To launch the US and Russian spacecraft onto an Earth-Jupiter-Sun trajectory and to simultaneously fly by the Sun, it is necessary to establish a Space-Rocket Complex (SRC). The SRC can be represented by the following scheme:

Launch Devices	**Space Head**	**Ground Control Complex**
Technical complex	*D top stage*	*Flight control center*
Launch complex	*Star 48 upper stage*	*Ballistic center*
Booster	*Adapters*	*Other facilities*
	US spacecraft	
	Russian spacecraft	
	Head fairing	

The Proton is baselined as the launch vehicle booster option, although the Proton-M will be available in 1996 and could also be used (see Table 2.2). The Baikonur site will be used for integration and launch.

Table 2.1 FIRE Trajectory Parameters

Project FIRE		
Radius of Perihelion	**4 Rs**	**10 Rs**
Timeline mission parameters		
Launch	10 Sept 2001	10 Sept 2001
Flight time Earth–Jupiter (days)	499	497
Date of Jupiter flyby	22 Jan 2003	20 Jan 2003
Flight time Jupiter–Sun (days)	830	832
Perihelion pass	30 Apr 2005	30 Apr 2005
Full mission duration (days)	1329	1329
Departure from Earth		
V (km/s)	10.933	10.954
(Geo-equatorial plane) (deg)	27.160	27.137
C_3 km^2/s^2	119.531	119.990
V_{imp} from low-Earth orbit (LEO) (km/s)	7.731	7.746
V maneuver: 4 Rs–10 Rs (30th day of flight) (km/s)	0.0	0.023
Jupiter flyby		
V (km/s)	12.82	12.88
Pericenter radius of Jupiter flyby ($R_{Jupiter}$)	8.94	8.66
Distance spacecraft–Sun (10^6 km)	793.676	793.607
Distance spacecraft–Earth (10^6 km)	648.648	649.297
Angle Sun–spacecraft–Earth (deg)	2.02	2.32
Angle Sun–Earth–spacecraft (deg)	10.97	12.60
Perihelion pass		
Perihelion velocity (km/s)	308.251	194.447
Angle spacecraft–Sun–Earth (deg)	89.986	90.058
Angle Sun–spacecraft–Earth (deg)	88.956	87.077
Distance spacecraft–Earth (10^6 km)	150.748	150.926

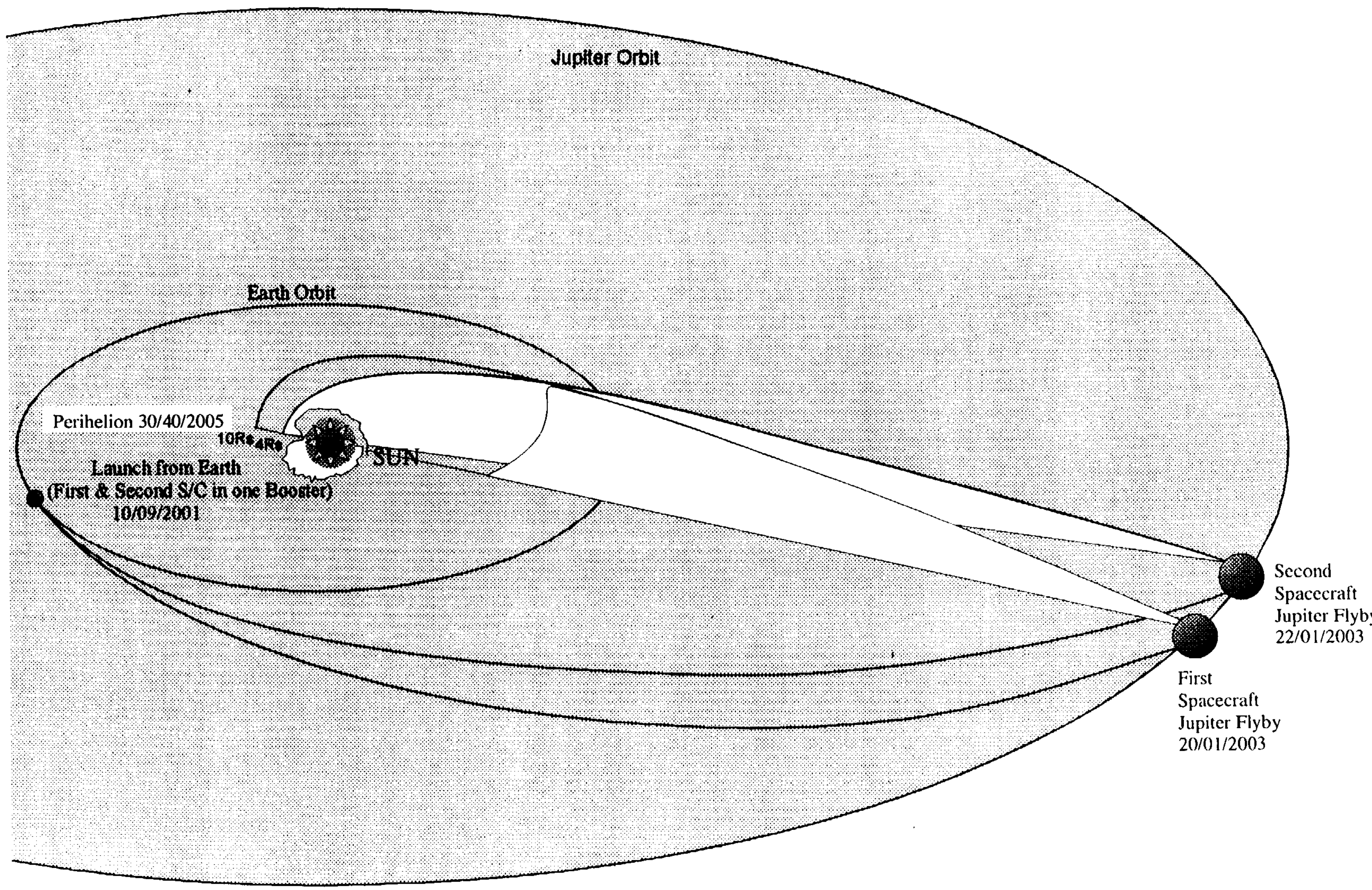


Figure 2-3. FIRE Interplanetary Trajectory Geometry

Table 2.2 Proton Booster Characteristics

BOOSTER		PROTON	PROTON-M
Manufacturer		Khrunichev State Space Center, Moscow	
Number of stages		4	
Mass on the Earth artificial satellite orbit before acceleration, kg		19790	21800
Circular orbit parameters	H, km	200	190
	i, arc. deg.	51.6	51.6
Launch site		Baikonur	
COMMENTS		Proton has been serially manufactured since the mid-1960s	Proton-M is a modernized Proton; regular production is planned for 1996

Different combinations of upper stages have been considered in the composition of the space head (or Proton payload) shown in Figures 2-4 and 2-5. Table 2.3 lists the performance with various upper stage combinations for the standard Proton launch vehicle. Note that the first table considers Star upper stage combinations while the second table considers the Fregat as an upper stage for the Proton. When the Fregat is used, an intermediate Earth orbit (with period T_0) is required to allow an optimum perigee maneuver that minimizes gravity losses and maximizes performance. The preferred option would require only one ignition of the "RB-DS" fourth stage of the Proton, providing launch mass performance of 720 kg for the Star 48B option and 690 kg for the Fregat option. The mass allocation of the US spacecraft will be ~250 kg, while the Russian spacecraft will be allocated ~350 kg. The sum of the two masses plus adapters and other launch hardware can be launched by the Fregat stage with the 690-kg capability, as listed in Table 2.3b. Table 2.4 lists similar performance characteristics for the modernized Proton-M booster. These combinations with the different upper stages launch the payload on a trajectory to Jupiter with the masses shown in Tables 2.3 and 2.4 for a C_3 = 125.44 $km/^2sec/^2$.

As discussed in the "Mission Sequence of Operation," the Proton will inject the "space head" into a trajectory to 4 Rs and the US spacecraft will then separate from the "space head." For the Fregat option, the first post-launch trajectory correction maneuver for the Russian spacecraft will be performed by the Fregat, placing the spacecraft on a 10 Rs trajectory.

In the case of the Star 48 upper stage and a standard Proton booster, the total spacecraft launch mass performance could be ~720 kg, as shown in Table 2.3a. Here the first trajectory correction to enable the 10 Rs trajectory will be the responsibility of the Russian spacecraft to provide a deterministic maneuver of 0.023 km/s at launch plus 30 days, as shown in Table 2.1.

Adapters are required between Russian and US spacecraft and between upper stages. The design of the fairing is analogous to the design used in the Mars Together mission.

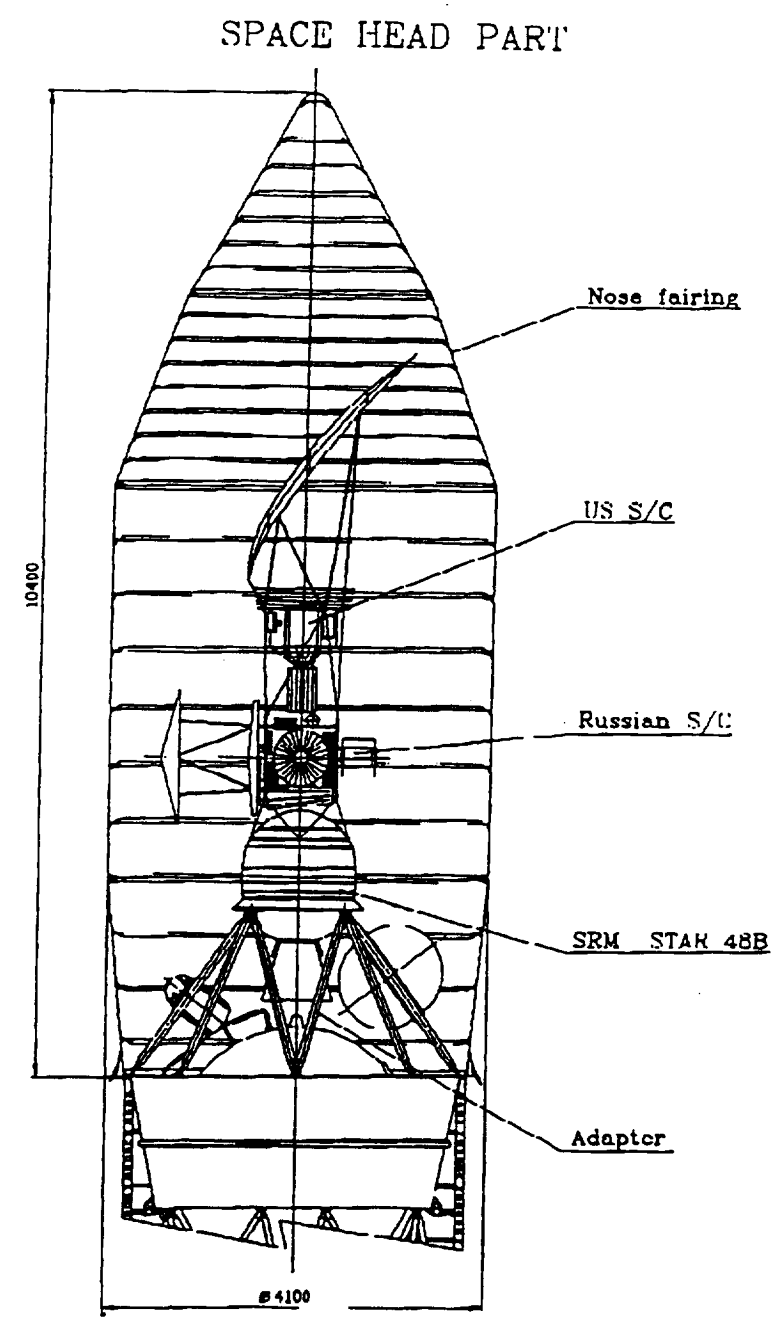


Figure 2-4. Recommended Space Head for FIRE Launch Using Star-48 Stage on Proton

SPACE HEAD PART

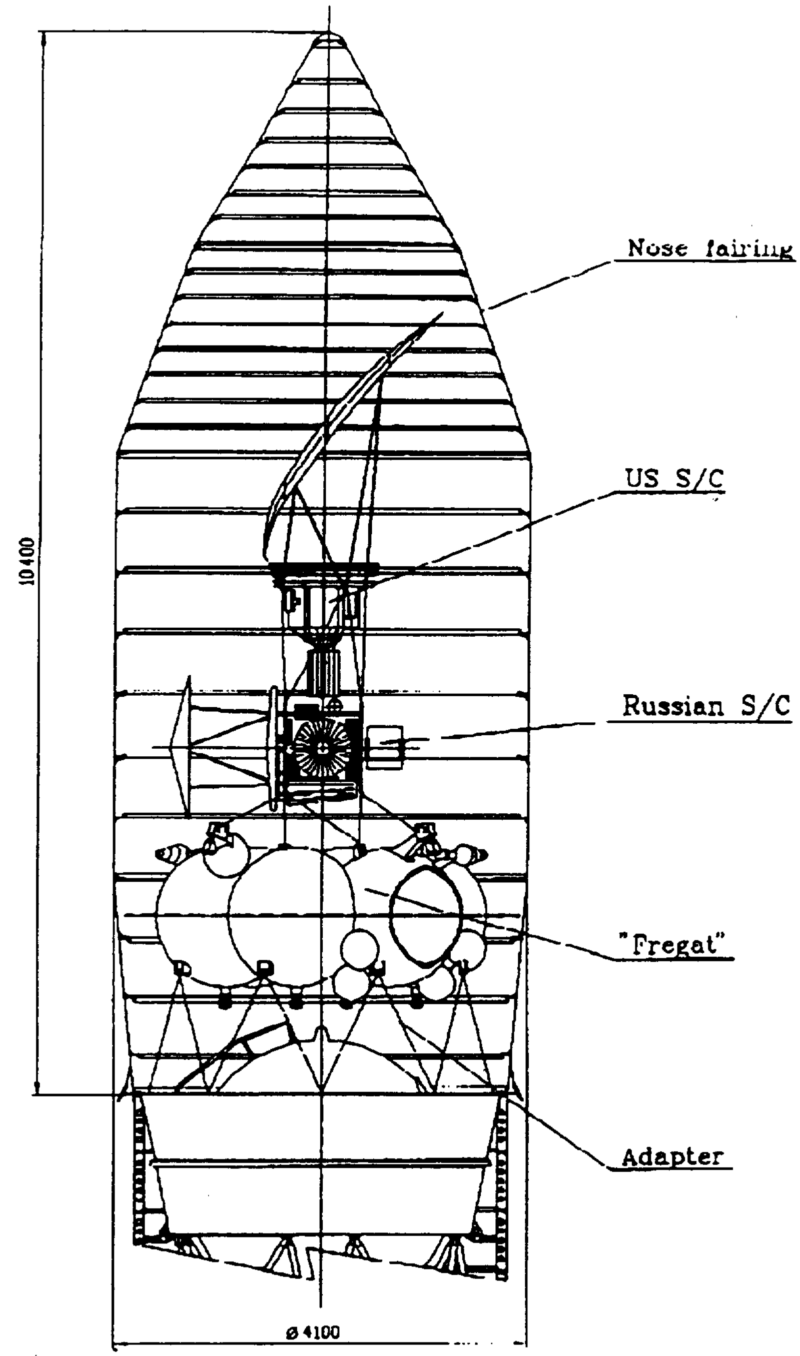


Figure 2-5. Option for Space Head for FIRE Launch Using Fregat Upper Stage on Proton

Table 2.3 Proton Performance Characteristics for the FIRE Mission

a. Star Upper Stages: Proton + RB DS + SRM (US)				
(C_3 = 125.44 km^2/S^2, V_∞ = 11.2 km/s, Δt = 150 s)				
N	**SRM**	**SV, km/s**	**Ms/c, kg**	**Number of RB DS ignitions**
1	48B	4.855	720	1
2	48A+31	3.868	785	2
b. Fregat Upper Stage: Proton + RB D + Fregat				
(C_3 = 125.44 km^2/S^2, V_∞ = 11.2 km/s)				
N	**SV, km/s**	**T_0*, day**	**Ms/c, kg**	**Number of RB DS ignitions**
1	8.082	2	690	1
2	8.089	3	770	2

Table 2.4 Proton-M Performance Characteristics for FIRE Mission

a. Star Upper Stages: Proton-M + RB DS + SRM (US)				
(C_3 = 125.44 km^2/S^2, V_∞ = 11.2 km/s, Δt = 150 s)				
N	**SRM**	**SV, km/s**	**Ms/c, kg**	**Number of RB DS ignitions**
1	63	8.155	795	1
2	48A+31	8.268	840	1
b. Fregat Upper Stage: Proton-M + RB D + Fregat				
(C_3 = 125.44 km^2/S^2, V_∞ = 11.2 km/s)				
N	**SV, km/s**	**T_0, day**	**Ms/c, kg**	**Number of RB DS ignitions**
1	8.085	30	850	1

* - T_0 = intermediate Earth orbital period

2.6 The Russian Spacecraft Concept

The Solar Probe spacecraft is a new-generation spacecraft whose structural and functional performance is based on the latest manufacturing capabilities and technologies. Manufacture and development will accord with modern requirements on safety and ergonomics and, in the case of any incidents, ecological damage should be minimal.

Figure 2-6 is a block diagram of the Russian FIRE spacecraft that indicates the functional modules in each subsystem.

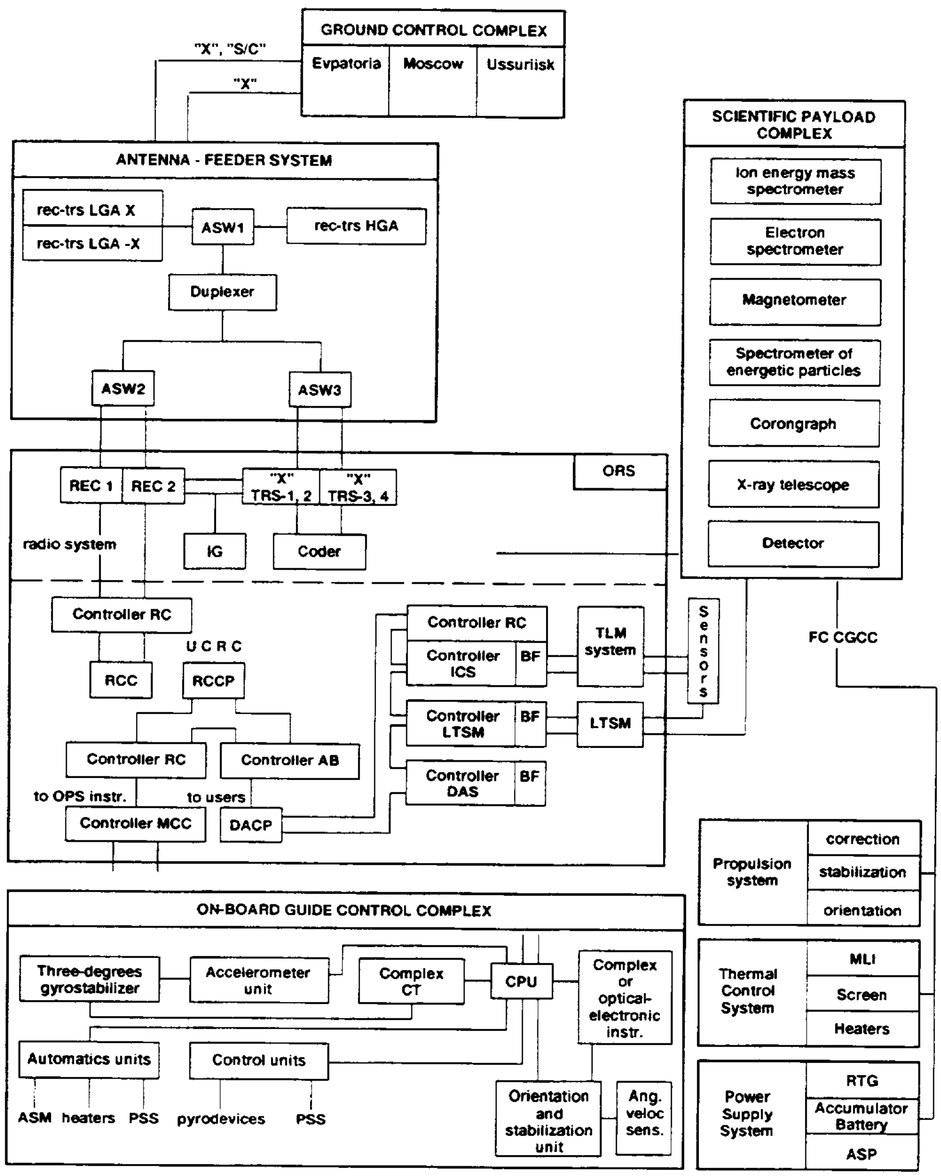


Figure 2-6. Russian FIRE Spacecraft Block Diagram

System Requirements

Perihelion radius	10 Rs
Spacecraft mass should not exceed	350 kg
Maximum power consumption	150 W
Frequency band	X-band
Period of active life no less than	7 years
Maximum telemetry rate (at a distance of 1 AU)	32 Kbit/s
Scientific payload total mass	no less than 35 kg

Subsystem Functional Characteristics

Onboard radio complex:	
• Mass	41 kg
• Receiving band	~7.1 GHz
• Transmitting band	~8.4 GHz
• Maximum power consumption	35 W
• Velocity of transmission from the Sun	32 Kbit/s
• Probability of receiving of a lie command	10^{-9}
• Transmitting information	telemetry, scientific
• Receiving information	command, trajectory
• Operating voltage	27 V
• Orbit determination provided with accuracy	no less than 10 mm/s, 10 m
Antenna system:	
• High-gain antenna:	
– diameter	0.6 m
– antenna gain	24 dB
– required pointing accuracy	20 arc min
• Low-gain antenna:	
– antenna gain	
» receiving	1.0 dB
» transmitting	3.0 dB
Power supply system:	
• Mass	up to 40 kg
• Composition:	
– Radioisotope Thermoelectric Generator	
– accumulator batteries	
– complex of automatics	
• Initial power consumption	10 W
• Output power	max. 150 W
• Output voltage	27 V
Guide control system:	
• Mass	57 kg
• Power consumption	max. 40 W

- Keeping orientation:
  - three-axis
  - one-axis
- Accuracy:
  - of three-axis orientation — 5 arc min
  - standby mode — 20 arc min
- Remaining angular velocities — 0.3 deg/s
- Accuracy of trajectory correction maneuvers — 1% from DV

Propulsion system:
- Mass — 30 kg
- Power consumption — max. 20 W
- Fuel — N_2H_4
- Mass of the fuel — 16 kg
- Pressurization gas — N_2
- Thrust of the correction engines — 50 N
- Thrust of the orientation engines — 0.04 N
- Number of ignitions:
  - of correction engines — 70
  - of orientation engines — 600000

Thermal control system:
- Mass — 25 kg
- Power consumption — 5 W
- Composition:
  - shadow screen
  - set of MLI packs
  - heat pipes with radiator
  - heaters
- Temperature of the interface places of instruments and units — 253 to 323 K
- Temperature at instrument mirror below the primary shield — 123 to 443 K

Structure:
- Shadow screen, shadow screen truss, adapter, antenna, magnetometer boom, etc. are made from carbon–carbon composites.
- Propulsion system units, separation system of the instrument frame, heat pipes, radiator, wave transmitters are made from alloy steels and aluminum alloys.

Scientific Instrument Accommodation:
- Payload mass — 35 kg
- Power consumption — 40 W

If necessary holes will be made in the shadow screen, cooled mirrors will be installed, and screens in sensor payload installation zones will installed, etc., as shown in Figure 2-7. A hole in the center of the shield allows direct solar disc observations using the reflecting mirror located just to the right of the secondary shields ("set of MLI packs" in Figure 2-7). Heat from the mirror is conducted by heat pipes to a radiator located just below the high-gain antenna (HGA), as shown in the Figure 2-7.

Figure 2-7 also shows the latest Russian FIRE configuration with a conical heat shield offset from the main bus to provide the shadow or umbra necessary to maintain thermal control during perihelion passage to 10 Rs. The HGA can be seen at the side of the bus which, because of the perihelion trajectory geometry, will point to the Earth continuously during perihelion passage while the shield remains nadir-pointed at the Sun.

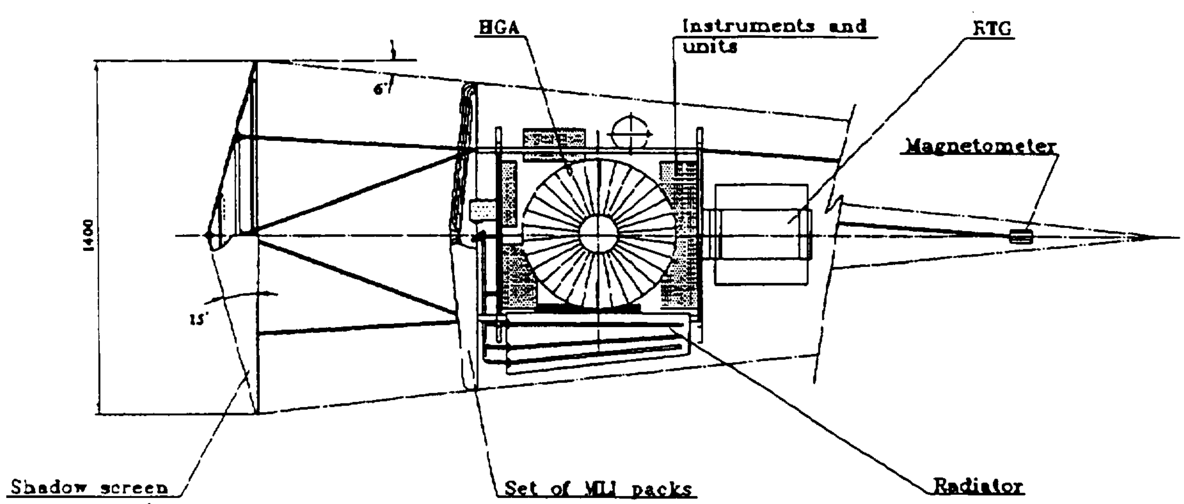


Figure 2-7. Russian FIRE Spacecraft

2.7 US Spacecraft Concept

The US FIRE spacecraft is an example of the use of advanced technology in electronics and materials to produce a high-performance, low-mass, and low-cost vehicle. It is constrained by two program guidelines from NASA. First, it must remain compatible with a Delta-launch vehicle that has a total launch mass constraint of less than 200 kg (at the JGA launch energies) and a total volume envelope to be accommodated under the Delta launch fairing (8 ft or 2.46 m diameter). Secondly, the US spacecraft must carry a non-nuclear powered option to be consistent with the low-cost constraint of the mission but which will cause the termination of the mission past perihelion. The system design is fundamentally affected by the close range to the Sun. The spacecraft must be shielded from intense solar flux (400 W/cm^2) at the perihelion of 4 Rs to allow the spacecraft subsystems to operate at near room temperature. Also, the telecommunications system must provide real-time telemetry at perihelion from within the corona. This can be detrimental to the communications link to Earth. A block diagram of the spacecraft system is shown in Figure 2-8. Component heritage from other programs is indicated in the legend by background shading. The spacecraft subsystem philosophy is to inherit wherever possible from Pluto Fast Flyby and other projects. The following summarizes the top-level design requirements:

- Perihelion radius of 4 Rs
- 2001 launch on a Jupiter gravity-assist trajectory
- Delta-launch vehicle compatibility
- Spacecraft mass less than 250 kg
- Spacecraft power less than 95 W
- Non-nuclear power option
- Perihelion telemetry rate: 4 kbit/s with X-band carrier
- Complete playback of data storage after perihelion
- Shield mass loss rate at perihelion of less than 2.5 mg/s
- Scientific payload total mass less than 20 kg

A preliminary spacecraft design concept exists that satisfies these requirements.

The US FIRE design shown in Figure 2-9 reflects a departure from traditional spacecraft design to reduce the total mass. This design relies both on advanced technology and the integration of functions, such as the use of the primary heat shield as the high-gain antenna. The shield casts a conical shadow or umbra over the spacecraft components at the 4 Rs perihelion as shown in the diagram. The primary shield also doubles as a parabolic reflector, allowing the probe to communicate with the Earth at all times during the perihelion passage. In addition, two secondary infrared shields lie between the main shield and the spacecraft. These shields are conical, allowing more surface area to radiate to space. An open structure provides a low-mass solution for the bus structure. A low-mass,

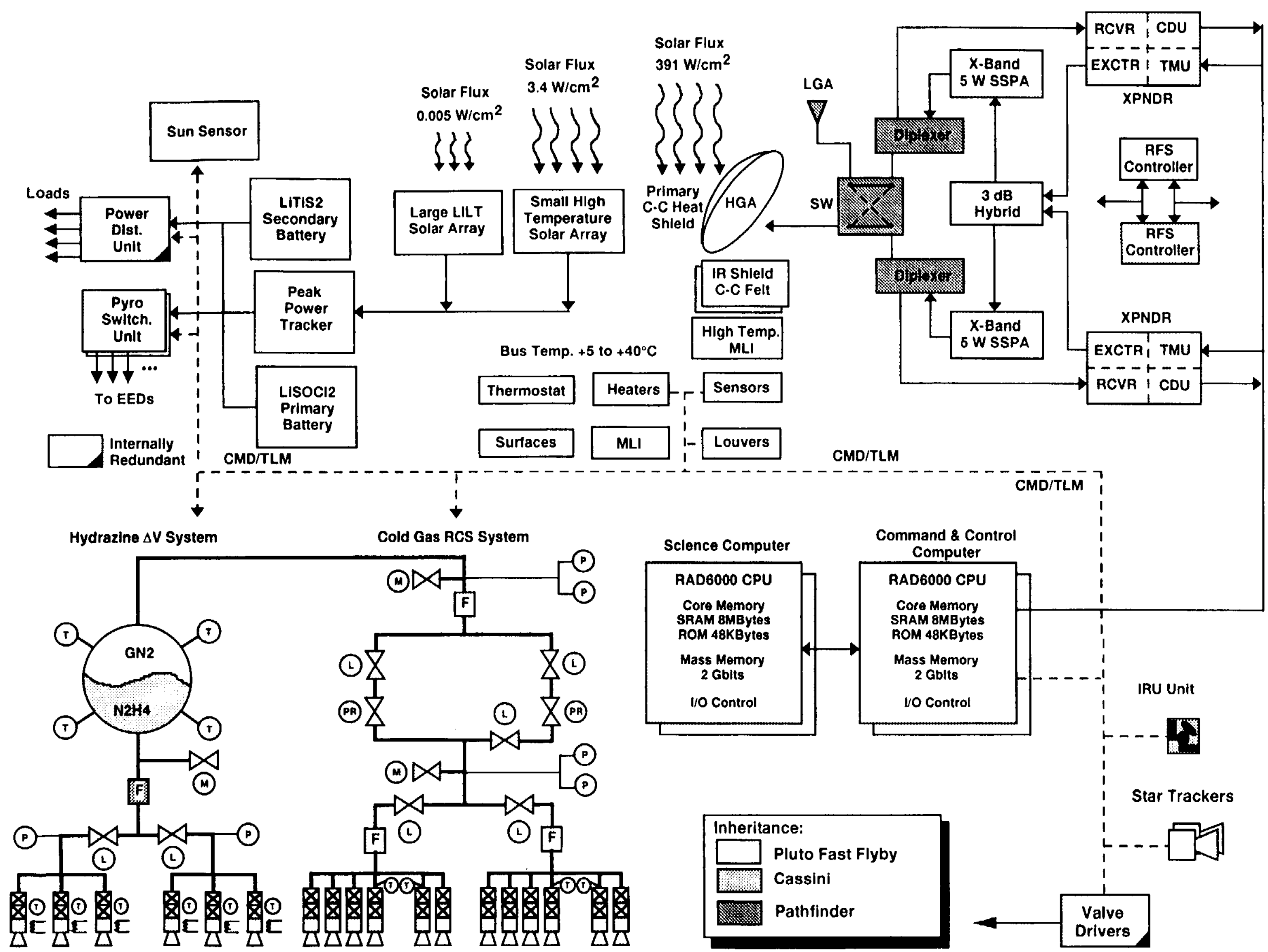


Figure 2-8. US FIRE Spacecraft Block Diagram

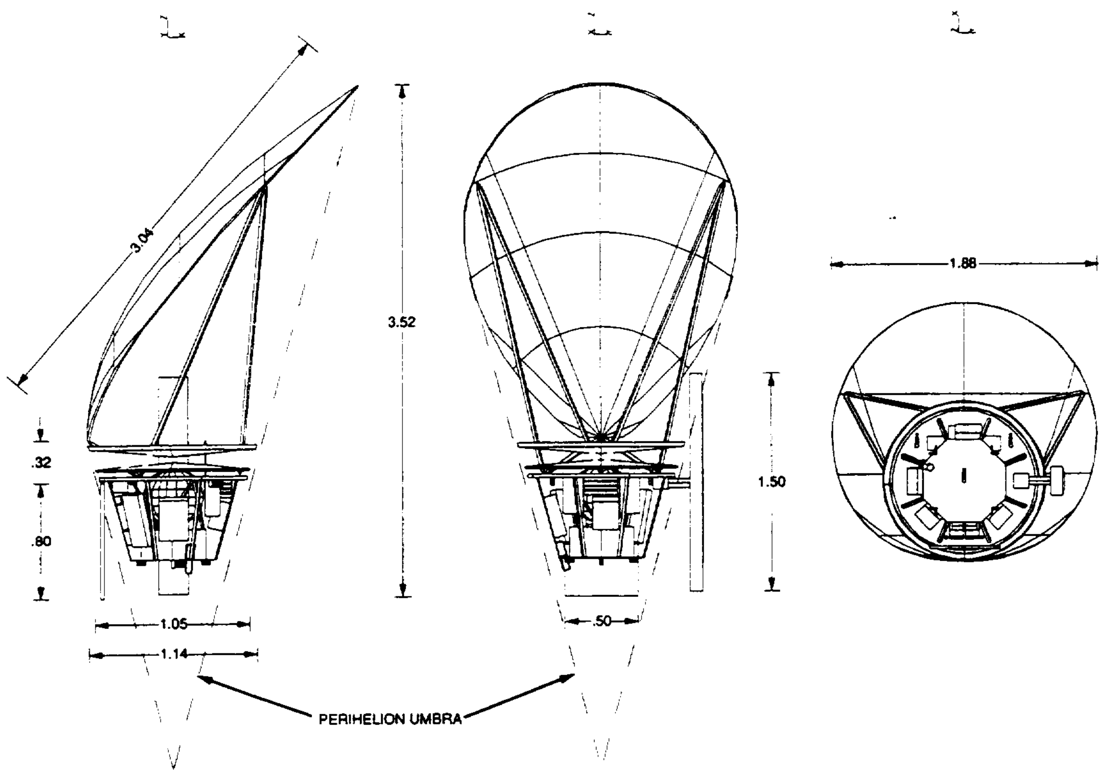


Figure 2-9. Stowed Configuration of the FIRE Spacecraft
(All dimensions are in meters.)

high-performance spacecraft data system is designed to provide multiple digital processing functions of central control, attitude control, data storage/control, spacecraft command detection/sequencing, and telemetry processing. Two different deployable solar arrays, primary batteries, and secondary batteries are used in supplying non-nuclear power for cruise and encounter in the non-nuclear option. This option requires the use of a primary battery for 5 days surrounding the perihelion passage. The spacecraft would cease to operate when the battery is exhausted, about 2 days after perihelion.

US FIRE Subsystem Mass and Power Summary

This list follows the nomenclature used in the Russian FIRE spacecraft design for direct comparison. Estimates include a 30% subsystem reserve, while the power reserves are 25%.

Subsystem	Mass (kg)	Power (Watts at Perihelion)
Control System	24	21
Radio	30	30
Computer	11	10
Power	54	9
Thermal	15	3
Structure	15	N/A
Propulsion	10	3
Science	22	19
	-----------	-----------
Dry Spacecraft	181	N/A
Propellant (200 m/s, I_{sp} 220s)	16	N/A
Launch Vehicle Adapter	6	N/A
	-----------	-----------
Total	203	95

FIRE Subsystem Functional Characteristics

Thermal Control

- C–C primary shield/antenna (< 2400 K at perihelion)
- Infrared radiation from the primary shield is intercepted by C–C secondary shields
- Conductive and radiative isolation of the bus
- Bus temperature maintained from 280 K–320 K at perihelion
- Mass loss < 2.5 mg/s at 4 Rs

Telecommunications

- X-band carrier frequency
- 5-watt Solid-State Power Amplifier (SSPA)
- Body fixed high-gain antenna/shield with 41 dB gain
- Perihelion data rate: > 4000 bits/second

Power (Non-nuclear power option)

- Low-intensity low-temperature solar array for deep space power (>0.7 AU)
- High-temperature solar array during approach to the Sun (0.7 AU to 0.2 AU)
- Primary battery (13.6 kW/hr) for perihelion operations
- Maximum load of 95 W at perihelion

Attitude Control

- Three-axis stabilized, nadir pointing at perihelion
- $\pm 0.2°$ pointing during Encounter (after 1 day on gyros)
- $\pm 0.5°$ to $\pm 5°$ pointing during Cruise
- Cold gas (GN_2), N_2H_4 (for control augmentation at perihelion)

Propulsion

- Monopropellant, N_2H_4 (I_{sp} = 200 sec)
- ΔV = 200 m/s

Spacecraft Data System

- Integrated attitude control, data handling, and control functions
- 2.5 MIPS performance, 2 Gb data storage

Structure

- Deck plate and open structure (Graphite composite)
- Carbon–Carbon support struts for shield subsystem

Science Payload Accommodation

Accommodation of the scientific instruments is facilitated by the solar wind velocity aberration at the perihelion of 4 Rs. The tangential spacecraft velocity is greater than 300 km/s and the nearly radial solar wind velocity is expected to be less than 200 km/s, allowing the solar wind to approach the spacecraft from the side. Thus the solar wind instruments need not point toward the Sun in order to take measurements in the direction of the solar wind velocity, as shown by the instrument fields of view in Figure 2-10.

The instruments will be provided low-voltage regulated power, control functions, and data processing from the spacecraft. Some instruments may be supplied high-voltage regulated power. This eliminates the need for power regulation within the instruments and so reduces their mass and power requirements. The instrument control functions can use the spacecraft data system capabilities to further reduce instrument complexities leading to even smaller instrument design concepts.

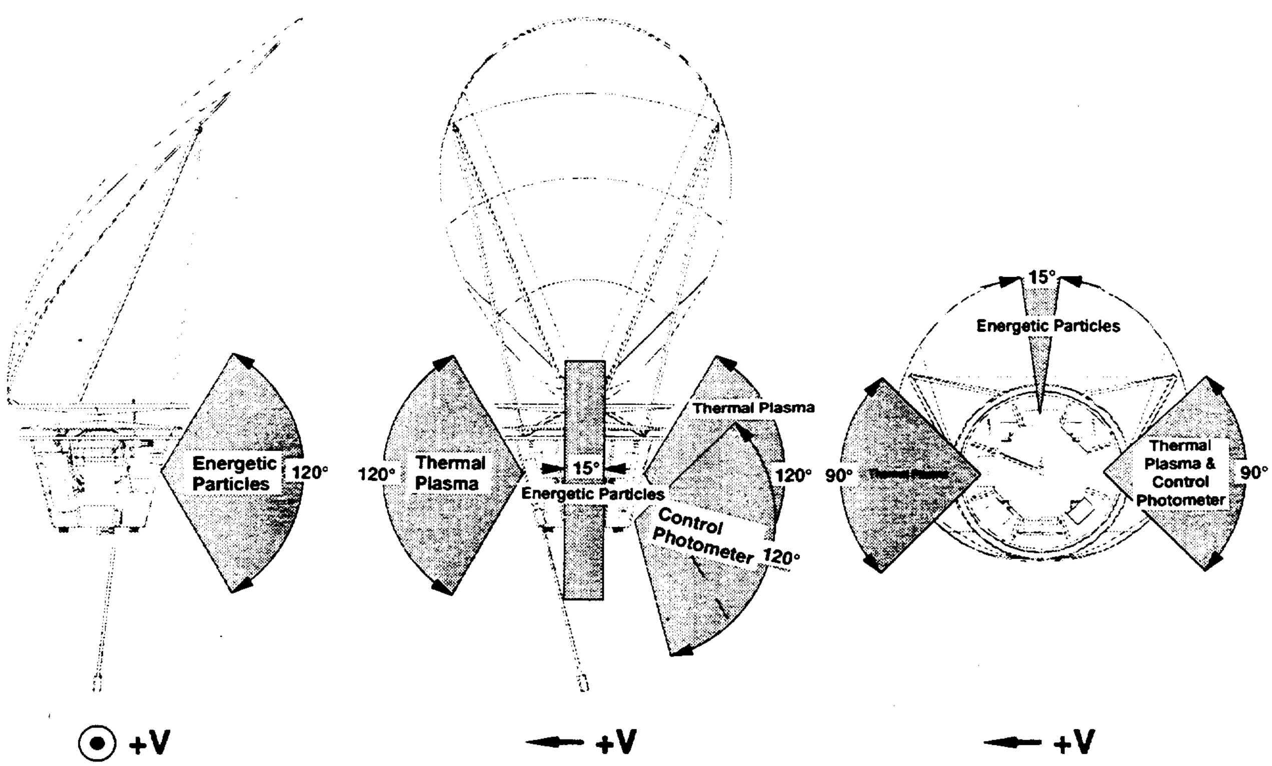


Figure 2-10. US FIRE Instrument Fields of View

Telemetry rates vary from over 100 kb/sec prior to perihelion to over 4 kb/sec at perihelion as shown in Figure 2-11. The effect of the dual-station coverage at perihelion as shown in the diagram may reduce the degradation caused by proximity to the Sun and the scintillation environment and allow significantly higher rates at perihelion.

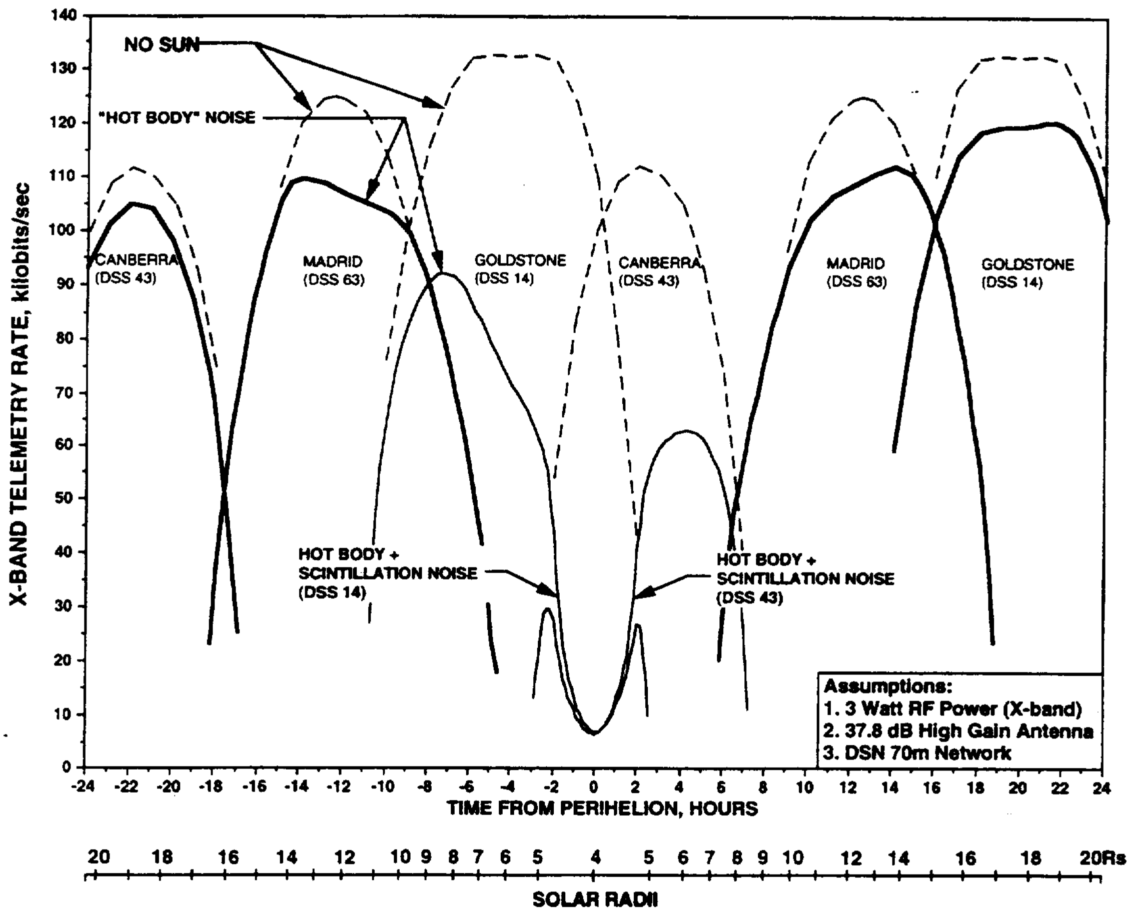


Figure 2-11. Telemetry Rates vs. Time from Perihelion for the US FIRE Spacecraft

FIRE Advanced Technology

The FIRE spacecraft relies heavily on advanced technology to solve the extreme mass and power constraints imposed on the 4 Rs spacecraft. A development program for miniaturized instruments has been proposed with support from the Technology Office at NASA Headquarters. Research into materials for the shield and further studies into telecommunications design is continuing at JPL and in industry. A NASA Research Announcement (NRA) is scheduled to be released in January 1995 to seek conceptual designs for miniaturized instruments consistent with the small (<20 kg) mass allocation for the entire scientific payload.

Testing continues to confirm the carbon–carbon (C–C) optical properties at high temperatures, as shown in Figure 2-12. The emissivity of the C–C materials is assumed to be about 0.83, but the error in this value remains large as shown in the diagram. Testing results are expected to reduce this error and provide more confidence that the mass loss specification can be satisfied. New testing of the C–C materials for their radio frequency (RF) performance at high temperature will be used to confirm the design concept that allows the C–C shield to be used as a high-gain antenna. Multi-environmental tests of C–C samples at high temperatures in vacuum will simultaneously measure emissivity and RF reflectance properties to provide the antenna performance estimated in Figure 2-11.

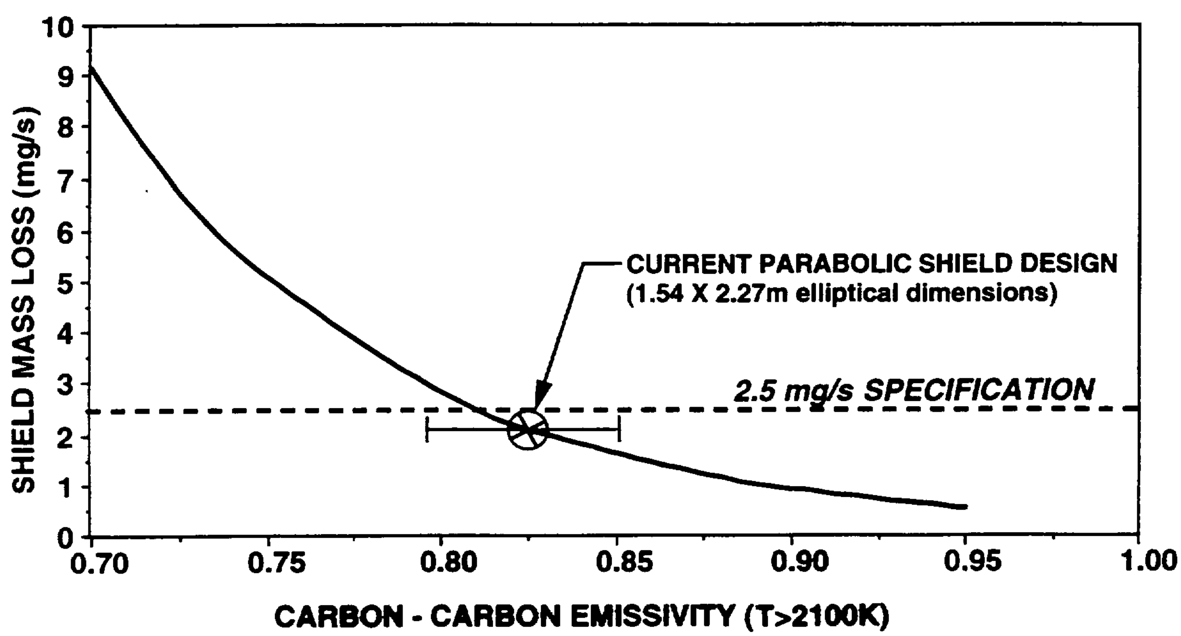


Figure 2-12. FIRE Spacecraft Mass Loss vs. Emissivity for Parabolic Shield

2.8 Open Issues

The major issue is the immediate need for RSA funding for the new-generation spacecraft to be built in Russia. Possible long lead times associated with project implementation in Russia should be considered in light of a required project (Phase C/D) start in 1997, necessary to meet the proposed launch year of 2001. Should a 2000 launch be required by the Russian space community, early funding will become even more imperative. Cooperative design-integration elements lack detail. Interface definition, definition of technical responsibilities, and early identification of technical personnel are required for a successful mission; therefore, every effort should be made to facilitate the early establishment of the necessary interfaces, protocols, and personnel.

US electronic piece parts may be provided for the new Russian spacecraft. How these parts are to be provided is still unclear. The required parts need to be identified as soon as possible because of the long lead times for US procurements. It has been agreed that the piece part requirements will be identified by the end of 1994.

NASA funding for technology development for the US FIRE spacecraft subsystem and for science instrument development needs to be addressed and funding sources identified. Key technology items and implementation schedules have been developed with associated costs and there is a tentative NASA commitment to fund instrument technology development.

The recommended option, one US and one Russian spacecraft with Proton-Star 48 launch vehicle, places on the US significant payload integration costs, which must be accurately estimated as part of the overall project proposal to NASA.

The launch approval procedures required for the FIRE mission need further definition. If the US were to choose the non-nuclear power option, it is unclear what US responsibilities would be if only the Russian component contains an RTG. Further discussion is provided in Chapter 4, Launch Vehicles.

The possible participation of additional countries should be explored as a method of cost-sharing. There may, for example, be interest on the part of the French space agency, CNES, to produce the thermal shield required on the US spacecraft, in return for French participation in the scientific payload. Opportunities for participation should be identified and pursued, especially when those areas may contribute enabling technology development.

2.9 Future Program Plan

Future planning for the FIRE program is dependent on new support from both NASA and the RSA. Neither agency is expected to make a commitment until after the Gore-Chernomyrdin meeting in late 1994.

Immediate tasks in 1995 will be to begin the technology studies/development of the instruments and spacecraft subsystems. The instrument studies/development announcement (the Scientific-Investigating Work) from Russia and the NASA Research Announcement from the US will initiate the studies/development of a new class of miniaturized FIRE instrument concepts. The technology studies/development for both the thermal shield and the telecommunications concept for the US spacecraft should also be initiated in 1995.

Joint science activities in 1995 will include an environmental modeling workshop in Russia and a near-Sun science workshop in the US. Both of these workshops will be held under the guidance of the FIRE Joint Science Steering Group. In addition, a joint development study group should be initiated in 1995 to consider common design issues for both the US and Russian spacecraft.

2.10 Membership

The Membership of the Joint US-Russian team on the FIRE mission is shown below:

J. Ayon	A. Galeev
W. Feldman	B. Jakovlev
V. Jones	V. Oraevsky
R. Miyake	O. Papkov
G. Powell	K. Pichkhadze
J. Randolph	N. Pissarenko
B. Tsurutani	O. Vaisberg
G. Withbroe	

CHAPTER THREE

ICE: The Pluto Mission

3.1 Introduction and Background

Pluto Flyby missions have been under detailed implementation study in the US since 1991, when the reconnaissance of the Pluto-Charon system was first recommended by the advisory Solar System Exploration Subcommittee (SSES) of the Space Science Advisory Committee (SSAC) as a high-priority new start for the 1990s. Several possible mission scenarios were concurrently studied by NASA, JPL, and the scientific advisory structure to NASA's Solar System Exploration Division. From these mission scenarios, the advanced, lightweight, sprint-trajectory Pluto Fast Flyby (PFF) was selected in 1992.

The PFF mission plan is to place two high-technology spacecraft, at a fraction of the weight and cost of the Voyager mission, into direct trajectories to Pluto in 2001. This will accomplish the first-ever flybys, during or before 2010, of the Pluto-Charon binary planet system, so as to study Pluto while it still possesses its short-lived, perihelion atmosphere. After rigorous debate in 1992 and 1993, the US scientific community settled on a highly constrained set of measurement objectives for PFF. Although the US PFF mission will not accomplish all of the possible scientific studies relevant to Pluto, it will accomplish the core set of basic reconnaissance objectives set forth by the NASA Outer Planets Science Working Group (OPSWG) and its parent, the SSES.

In early 1994, US–Russian contacts identified the possibility of a joint US–Russian PFF mission that would be of interest to both national space programs and scientific communities. Such a joint mission could, at the same time, enhance the scientific return of the PFF mission, provide Russia with its first entrée into outer solar system exploration, and reduce NASA's mission costs. The basic architecture of the proposed joint US–Russian PFF mission accomplishes these goals by launching the PFF flyby spacecraft on Russian Proton vehicles equipped with some combination of US and/or Russian upper stages. It will also carry a Russian-built atmospheric probe, called the Pluto Drop Zond, to enhance the PFF flyby mission; the probe will enter Pluto's atmosphere and study the planet until the probe impacts the surface.

To evaluate the basic scientific and technical feasibility of the US–Russian joint Pluto mission in greater detail, a PFF Joint Science Steering Group (PJSSG) was formed as a part of the NASA/Russian FIRE & ICE Joint Technical Study. As stated below, the joint US-Russian PJSSG set out to determine the science objectives and strawman payload for the Pluto Drop Zonds.

The charter of the PJSSG states that the group is

> *responsible for providing science support to the US-Russian Technical Team now conducting studies concerning FIRE AND ICE concepts for a cooperative mission to Pluto. The PJSSG is to provide advice on science and measurement objectives for the Pluto Fast Flyby (PFF) mission, maximizing total science return from the flyby spacecraft and the Russian drop zond. The issues to be addressed include, but are not limited to:*
>
> - *Science objectives for the drop zond, considering its in situ capability and complementary to the 1a science objectives defined for the flyby spacecraft*
> - *Strawman instrument payload and measurement requirements for the drop zond*
> - *Drop zond encounter options (near and far; spin axis perpendicular or parallel to velocity vector)*

The PJSSG was chaired by the NASA Headquarters PFF Study Scientist and provided input directly to the US-Russian Technical Team.

The group concluded that the Drop Zond mission is both exciting and technically feasible and recommends the formation of a Joint Science Definition Team to pursue more detailed analyses. The detailed findings of the PJSSG, and of the ICE portion of the NASA/Russian FIRE and ICE Joint Technical Study follow.

3.2 The Pluto Program

The Pluto-Charon system is widely recognized as a scientifically important target for planetary exploration and is the last planet in the solar system to be explored by spacecraft. Its study would complete the reconnaissance of the planets. Given these motivations, NASA directed the OPSWG to take scientific responsibility for Pluto mission development.

During 1991 and 1992, OPSWG defined the most compelling scientific objectives for a first Pluto reconnaissance mission. The OPSWG also prioritized this set of possible objectives and defined a constrained subset that could be accommodated on a low-cost, fast-flyby mission. Objectives that could be accomplished from present or future observatories on Earth or in Earth orbit (e.g., refinement of the radii of Pluto and Charon) were not allowed to drive payload and spacecraft requirements. Similarly, objectives that were judged not absolutely essential to obtaining a first-order understanding of the Pluto-Charon system or that could not easily be accomplished from a flyby were also given lower priority.

The final ranking of these scientific objectives is summarized below. Category 1a objectives are considered absolutely essential to the first scientific reconnaissance mission; Category 1b objectives are considered important but not mandatory; Category 1c objectives are considered desirable, but secondary. Some objectives (not shown) were given an even lower priority, called Category II. These definitions were specifically designed to cull out a scientifically compelling set of focused goals for a first reconnaissance. They were also designed to identify the most important qualitative advances needed at Pluto-Charon to complement the Voyager 2-class reconnaissance of Triton.

Category 1a Objectives:

- Characterization of global geology and morphology
- Surface composition mapping
- Characterization of neutral atmosphere

Category 1b Objectives:

- Surface and atmosphere time variability
- Stereo imaging
- High-resolution terminator mapping
- Selected high-resolution surface composition mapping
- Characterization of Pluto's ionosphere and solar wind interaction
- Search for neutral species including: H, H_2, HCN, C_xH_y, and other hydrocarbons and nitriles in Pluto's upper atmosphere. Obtain isotope discrimination where possible
- Search for Charon's atmosphere
- Determination of bolometric bond albedos
- Surface temperature mapping

Category 1c Objectives:

- Characterization of the energetic particle environment
- Refinement of bulk parameters (radii, masses, densities)
- Magnetic field search
- Additional satellite and ring search

A strawman payload was developed that would meet the Category 1a science and measurement objectives. This strawman payload consists of three optical instruments (an imaging visible camera, an imaging infrared spectrometer, and an ultraviolet spectrometer) using advanced miniaturization technology, and a radio science experiment that is highly integrated into the spacecraft telecommunications subsystem. This advanced payload will weigh less than 7 kg and use less than 6 W of power.

The mass and power consumption of the strawman Pluto reconnaissance payload is more than an order of magnitude smaller than the Galileo/Jupiter and Cassini/Saturn orbiter payloads. As shown in Table 3.1, however, this payload far surpasses the capabilities of Voyager 2 during its successful flyby of Triton. The PFF spacecraft concept has been designed around the 1a measurement objectives and payload. It is a highly miniaturized descendent of the present class of outer solar system vehicles. Based on Phase A design work the spacecraft dry mass will be less than 120–140 kg. Within that small mass, the spacecraft (see Figure 3-1) will carry all of the usual subsystems and services flown on past flyby missions, with the exception of a scan platform (all of the instruments will be body-mounted). The mission design goals given by NASA to JPL were simple: Satisfy the 1a science objectives and keep the cost to build two spacecraft under $400M, including budget reserves.

The proposed spacecraft design resulting from these goals can be summarized as follows. The spacecraft structure is a composite hexagonal bus with no deployable structures. Power is provided by an RTG that generates 94 W (electric) at launch and 74 W after the 8- to 10-year cruise to Pluto. The spacecraft communicates to Earth via a fixed, composite-structure 2-m high-gain antenna that employs an X-band uplink receiver and an X- and Ka-band downlink transponder. The estimated data rate at Pluto (35 AU) should be 80–800 bps, depending upon the wavelength and set of Deep Space Network (DSN) stations used. The spacecraft data subsystem is centered around a 2-MIPS RISC-based

Table 3.1 Science Capabilities Comparison

	Pluto Fast Flyby Baseline (2 spacecraft)	Voyager Triton
Imaging	Global 1-km resolution Selected High-resolution (50–100 m) 8 bits, CCD, square-root encoding Optimized Filters 0.3–0.9 µm	Global Low Resolution Coverage Substantial 1–3 km Resolution 8 bits, Vidicon Non-Optimized Filters 0.35–0.56 µm
Surface Composition	Global 2D Maps 1–2.5 µm, $\Delta l \sim 0.01$ µm 10–20 km best, 50-km Global Resolution Selected High-resolution Tracks	No Surface Composition Instrument N/A N/A
Atmospheric Characterization	4 UVS Solar Occultations UVS Airglow Mapping 4 RSS Pressure, Temp. Profiles Determination of Ionospheric e^- Column and Height	2 UVS Solar Occultations UVS Airglow (Spatially Unresolved) Base T, P Measured Reliably, Altitude Profile Extrapolated Determination of Ionospheric e^- Column and Height
Fields & Particles	No Capability N/A	No Triton $\bar{B}$ Detected Magnetospheric Interaction Detected
Other	5% or Better Mass Resolution J_2 Probably Not Detectable Satellite and Ring Search Potential for Nightside Imaging Precise Shape and Figure Timebase of Observations: ~18 months 16 km/s Flyby Speed	3% Mass Resolution J_2 Not Detected N/A N/A Shape & Figure Timebase of Observations: ~2 months 25 km/s Flyby Speed

computer capable of processing a peak science data stream at 5 Mb/s. Onboard solid-state data storage exceeding 1 Gb is provided; compression increases the effective data volume several times. Excess RTG heat and possible radioisotope heater units (RHUs) are used to provide active thermal control where needed (e.g., propellant conditioning). The attitude control subsystem is based around a wide-field star sensor and a set of three solid-state rate-integrating gyros. Pointing knowledge will exceed 1.5 mrad, with a stability of 10 mrad over 1 sec. A 90^o slew can be completed in 3 minutes. The propulsion subsystem is a pressure-fed hydrazine monopropellant design that delivers 310 m/s of DV for post-launch and cruise trajectory maneuvers. The tank is capable of storing propellant for up to 600 m/sec DV in order to accommodate a possible backup mission. Attitude control is provided by small cold gas thrusters. As the initial design evolves, the mass and power requirements of various subsystems are expected to be reduced by using lighter weight structures, advanced electronics packaging, and a more efficient power conversion system. Work is under way to define the optimal degree of onboard redundancy.

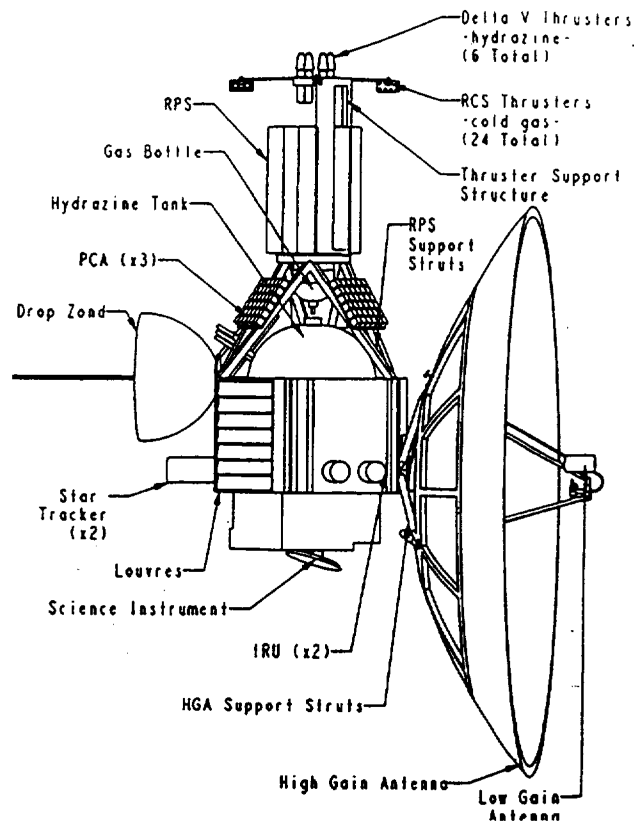


Figure 3-1. Pluto Spacecraft with Drop Zond

The baseline mission envisions the launch of two Pluto spacecraft on separate launch vehicles augmented by two existing solid rocket motor upper stages to achieve the required 200–400 km^2/sec^2 specific injection energy for a direct trajectory to Pluto. The mission plan includes two spacecraft for several reasons, including reduced risk of a malfunction fatal to the mission and significantly improved science return, particularly in accomplishing complete mapping of Pluto and Charon.

Given the limitations of existing launch vehicles, direct trajectories (see Figure 3-2) are preferable to a Jupiter gravity assist because they are quicker (for small spacecraft), do not depend on Jupiter being in the right position, and avoid the need for the heavy radiation shielding made necessary by the Jovian magnetosphere. The baseline spacecraft can travel to Pluto in 8–10 years, much faster than the 12-year Voyager journey to Neptune and Triton. The approach speed at Pluto will be 12–18 km/sec, akin to the 17-km/sec Voyager 1 flyby speed at Titan, and 30–50% slower than the 24-km/sec Voyager 2 encounter speed at Triton.

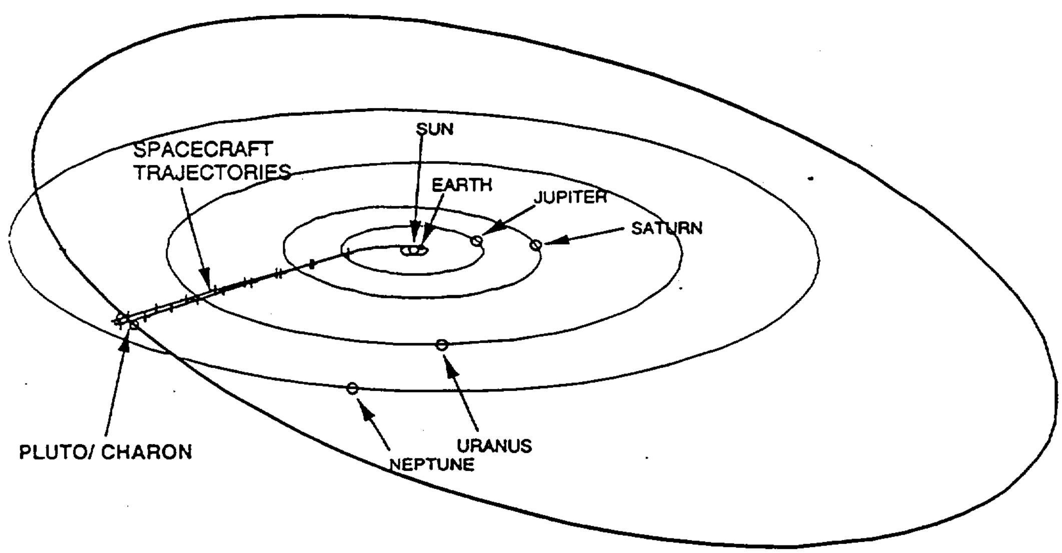


Figure 3-2. Pluto Fast Flyby Interplanetary Trajectories

During cruise each spacecraft will be tracked and interrogated by the DSN on a weekly basis. At present no dedicated cruise science is planned. However, the strawman payload offers possibilities for focused imaging, interplanetary H/He, and radio science studies. The possibility of achieving an asteroid flyby to test the spacecraft in flight and increase cruise science return has also been investigated; several interesting targets are available virtually every launch year. The possibility of flying a cruise science particles and fields instrument has also been examined.

Distant remote-sensing observations of the Pluto-Charon system will begin some 4–6 months before closest approach. At this point, imaging resolution will exceed that of the repaired Hubble Space Telescope. During 20–35 rotations, Pluto and Charon will be observed at increasing resolution and a search will be made for faint satellites. During distant approach, ultraviolet (UV) spectrometer observations will search for an H/H_2 corona around Pluto, and in the days leading to closest approach, infrared (IR) surface mapping and UV airglow studies will become a priority.

The flyby design will bring the first spacecraft to within 15,000 km of Pluto and will permit both Earth and solar occultations. This trajectory will place the first spacecraft at least 3 times closer to Pluto than Voyager came to Triton. Post-flyby studies will include high-phase angle mapping, searches for orbiting dust structures, and nightside IR/UV spectroscopy.

Since two spacecraft will be launched, their encounter trajectories can be separately optimized. In order to complete the 1-km global mapping requirement, the second spacecraft will be targeted to arrive over the opposite hemispheres of Pluto and Charon. It is expected that the two flybys will be separated by 180 days. This will allow data from the first encounter to be sent down and analyzed to optimize the science return from the second and will provide a substantial timebase of observations to detect atmospheric decay and surface volatile transport. The second encounter could feature an approach within 2000–3000 km of Pluto, Charon radio/solar occultations, or other objectives. After the two spacecraft leave the Pluto-Charon system, they will be traveling nearly along the apex of solar motion toward the heliopause at 3 AU/yr. An extension of the mission to fly by a Kuiper Belt object has been suggested and is worthy of consideration.

The exploration of the last known planet in the solar system is an exciting possibility, with strong prospects of renewing the public's sense of drama and boldness in planetary exploration. Equally important, in achieving its geophysical, geochemical, geological, and atmospheric objectives, the Pluto-Charon reconnaissance mission will also answer some of the most compelling questions in all of planetary science.

3.3 Rationale for a Joint Mission

Scientific and Exploration Rationale: The Pluto-Charon system is unique in several respects: It is the only true double planet in the solar system; it is the only planet that appears closely related to the newly discovered mini-worlds of the Sun's distant Kuiper comet disk; it displays unique atmospheric phenomenology not observed anywhere else in the solar system; it is the most distant known planet; and it is the only known planet not yet explored by a spacecraft.

The scientific advisory committee charged with advising NASA on the objectives and merits of possible outer planet exploration missions is the 21-member OPSWG. After detailed analysis and debate from 1991 through 1993, OPSWG recommended that the initial reconnaissance performed on the PFF mission to the Pluto-Charon binary system consist of three related objectives:

- Obtaining high-resolution global geologic maps of both Pluto and Charon in several bandpasses
- Obtaining high-resolution global composition maps of both Pluto and Charon
- Determining the major component composition and the vertical temperature and pressure structure of Pluto's atmosphere before its post-perihelion (i.e., ~2010) collapse or decay

The OPSWG documented its agreement that PFF would not be scientifically worthwhile unless all three objectives could be accomplished and that none could be sacrificed if a first-order understanding of the Pluto-Charon binary was to be obtained. The OPSWG also documented its position that, while other important scientific objectives existed for the Pluto-Charon binary, none were as important as these, called the 1a Objectives.

With the opportunity to fly the Russian Drop Zond (DZ) entry probes into Pluto's atmosphere and down to destructive impacts on its surface, it becomes possible to augment the 1a objectives of the PFF flyby spacecraft with additional, entry probe objectives for the DZ. However, owing to its limited mass, power, and data transmission capabilities, the DZ can carry out only a few carefully chosen investigations.

The PJSSG evaluated a broad suite of possible investigations and scientific objectives for the PFF DZs. Among the investigations evaluated were:

(a) Super-high resolution surface imaging of Pluto and/or Charon
(b) *In-situ* atmospheric studies of Pluto (Charon has no atmosphere)
(c) Studies of Pluto's surface thermal properties
(d) Better measurements of the higher order gravitational moments of Pluto and Charon
(e) Studies of the particle and fields environment around Pluto and Charon
(f) Searches for dust around Pluto and Charon

Technical and/or cost limitations on the DZ and its payload argued against objectives (a), (c), and to some extent (e). The low potential for unique scientific return argued against (a), (f), and (d). The PJSSG concluded that the most important contributions the Russian DZ could make to the PFF mission were *in-situ* atmospheric studies and wrote a focused 1a scientific objective for the DZ: "To make *in-situ* studies of atmospheric composition and structure, including hazes."

Taking into account the power, mass, data storage and transmission, and entry/stability characteristics of the envisioned DZ, the PJSSG identified the following strawman entry payload that accomplishes the DZ 1a objective listed in priority order:

Mass Spectrometer or Mass-Energy Retarding Potential Analyzer: To detect minor species in Pluto's atmosphere, including possible noble gases, and the photochemical by-products of Pluto's N_2-CO-CH_4 atmosphere; measure the mixing ratios of both minor and major species in Pluto's lower atmosphere; determine the kinetic temperature of the atmosphere as a function of altitude.

Wide-Angle Limb Imager: To study the density, vertical structure, distribution, and optical properties of Pluto's limb hazes; measure limb topography.

Accelerometer: To measure Pluto's atmospheric density structure.

Particle Sensor: To measure Pluto's atmosphere/solar wind interaction and constrain or detect the presence of a magnetic field on Pluto.

These investigations largely require *in-situ* sampling and complement the science to be accomplished by the PFF flyby spacecraft. In addition, the Limb Imager will produce publicly and professionally exciting images of Pluto as the Drop Zond makes its terminal descent.

As a result of this study, the prospect of greatly enhanced science return from the PFF mission with the addition of a small Drop Zond entry probe has become clear. Equally important, however, it has also become clear that a joint US–Russian mission to reconnoiter the last of the nine known planets offers strong programmatic benefits to both sides. For the US, collaboration can lower costs to NASA. For Russia, collaboration can provide experience in long-lived mission technologies necessary to open the door to the outer solar system, which Russian space vehicles have not yet penetrated. Further still, in completing the reconnaissance of the last known planet together, the world's two foremost planetary exploration programs will leave a lasting historical legacy and a stirring capstone to humankind's first era of planetary exploration.

Programmatic Rationale: The flight of a joint US–Russian mission to Pluto opens up new opportunities to both the United States and Russia that would not be available without mutual cooperation. Some of the major advantages of this joint program follow:

- This mission will provide humanity with the first information on the most distant known planet far sooner than either a US or a Russian mission could alone.
- The rapid flight to Pluto, made possible by the powerful Russian Proton launch vehicles with US upper stages, offers the opportunity to study Pluto's atmosphere while it is still active and measurable. Once the atmosphere condenses onto the surface, it will not return for another two centuries.
- The Russian Drop Zonds enable direct measurement of the atmosphere that would not be possible with two simple US flyby spacecraft. In return, the flyby spacecraft permit accurate Drop Zonds navigation and the relay of volumes of encounter data back to Earth.
- By carrying the Drop Zonds on the US flyby spacecraft, Russia can accomplish its first outer planet mission.
- Engineers and scientists of both nations will profit by learning of the unique capabilities each has developed over three decades of spaceflight. This knowledge will be valuable in developing scientific sensors, construction of reliable electronics, launching a variety of scientific exploration missions, and other mutually beneficial ventures.
- Cooperation on this mission will serve as an example for young people in both nations. The Pluto mission is being designed to actively involve students in its development and operation.

Public Interest Rationale: International cooperation between Russia and the US is reinvigorating the dream of space exploration in both nations. Both the Russian and American people will benefit from this new era of "faster, better, cheaper" cooperative planetary exploration through the more open sharing of knowledge and by reaping the handsome dividends of scientific knowledge, at much lower cost to each country.

In addition to its scientifc and engineering goals, the Pluto Mission places great emphasis on enhancing student education. Its goal is to inspire and educate students in a variety of disciplines through hands-on experience and other forms of participation in the mission and results.

Joint international participation in the Pluto Mission provides the opportunity to work together in three areas:

- *Student Involvement:* The Pluto Educational Outreach Program is designed to involve students in the comprehensive process of space exploration from mission planning through to the interpretation of data.
- *Long-Term Outreach:* The Educational Outreach Program is also an element in long-term outreach designed to inspire young people and inform the general public both about the Pluto Mission itself and the general importance of an on-going space program.
- *Intercultural Communication:* The Educational Outreach Program may also function to foster intercultural communication by creating mutual exchanges focused on the space program.

3.4 Options Studied

Proton Launch Option

Launch System Requirements—Baseline: The baseline mission uses a direct trajectory from Earth to Pluto with launch in late January or early February 2001. There is a strong programmatic desire to get to Pluto as quickly as possible, before the atmosphere freezes, and in less than 10 years. Thus the minimum launch energy (C_3) required is 206 km^2/sec^2. Greater launch energies are highly desirable to provide shorter flight times to Pluto and to reduce mission operations costs and increase the chance of arriving before the bulk of the atmospheric freeze-out occurs. In addition, to minimize life-cycle costs, both spacecraft will be launched during the same 20-day launch period.

Backup: A backup mission is possible using Earth and Jupiter gravity assists in November 2001 (see mission design section for details). The launch energy requirement for the backup mission is 50 km^2/sec^2, although in this case higher C_3 energies do not substantially reduce the flight time. Finally, as in the baseline mission, both spacecraft will be launched within a 20-day launch period.

Meeting the Requirements: The four-stage Proton was selected as the baseline launch vehicle and as a method of expanding Russian participation in the mission. (The fourth stage is actually the Block DM upper stage; this stage includes the mass penalty for its own guidance and control package. The US Titan IV/ Centaur is also capable of meeting the requirements.) The Khrunichev State Research and Production Space Center is responsible for the overall Proton and manufactures the first three stages. NPO Energia manufactures the fourth stage. The Russian Space Agency would provide Proton launch service from the Baikonur Cosmodrome in Kazakhstan on a no-exchange-of-funds basis.

No existing Russian or US launch vehicle/upper stage combination can meet the required C_3 for the Pluto baseline mass of 180 kg (including propellant and Drop Zond), so additional propulsion stages are necessary to augment the launch system. A number of options were suggested, including solid, liquid, and electric propulsion. At this time, staged solid rocket motors appear to best meet mission needs and were selected as the baseline. Solid-propellant motors currently outperform and are less expensive than liquid-propellant motors for a high-energy injection such as that of the Pluto mission. Electric propulsion promises improved performance; however, in all cases, the technology is either non-applicable or is currently not ready for this mission. In addition, since electric propulsion is a low-thrust implementation, the cost of operations increases because electric propulsion must be used over a longer period of time (2–5 years for electric propulsion versus minutes for conventional solid or liquid propulsion). However, these alternative propulsion technologies will be watched closely and reevaluated as they mature.

Both the US and Russia have analyzed the optimal solid rocket motor staging for the Pluto mission. Russia currently does not manufacture solid rocket motors in the size range needed; there are at least two manufacturers in the US with existing motors that are close to optimal. For this reason, a US stack of solid rocket motors was selected. Cost, design, and performance calculations were performed for two-stage and three-stage stack combinations by both countries, with similar results. While the three-stage stack provides significant performance benefits, a two-stage stack is favored because of reduced cost and complexity. On completion of the parallel analyses, a two-stage stack using the Thiokol Star 48 and Star 27 solid rocket motors (or equivalents) in a spin-stabilized mode was baselined. (It is possible, at greater expense, to use these motors in a three-axis stabilized mode and reduce the weight of the onboard spacecraft propellant, thus reducing the flight time to Pluto.)

A Proton launch is baselined. The first three Proton stages place the fourth stage, the stack, and the spacecraft/zond into a low-Earth orbit. On reaching the correct injection targets, the fourth stage and the two solid rocket motors fire sequentially to achieve the required launch energy and direction. This launch/injection sequence will take approximately one hour; the resulting flight time to Pluto is about 9 years. Protons have routinely launched seven days apart and less, thus meeting the short launch period requirement.

A particular issue with the baseline mission is the safety of the spacecraft's RTG in the unlikely event of a severe launch accident. The Working Group considered providing a spacecraft escape system within the integrated launch system to remove the spacecraft and RTG from hazardous accident situations. However, it is very complex to ensure the Proton, the US stack, and the spacecraft operate together to provide a safe escape in a launch accident. Further study of the need for and nature of such a system is in progress.

A modernized Proton, Proton-M, is currently under development and may be available for the Pluto mission. This vehicle potentially has greater performance, offering an opportunity to reduce mission flight time. Some elements of the Proton-M have already been incorporated into the existing Proton. The Pluto mission will maintain the existing Proton baseline until the readiness and the benefits of the Proton-M are understood.

The launch energy requirement of the backup trajectory can be adequately met by the four-stage Proton without the use of additional solid rocket motors or by a number of US launch vehicles (the Delta II is one candidate).

Drop Zond

Potential Science: The Drop Zond proposed by the Russian contingent of the study team offers an opportunity to obtain unique science data within the constraints of a package of approximately 6 kg mass (Figure 3-3). Other characteristics of the Drop Zond are described in Table 3.2. In the nominal mission, each of the two Pluto spacecraft will carry a Drop Zond. Each will be deployed from the parent spacecraft at a distance of approximately 34 x 10^6 km from the planet and each will be targeted to a specific location, perhaps one at the center of the illuminated hemisphere and one near the limb. Under the best conditions, reconstruction of the impact point on Pluto's surface is expected to be accurate to approximately 10 km. The Drop Zond will operate on battery power for about 2000 seconds and will transmit science and engineering data until radio transmissions are interrupted by the ion sheath created upon entry into Pluto's atmosphere. This is expected to occur at an altitude of 500 km or less above Pluto, depending on the characteristics of the real atmosphere at the time of encounter.

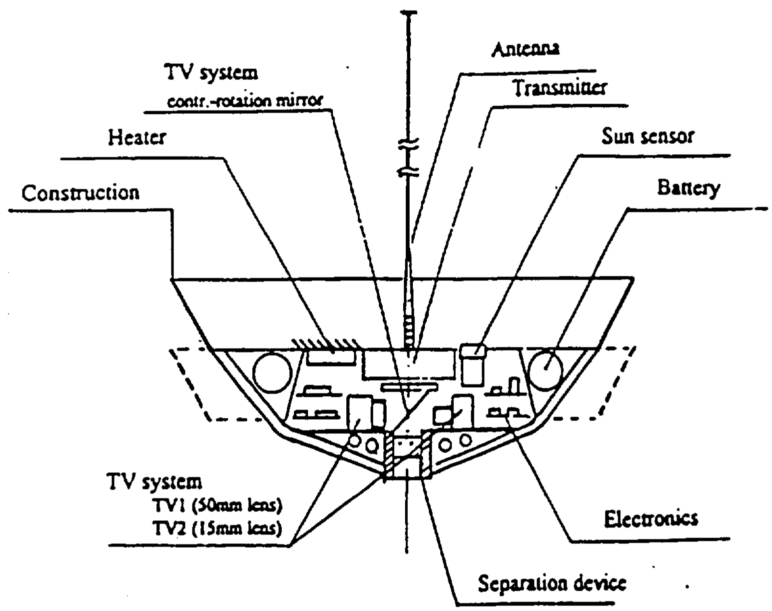


Figure 3-3. Russian Drop Zond

Opportunities for science experiments aboard the Drop Zond include:

- *In-situ* measurement of the composition of Pluto's upper atmosphere. This can be accomplished with a mass spectrometer working up to 150 amu, with resolution 0.5 amu. Alternatively, such measurements can be made with a retarding potential mass detector. The atmosphere is probably dominated by molecular nitrogen and may also possess a variety of chemically produced trace species, perhaps even neon and argon which, if abundant, would have major implications for the origin and development of the atmosphere and surface of Pluto.
- Wide-angle imaging of the surface and horizon with a fish-eye lens to detect and determine the optical properties of uniform or patchy haze in Pluto's atmosphere. The large phase angle afforded by the descending Drop Zond will make hazes and any inhomogeneities in them more readily visible than from the mother spacecraft. Accurate measurements of the brightness of sunlight scattered from hazes at high phase angle will give important information on their optical properties and hence their composition. (Imaging of the surface of Pluto to supplement images made from the mother spacecraft has been considered. Plausible operating scenarios offer only modest improvement over the spatial resolution that will be achieved from the mother spacecraft, and special

efforts will be needed to ensure image sharpness because of the spin of the Drop Zond, required for orientation stability.)

- Measurement of the deceleration profile of the Drop Zond during descent into Pluto's atmosphere to provide data from which information on the atmospheric density and its vertical distribution can be derived.
- Measurement of the plasma environment at the Pluto-Charon system to establish fundamental information on the presence or absence of a magnetic field in these bodies. Because the plasma measurements must be initiated at a distance from Pluto greater than the anticipated Drop Zond turn-on distance, it may be preferable to place the appropriate instrumentation on the mother spacecraft.

While each of the two Drop Zonds could carry different instrument packages, considerations of science redundancy, economy of cost, and streamlining integration may dictate the use of two identical Zonds.

Table 3.2 DZ Equipment Characteristics

N	Equipment	Mass, g	Power, W	Comment
1	TV system	600	2	
	TV1 (50 mm lens)	300	1	
	TV2 (15 mm lens)	200	1	
	contr.-rotation mirror	100		
2	Mass-energetic analyzer	500	4	a.m.<150
3	Accelerometer	300	0.1	1 mm/s^2
4	Battery	700		150 Wh/60 Wh, 4A
5	Transmitter	600	50	20 W, 0.3+0.6 GHz
6	Electronics	200	1	20 MHz
7	Processor unit and timer	200	1	
8	Sun Sensor	100	0.1	
10	Antenna	500		G = 15 dB
11	Heater	200		Radioisotope Pu
12	Construction	1350		
	shield	400		
	back cover	250		
	frame	500		
	other	200		
13	Separation device	500		
	for spacecraft	400		spacecraft mass only
	for DZ	100		
14	Cables	200		
15	Reserve	450		
		6000	58.2	

Mission Design

Baseline Description: During cruise, engineering data for spacecraft health assessment and radio navigation purposes will be transmitted to Earth once a week in a 4-hour segment per spacecraft. The data will be collected by the DSN and relayed to JPL and other operations sites. The possibility of also using Russian antennas has been proposed and will be considered in future discussions. Currently, no cruise science is planned for the mission. However, a low-mass, low-power, particles and/or fields experiment may be added if funding permits.

Starting about 6 months prior to Pluto encounter, the spacecraft will begin taking and transmitting to Earth images of Pluto, for both scientific and navigation purposes. This optical navigation data will reduce the errors in knowledge of Pluto's orbit in order to target and release the Drop Zond onto a Pluto (or Charon) impact trajectory. Zond release will occur roughly 30 days before Pluto closest approach (PCA). Meanwhile, the flyby spacecraft will perform a propulsive maneuver to retarget for a 15,000 km flyby of Pluto.

The Zond will be in a sleep mode for the bulk of the 30 days or so it is in cruise, waking up periodically to gather far-encounter data and relay it to the spacecraft. Thirty minutes before impact with Pluto (or Charon), it will begin its prime mission, collecting and transmitting its data to the spacecraft. The total amount of data collected by the spacecraft from the Zond will be some 30–40 Mb.

The geometry of the spacecraft flyby of Pluto is shown in Figure 3-4. Since one of the science requirements is to image both hemispheres of Pluto and Charon, one encounter will have a far Charon flyby and one will have a close Charon flyby. The flyby geometry is largely dictated by orbital mechanics, but the requirement to have Pluto and Charon occultations (as shown in Figure 3-4) for atmospheric measurements determines where the aim point for the flyby shall be. The flyby speed with respect to Pluto is around 50,000 km/h. Beginning at PCA -3 days, the optical navigation solutions will be performed on board the spacecraft since the one-way transmission time from Pluto is too long (roughly 4.5 hours) for the images to be of use to ground-based navigators.

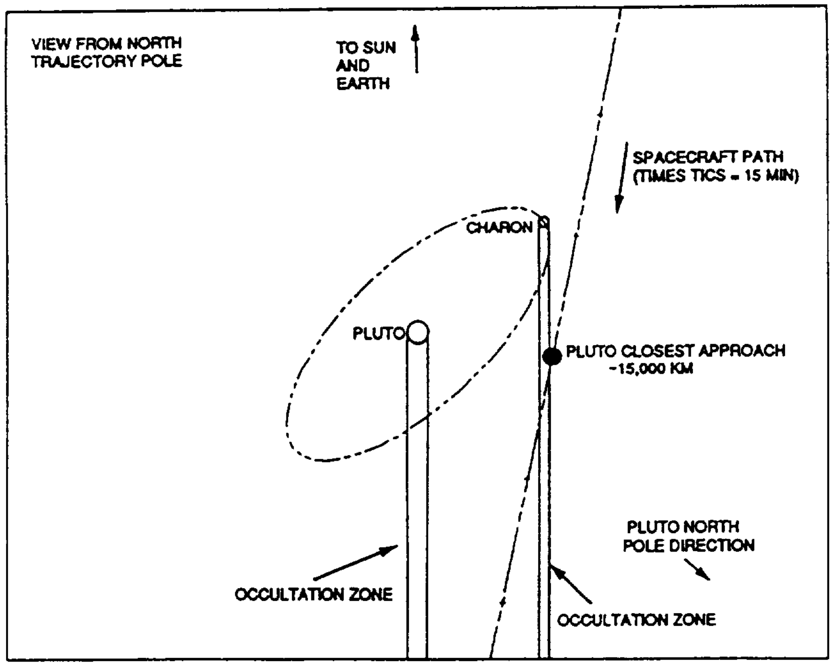


Figure 3-4. Pluto VSS: Pluto/Charon Flyby

The spacecraft are designed to meet the 1a science objectives (see Section 3.2) and this determines, to a large extent, the sample encounter sequence of events shown in Figure 3-5. Most of the 1a science objectives are satisfied in the five hours around closest approach to Pluto and Charon. Each spacecraft will collect more than 1 Gbit of science data. This will be stored on the spacecraft for transmission after encounter since the data rate is too low for real-time transmission. From PCA -30 minutes to PCA -15 minutes and while the spacecraft is already imaging Pluto, the spacecraft will be able to receive data from the Zond. The spacecraft-Zond separation distance will be about 20,000 km at this time.

At PCA +2 hours, data collection from the flyby spacecraft will cease and transmission to Earth will begin. It will take approximately 6 weeks (with contingency) to transmit all the data back to Earth. Once the data from the first spacecraft is collected and interpreted, corrections to the trajectory or science sequence can be made based on the new findings.

- 2 spacecraft encounters at Pluto/Charon occur 6 months apart
    - Flight time to Pluto 7.5 - 9.5 years

- Far encounter begins 0.5 - 1 year before Pluto closest approach (Pca)
    - Primarily optical navigation

- Spacecraft will target to obtain Earth and Sun occultations at Pluto and Charon (see Arrival Targeting)

- From Pca - 40 hours to Pca + 2 hours, all science data is stored onboard spacecraft for post-encounter transmission to Earth

- Most of category 1a science data collected from Pca - 3 hours to Pca + 2 hours
    - See example timeline (below)

- Science and engineering data transmitted to Earth at 425 bits/sec for up to 6 weeks after encounter

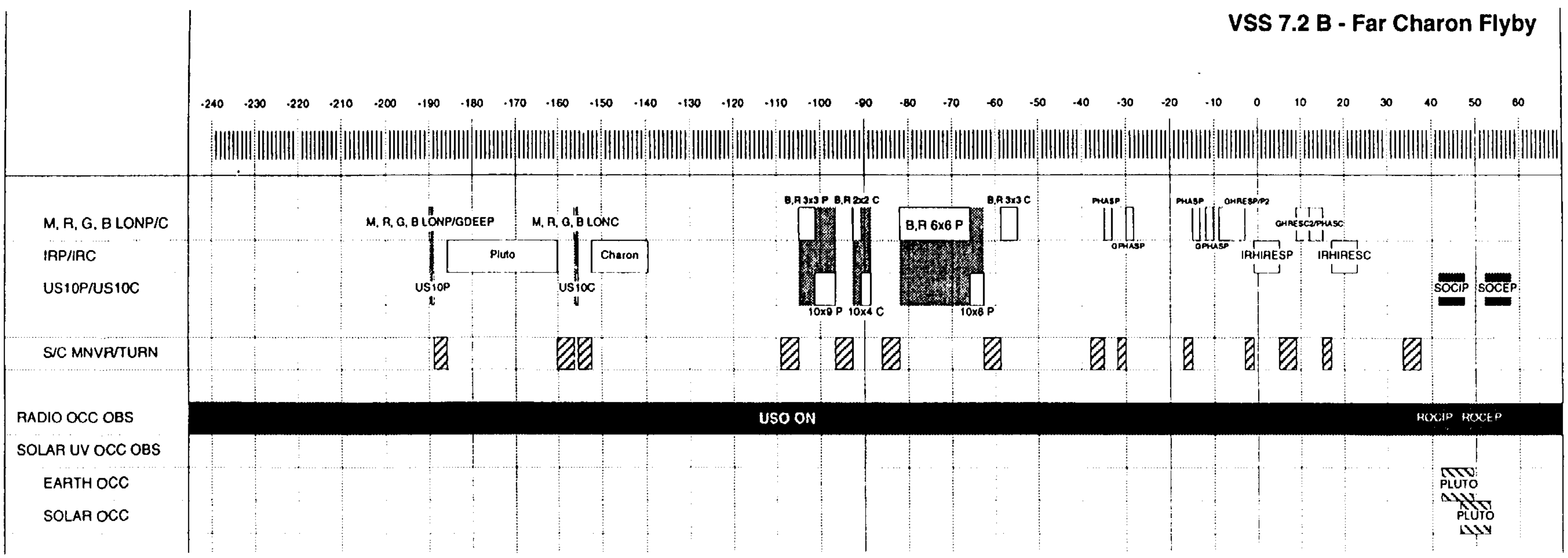


Figure 3-5. Pluto/Charon Strawman Encounter Scenario Overview

Backup Mission: The key difference between the baseline and backup missions is the trajectory type (Figure 3-6), which drives changes in the choice of launch system and spacecraft design. The backup trajectory launches into a roughly 3-year orbit about the Sun. Halfway through this orbit, the spacecraft must perform a propulsive maneuver (ΔV) to retarget for an Earth flyby. After flying by Earth for a gravity assist and then onto Jupiter for another gravity assist, the spacecraft will have gained enough energy to get to Pluto. The benefit of this trajectory type, called a 3+ΔVEJGA (3+ year, ΔV, Earth, Jupiter, Gravity Assist), is that the launch vehicle does not have to be as powerful since the gravity assists ease the required launch velocity. Therefore, less capable and/or less expensive launch systems may be used without augmentation by staged solid rocket motors. There are launch opportunities in November 2001, January 2003, November 2003, and January 2004; afterwards, this trajectory cannot be used for over another decade since Jupiter moves too far off the path to Pluto to be of use. While no cruise science is planned for the mission, the Earth and Jupiter flybys (and potentially an asteroid flyby) offer opportunities for scientific observation or instrument calibration.

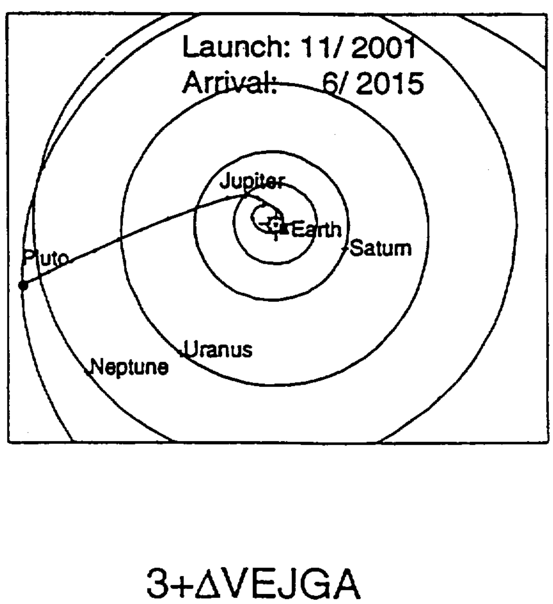


Figure 3-6. 3+ΔVEJGA Trajectory

The major disadvantage of the 3+ΔVEJGA trajectory is the flight time to Pluto. Since Jupiter has a harsh radiation environment, the spacecraft cannot fly as close to the planet as desired, resulting in a flight time to Pluto of around 13.3 years. (In fact, the spacecraft picks up a large dose of solar radiation from its 3-year orbit about the Sun, which happens to fall at solar maximum.)

A flight closer to Jupiter, possibly reducing the flight time by 2–3 years, requires the addition of heavy radiation shielding and radiation-hard electronic parts, which tend to be expensive and are becoming more difficult to find. In addition, a large reduction in flight time also requires an additional propulsive maneuver at the Earth flyby, increasing the amount of propellant needed, and the size of the tanks and, therefore, the spacecraft itself. Finally, the additional cost for operations of this longer and more intensive trajectory is some $45 million; the savings in launch system costs may not offset this impact, depending on the choice of launch vehicle. In addition, due to the later arrival time, the backup mission also jeopardizes the key flyby and Drop Zond scientific goal of studying Pluto while its perihelion atmosphere is intact. After the Jupiter gravity assist, the rest of the mission is basically identical to the baseline mission.

Other Options Studied

Overall, it was agreed that the right type of cooperative agreement to strive for involved flying Zonds to Pluto together with Proton launches. However, other options the Russians proposed are listed below.

Application of Electric Propulsion to the Mission: The fast trajectory to Pluto may allow the application of low-thrust electric propulsion (EP) to increase the spacecraft payload or shorten the flight time for a given payload mass. Because the trajectory is fast and the spacecraft velocity is relatively high, in this scenario gravity loss is rather low. Flight time is long enough (7–8 years or more) so that a significant effect from the EP application can be used. The RTGs produce some amounts of extra power during the flight that could be used by the electric propulsion. Necessary correction maneuvers and the escape maneuver after the detachment of the Drop Zond could also be performed by means of the EP thruster.

The existing Russian stationary Plasma Thruster SPD-70 was examined for use on the Pluto mission: this thruster has been used for geostationary satellites station-keeping purposes for the last 15 years and is quite reliable. Its main characteristics are:

Input power	- 700 We
Efficiency	- 0.5
Specific impulse	- 1500 s
Thrust	- 4 gram
Mass flow	- 3.2×10^{-6} kg/s
Operational lifetime	- 3000 hr

The current onboard Pluto Fast Flyby power that EP could use is about 30 W. Therefore, a rechargeable battery would be required to accumulate power and provide EP with the necessary 700 W for short spans. If as much as 50 W were available onboard, EP could operate for approximately 1/14 of a fraction of the time, and the average thrust and mass flow would be about 0.3 gm and 2.5×10^{-7} kg/s, respectively. This would simultaneously solve the problem of the rather short EP operational lifetime.

If more power were available during cruise, EP application to the Pluto mission would provide a payload increment of about 25% (taking into account the battery mass) or shorten the flight time by about 1 year. The EP would run for about 70% of total flight time (actual operation time would be about 1/20 of flight time). Attitude control during EP operation could be simplified by requiring constant thrust direction in each of two parts of the operational time. This control strategy is a simplified version of an optimal one and provides nearly the same payload.

At present the RTG power available for electric propulsion is substantially below 50 W for the first 5 to 7 years. If more power should become available, this concept will be reexamined.

Fregat: The Fregat is a proposed upgrade to the APU that was built for the Russian mission to the Martian satellite Phobos. The APU was a liquid bipropellant system designed to perform propulsive maneuvers at trans-Mars injection from low-Earth orbit as well as at the rendezvous with Phobos. Initially, the hope was that the Fregat would replace one of the solid rocket motors in the stack on Proton. However, the low thrust associated with the bipropellant system was not able to provide the performance for the type of high-energy injection required by the baseline mission. Fregat is not necessary for the backup mission since adequate launch system capability exists.

Russian RTG: The Russians proposed to build RTGs for the mission. Currently, the Russian RTG has much smaller electrical power output than US RTGs and are not large enough to meet the power and thermal requirements of the mission. Use of Russian RTGs would necessitate a major new development program by the Russians. This effort is not necessary since mission requirements can be met with existing US RTGs such as the spare Cassini unit.

Cruise Instruments: A proposal was made by the Russians to fly small low-power instruments on the US spacecraft for operation during cruise. As with other such proposals, this is under consideration, and no decision will be made until it has been determined whether the extra mass, power, and cost margins are available.

Russian Antenna Sites: The use of Russian antenna sites for cruise operations and/or encounter data downlink could improve the mission. More information is required to assess this possibility.

Joint Educational Outreach Ventures: The possibility is under study of connecting students in the two countries through Internet and other means to share ideas while studying space sciences. This would be facilitated by the creation of curriculum materials useful to both Russia and the US.

3.5 Recommended Options and Rationale

Several options surfaced as the most desirable and mutually beneficial, providing clean mission and spacecraft interfaces. In summary, the US will provide two flyby spacecraft with flyby science payloads, two upper stage stacks, and flight operations. Russia will provide two Proton launch vehicles and Block DM upper stages, two Drop Zond atmospheric entry probes with science payloads, and Drop Zond receivers for the flyby spacecraft. This configuration provides several mutual benefits, namely significant cost savings, significantly improved mission science, enhanced public appeal, and symbolic Russian/US cooperation in solar system reconnaissance.

The key results of the US/Russian discussions:

- Agreement that the Drop Zonds are the viable component of Russian participation in the mission, together with the Proton launch vehicles
- Agreement on the mass, electrical interface, mechanical interface, telecommunications, commanding, etc., for the Drop Zond
- Convening of the temporary Joint Science Steering Group to recommend Pluto Flyby and Drop Zond options, science, and measurement objectives
- Agreement that the overriding benefit of the Drop Zond is the direct sampling of the atmosphere. *In-situ* capability is paramount with a mass spectrometer as the first-priority instrument. Other possibilities include high-resolution imaging, accelerometer density profiling, and a magnetometer.

3.6 Open Issues

Launch Approval: A key consideration for a Proton launch of the Pluto mission is ensuring a safe RTG launch through an appropriate joint safety certification process. Chapter 4 of this report describes in further detail the findings associated with launching US RTG-powered spacecraft and Russian RHU-heated Drop Zonds from Kazakhstan using Russian Protons. Progress in this area will be critical to continued cooperation on the Pluto mission.

Launch Vehicle Integration: A number of basic concerns remain regarding integration of the US stack and spacecraft within the Proton launch vehicle and launch processing system. The feasibility of Proton use cannot be ascertained without a joint understanding of the potential integration process, nor without analyzing specific technical items, such as the injection accuracy of the fourth stage and the interfaces and operations involved in the proposed spacecraft escape system. Additionally, the implementation of the integration process has a direct effect on launch system costs for both countries. A forum should be established to allow technical specialists from both sides to exchange the detailed data necessary to define the joint Proton/US stack/ Pluto Flyby mission.

Drop Zond Release Mechanism: The accuracy requirements associated with the Zond release mechanism must be worked out, since even small errors propagated over the 30 days to Pluto impact may override the best optical navigation campaign and cause the Zond to miss Pluto. Also, a targeting strategy for the second Zond needs to be determined, in case the first Zond fails.

Alternative Upper Stages: In order to minimize mission cost, both sides will continue to examine alternatives to a US-only provided upper launch stack. Other possibilities include, for example, the incorporation of Russian electric propulsion.

3.7 Recommended Next Steps

The Study Team cautions that this cooperative mission relies upon the Russian Drop Zond arriving while Pluto still has its perihelion atmosphere. For this reason, the mission is particularly time-critical, and the following recommendations are made so that it may proceed in a timely manner:

- A Joint Science Definition Team should be formed immediately to continue the definition of the flyby spacecraft and Drop Zond science payloads and to provide an understanding and an encounter prediction of the Pluto atmosphere.
- The definition of launch vehicle and spacecraft interfaces and integration issues should be continued through the existing joint engineering team.
- A launch approval plan consistent with launch in 2001 should be cooperatively developed.
- Joint phase B mission definition should be initiated in budget year 1996 in order to maintain the unique opportunity of a cooperative mission, arriving at Pluto by 2010, and thus able to investigate the atmosphere of Pluto.

3.8 Membership

Membership of the Pluto Mission Joint US/Russian team is listed below:

D. Abraham	A. Galeev
H. Brinton	V. Gotlib
D. Cruikshank	V. Karrask
C. Elachi	V. Linkin
E. Mastal	B. Martinov

J. Giuliano
H. Price
R. Shope
R. Staehle
A. Stern
R. Terrile
S. Weinstein

V. Moroz
O. Papkov
K. Pichhadze
A. Soukhanov
O. Weisberg
A. Zakharov

CHAPTER FOUR

Launch Vehicles

4.1 Introduction and Background

Against the background of many years of experience in both the United States and Russia of launching space missions, the discussions on launch and transportation configurations needed to place these several US and Russian spacecraft en route to their various destinations have been very interesting.

In this joint activity, most of the transportation components will be Russian: the three-stage Proton, the Block D fourth stage, and a Russian fifth stage. These represent all transportation elements of the Mars Together mission. For the FIRE and ICE missions, one and two US solid stages in place of a Russian fifth stage, respectively, are being considered. The joint study team has established to date that the required transportation capability exists and that top-level integration issues have been addressed. Any remaining problems appear to have credible solutions.

From the start, launch vehicles have been an integral part of potential joint mission cooperation. The launch system is a significant technical and cost element within any planetary science program. Throughout the history of the US and Russian space programs, new science mission requirements have driven the need for development and modification of launch systems. The study team has drawn upon both nations' resources and selected a launch system that meets mission needs and provides the best technical and programmatic features. The team considers the Russian Proton launch vehicle, in combination with mission-unique US or Russian upper stages, the best approach in meeting these needs.

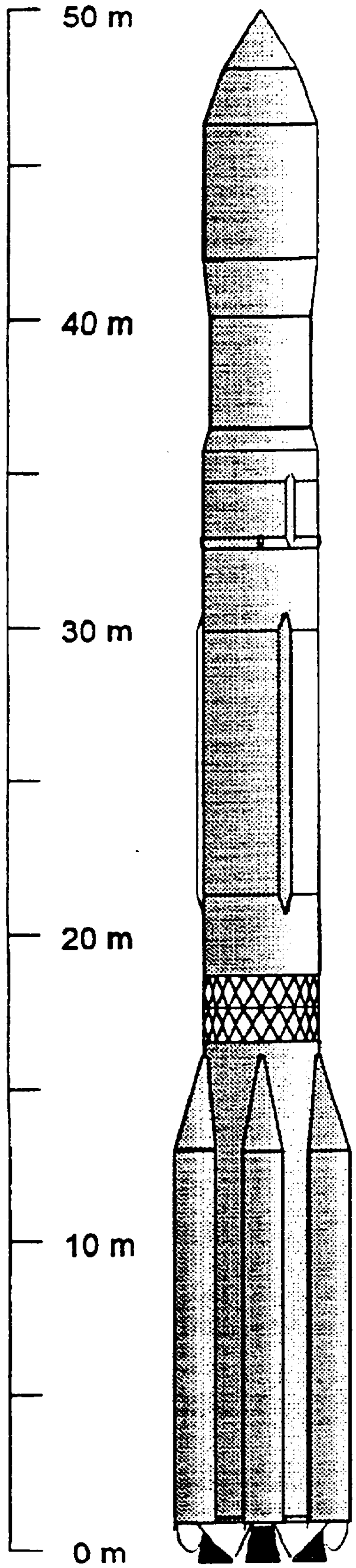
4. 2 Proton Launch Vehicle

The Proton has been the primary launch vehicle for the Russian lunar and interplanetary science programs launching, between 1967 and 1988, Zond, Luna, Venera, Mars, Vega, and Phobos missions. A total of 220 Protons has been launched between 1970 and August 1994.

The Proton is flown regularly in three-stage and four-stage versions. The four-stage version can meet the needs of the joint missions under study. The Khrunichev State Research and Production Space Center has overall responsibility for the Proton (Figure 4-1) and manufactures the first three stages. NPO Energia manufactures the fourth stage. The Proton lift-off mass is approximately 700 Mg. The lower three stages burn storable propellants, unsymmetrical dimethylhydrazine (UDMH), and nitrogen tetroxide. These three stages alone are used for delivery of heavy payloads to low Earth orbit, often in support of the Russian manned space station programs. Proton is launched from the Baikonur Cosmodrome in Kazakhstan. The third stage delivers the payload (which may include the Proton fourth stage, as described below) to a circular low Earth orbit with an altitude of approximately 200 km. Launch into orbits with inclinations of 51.6°, 65°, and 72° is possible; the 51.6° inclination is most advantageous for interplanetary missions.

The fourth stage, the Block D, is used on missions to higher energy orbits, primarily to geosynchronous orbit, but also to other intermediate Earth orbits and to Earth escape. Various versions of the Block D have been considered for use on the joint missions. The Block DM, used extensively for Earth orbit missions, has its own control system and operates autonomously. The Block D, with the control system removed, has been used primarily for interplanetary missions to allow maximum launch vehicle performance and spacecraft payload. In these missions, the payload controls flight of the Block D. A third version, the Block DS, is currently in development. It is functionally similar to the Block DM, although the Block DS control system, derived from spacecraft systems, is expected to have lower mass, thereby increasing performance compared to that of the Block DM. The fourth stage burns liquid oxygen and kerosene propellants and is capable of multiple starts. The capabilities of the fourth stage allow a special Proton ascent trajectory with increased performance. In this case, the third stage injects the fourth stage and spacecraft into a ballistic trajectory; the fourth-stage first burn completes the insertion into a low parking orbit. This configuration is available for the proposed joint missions.

A range of payload fairings, built by various launch vehicle and spacecraft manufacturers and which meet the needs of the proposed missions, is available for Proton missions.



Injection path parameters

Activity	Time (sec)
Launch	0
1-2 stages separation	130
Fairing jettisoning Velocity Altitude	180–190 21.75 m/s 80 km
2-3 stages separation	340
Insertion into parking orbit	590

Parking orbit parameters

Parameter	Value
Inclination to Earth Equator	51.6°
Altitude	190–200 km
Launch site	Baikonur

Figure 4-1. Proton Launch Vehicle and Main Injection Parameters

Proton has a record of success that places it among the world leaders in expendable launch vehicle reliability. Over the last 50 flights, Proton has achieved a success rate of 97%. Over a longer term, dating back to 1979, Proton has demonstrated a success rate of approximately 94% during 150 flights. Improvements to the Proton have been made to increase system reliability.

A Proton modernization program is currently in progress, aimed at increasing reliability by updating obsolete vehicle systems, increasing performance and payload volume capacity, and ultimately reducing the environmental effects of spent stages impacting in remote areas of Kazakhstan and Russia. Elements of the modernized Proton, Proton-M, have already flown on routine Proton missions. It is likely that the Proton-M will be available for some of the proposed joint missions and will offer performance, reliability, and cost benefits. The progress of the modernization program will be considered in the joint development of these missions.

4.3 Launch Approval Considerations

Each of the proposed missions involves the launch of plutonium in radioisotope thermoelectric generators (RTGs) to power the spacecraft. In the Mars Together and FIRE missions, the RTGs are Russian. The ICE mission uses US RTGs and the ICE mission Drop Zonds carry radioisotope heater units. In both the US and Russia, a special launch approval process is required before RTGs can be used. In the US, the impact of the National Environmental Policy Act also needs to be understood for each mission. As part of the launch system assessment, the study team has become familiar with both processes and has assembled relevant information. Discussions over the last three months reveal that the procedures appear, in many respects, to parallel each other. However, launch approval in both countries is challenging and time-consuming.

It appears that the technical challenge of the launch approval procedure can be met. It may be more difficult to organize information exchange and surmount language and terminology barriers to effective communication. The study team's experience to date in working together suggests that these hurdles can be overcome. Further discussions of launch approval procedures are expected to reinforce these conclusions.

Each mission is different, so detailed discussion of the specific issues are contained in the mission sections that follow. No discussions or planning for launch approval has occurred; the team spent time trying to understand the procedures each country has followed for previous missions. These current missions are sufficiently different that individual launch approval procedures will also be different. Defining the launch approval procedures for the approved missions will be an immediate and crucial activity.

4.4 Mars Together Mission Description

The selection of a launch system for the Mars Together missions focused on the proposed cooperative mission in 1998 (MT-98). In this mission, a Russian descent module, containing the Mars Balloon and a Mars Rover, and a US Mars Surveyor orbiter are delivered to Mars by a Russian propulsion stage.

Requirements: The Mars Together 98 mission is planned for launch in December 1998, within a 20-day launch opportunity. The ultimate objective, delivery of the spacecraft to the Mars orbit and surface destinations, is accomplished with the combined launch system and spacecraft propulsion module. The launch energy (C_3) required to provide the planned October 1999 Mars arrival is approximately 11 km^2/sec^2; however, some of this energy is provided by the spacecraft propulsion module, the amount being dependent on spacecraft configuration. Using the reference configuration described below, the launch vehicle must deliver a 7985-kg payload to an intermediate injection orbit.

Launch System Baseline: Selection of the Mars Together launch system was simplified by past planning for the Russian Mars 96 and Mars 98 missions and the nature of the proposed joint spacecraft. The following launch system, similar to that planned for Mars 96, is proposed:

- Three-stage Proton launch vehicle
- Proton fourth stage Block D (without control system module)
- Russian liquid propellant fifth stage (included in the spacecraft assembly)
- 4.1-m-diameter fairing (under development at NPO Lavochkin)

The combined spacecraft, fifth stage, and fairing are illustrated in Figure 4-2.

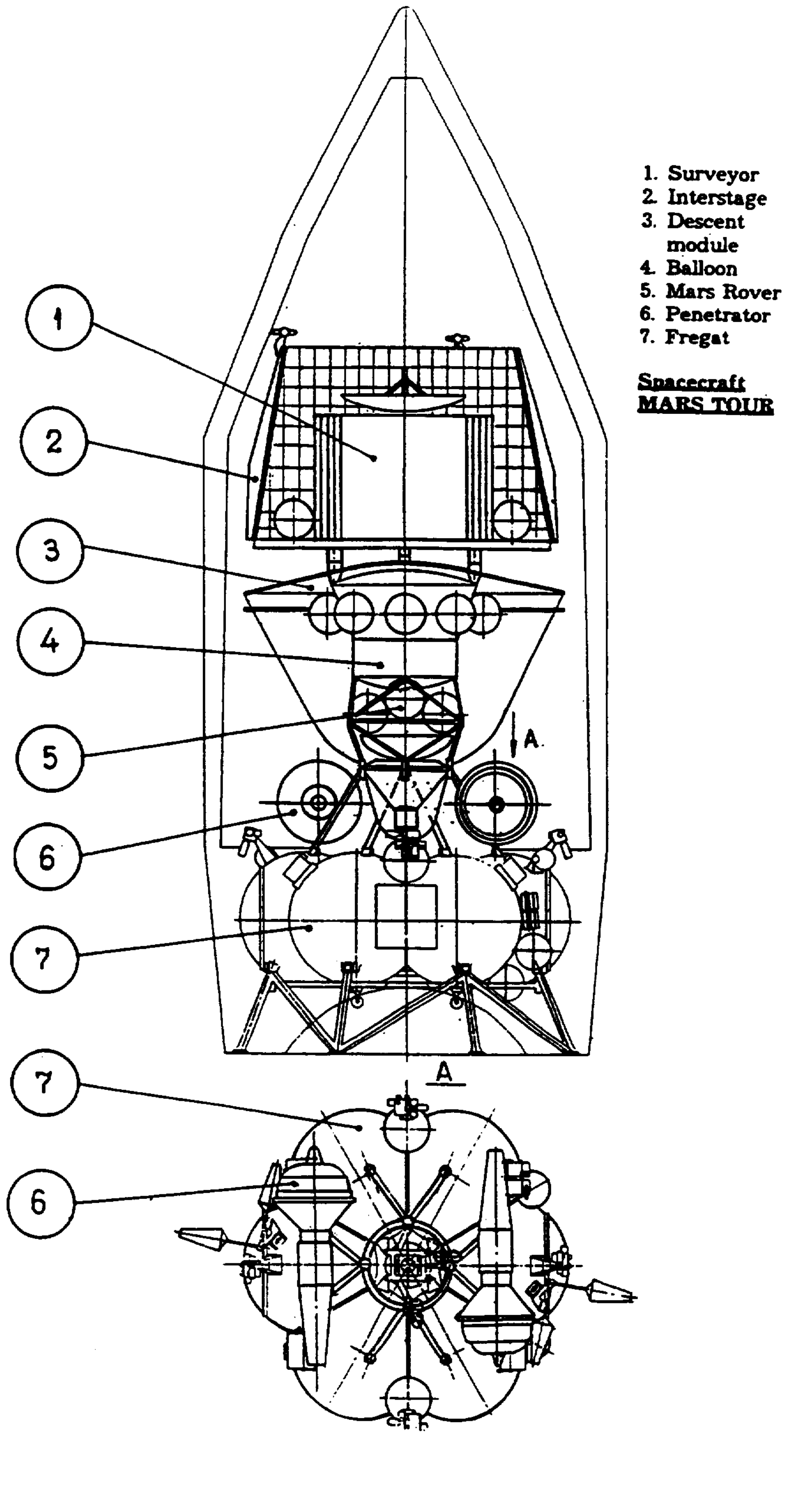


Figure 4-2. Mars Together 1998 Basic Configuration

The three stages of the Proton launch vehicle insert the Block D and spacecraft into an elliptic transfer orbit with a 51.6° inclination, 160 km apogee altitude, and a perigee altitude below the Earth's surface. The first burn of the Block D propulsion system will be used to transfer the Block D and spacecraft to a circular parking orbit at an altitude of 160 km. A second Block D burn will occur at the end of the first parking orbit to transfer the spacecraft to an escape orbit. During all flight stages, the Block D will be controlled by the Russian fifth stage. After the spacecraft is separated from the Block D, the fifth stage will burn to complete the spacecraft insertion into the trajectory to Mars. This additional burn will increase the final payload mass delivered to Mars transfer orbit. The entire launch through insertion sequence will take approximately 1.5 hours.

Several options have been considered for the Russian liquid propellant fifth stage, including: a derivative of the propulsion module on the Phobos spacecraft; the Fregat, an autonomous stage under development at NPO Lavochkin; and the Briz, a similar stage, produced by Khrunichev, currently in use as a third stage on the small Roket launch vehicle. Final stage selection was not necessary within the scope of the study team; however, it is critical in defining the Mars Together spacecraft and launch system. These stages offer various technical and programmatic advantages and disadvantages that need to be carefully considered in defining the mission. Final selection of this stage, led by the Russian Space Agency, is required immediately.

Launch Approval: All the transportation elements for the Mars missions under discussion are Russian: the first three stages of Proton, the Block D fourth stage, and a Russian fifth stage. The payload consists of a Russian and a US spacecraft. Only the Russian spacecraft includes an RTG. The US spacecraft does not carry any nuclear materials. Discussions over the last three months have resulted in a common substantive understanding of both launch approval processes. From the information available, it appears that any US and Russian launch approval requirements for this mission may be largely or totally satisfied by the Russian process. A deeper understanding of the requirements and approval processes is expected to reinforce that conclusion, and the study team recommends that substantive discussions on launch approval proceed as rapidly as possible.

Other Options Studied: The study team did not consider any other launch vehicle options, other than a variety of options for the fifth stage. It should be noted that the launch vehicle baseline is not an enabling factor for the joint mission. Each country could continue with independent programs using existing launch system resources but at considerably greater cost to both.

4.5 ICE Mission Description

Requirements: The baseline ICE mission is to separately launch two spacecraft with companion Zonds on direct trajectories from Earth to Pluto, with launch in early 2001. A strong programmatic desire to arrive at Pluto in less than 10 years, before the atmosphere is expected to freeze out, sets the minimum launch energy (C_3) requirement at 206 km^2/sec^2. Launch energies greater than this result in shorter flight times to Pluto, reducing mission operation costs and increasing the chances of arriving before the bulk of the atmospheric freeze-out occurs, and thus are highly desirable. The arrival of the second spacecraft will be delayed 6 months in order to return scientific and engineering data from the first encounter to Earth for interpretation and use in planning the second encounter.

The launch period for the two spacecraft is 20 days long and occurs late January through early February in 2001. A launch opportunity with similar performance occurs once a year. Launch of both spacecraft in the same launch period will minimize program costs.

Launch System Baseline: The Russian Proton (using Block DM) was selected as the mission launch vehicle. An additional propulsion stage is needed to meet the mission injection requirements with the 180 kg spacecraft. A number of options were suggested, including solid, liquid, and electric propulsion systems (see Chapter 3 on the ICE mission for details). At this time, staged solid propellant motors appear to best meet mission needs and were selected as the baseline. The team will continue to consider other alternatives as their potential benefits warrant. It is clear that the mission performance objectives can be met with Proton and one of many of these stage options.

The US and Russia have both analyzed the optimal solid motor staging for the ICE mission. Russia currently does not manufacture solid rocket motors in the size range needed; however, there are at least two manufacturers in the US with existing motors close to optimal. For this reason, a US propulsion stage consisting of US solid motors was selected. Design and performance analyses have been performed by both countries for two-motor and three-motor stage combinations, with similar results. While the three-motor stack provides significant performance benefits, a two-motor stack is preferred as cheaper and less complex. Upon completion of the parallel analyses, a two-motor stack (Figure 4-3), using Thiokol STAR 48 and STAR 27 motors in a spin-stabilized mode, was baselined.

Proton is launched from the Baikonur Cosmodrome in Kazakhstan. Protons have routinely been launched 7 days apart or less, thus meeting the short launch period requirement. The flight sequence is illustrated in Figure 4-4. In the standard Proton trajectory mode, the first three Proton stages place the fourth stage, the US solid motor stage, and the spacecraft/Zond into a low Earth orbit. On reaching the correct injection targets, the fourth stage and the two solid motors fire sequentially, achieving the required launch energy and direction. This launch and injection sequence will take approximately one hour; the resulting trip time to Pluto is about 9 years.

An important issue for the ICE mission is safety in the unlikely event of a launch accident (see launch approval section below). The team has considered providing a spacecraft escape system within the integrated launch system in order to remove the spacecraft RTG from hazardous accident situations. This is complex because the Proton, the US upper stage, and the spacecraft would have to operate together to provide safe escape from a launch accident.

Launch Approval: As described above, the ICE mission plans to launch on the four-stage Proton vehicle topped by two US solid stages. Each spacecraft includes a US RTG; the Drop Zonds contain radioisotope heating units. Discussions over the last three months have resulted in better understanding of both the US and Russian launch approval processes.

Since the launch includes both US and Russian stages, and US RTGs are on the spacecraft, it is probable that launch approval will be required both in Russia and the US. Each country will require information from the other. The US will need data on the Proton and spacecraft information describing the Drop Zond. Russia will need information on the US stages and the spacecraft. It appears that the launch approval processes are sufficiently similar that the technical challenge of completing the procedures required for the ICE mission can be met. Further discussions of launch approval processes are expected to reinforce this conclusion.

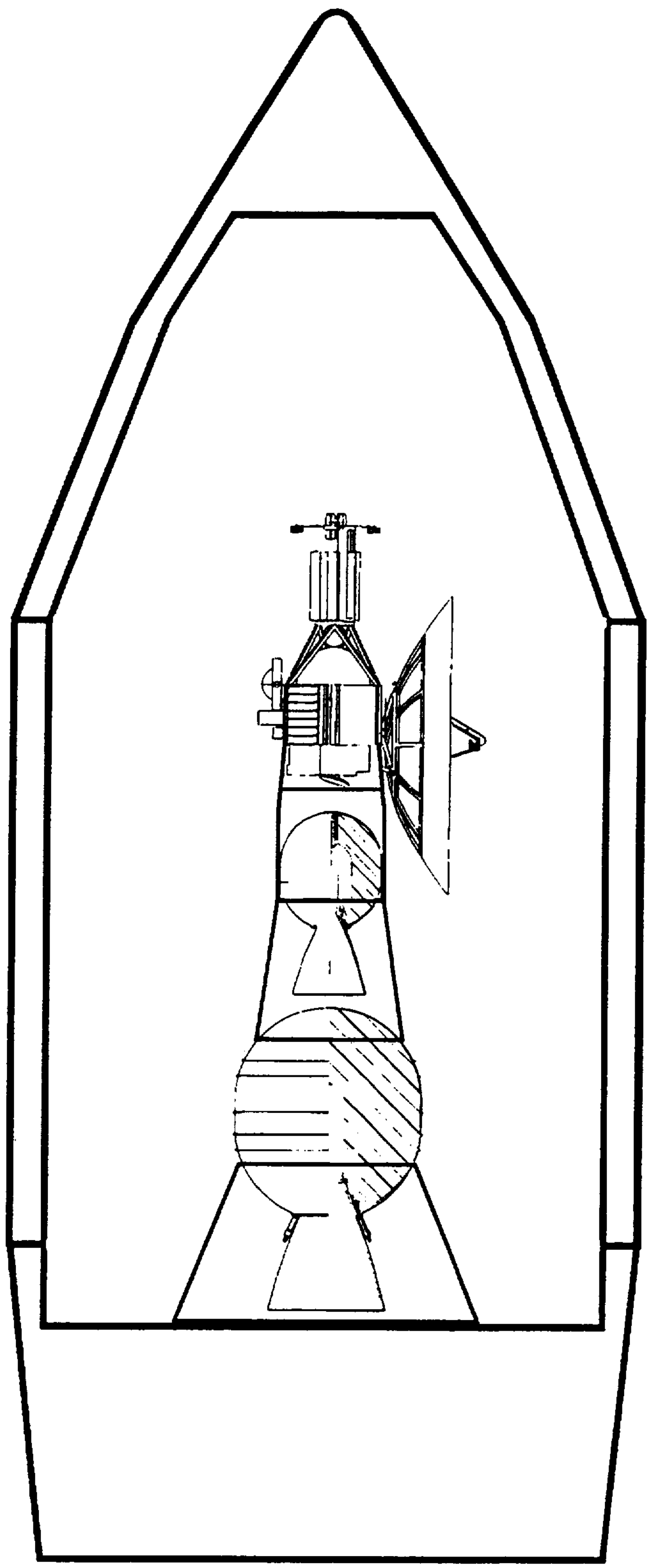


Figure 4-3. Configuration for ICE Mission

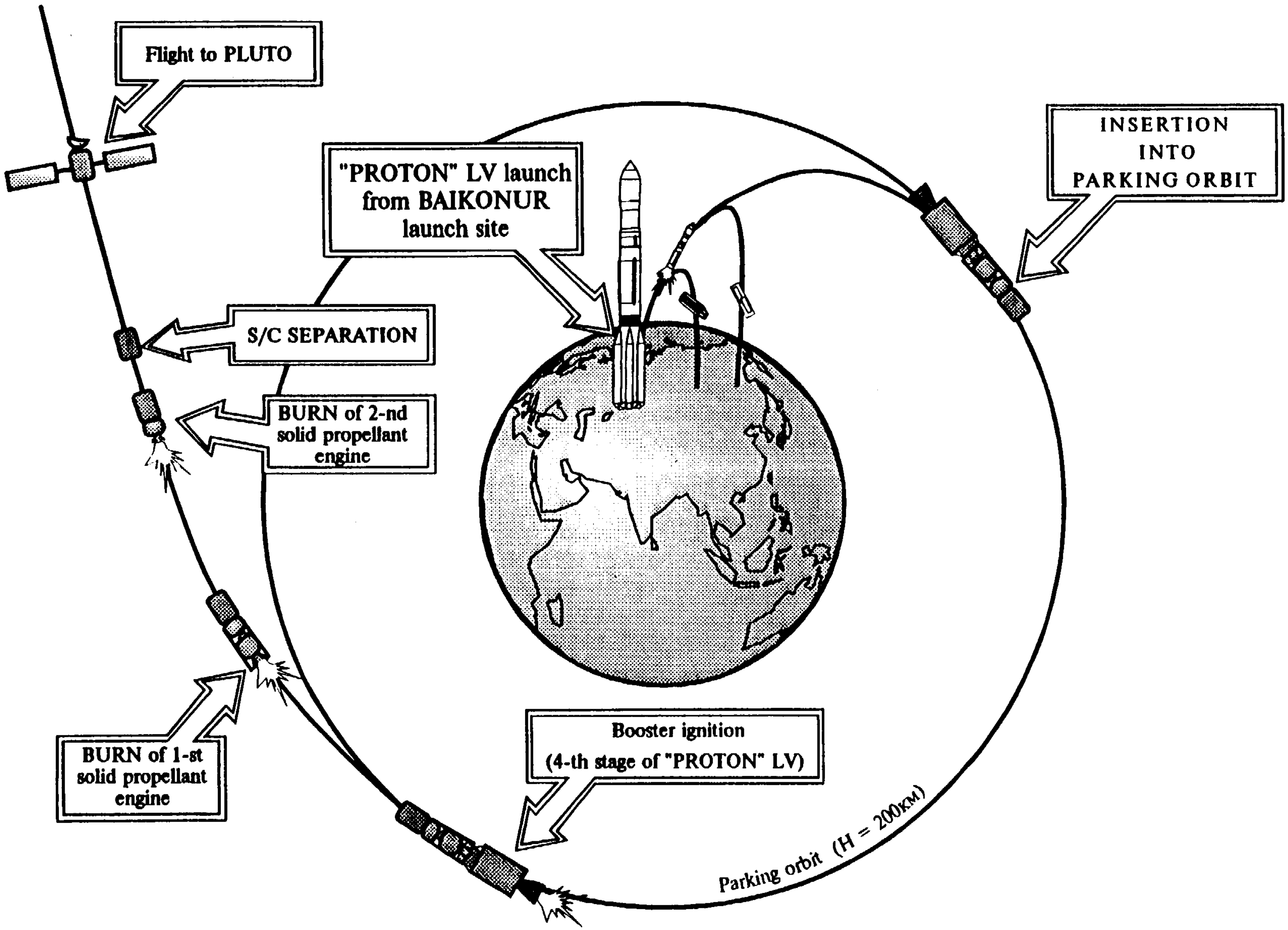


Figure 4-4. Profile of S/C Insertion into Interplanetary Trajectory

Other Options Studied: Option analysis centered on the selection of the upper stages, including consideration of the three Block D variations, Russian liquid propellant stages, solid rocket motors, and electric propulsion systems. As described previously, almost any of these could provide a mission that meets trip time objectives. Besides performance, many differences exist in development status and risk, operational capabilities to meet other spacecraft requirements, and cost.

Other mission trajectory options also exist, but were not studied in detail. In particular, a trajectory using Earth and Jupiter gravity-assists might be achievable with a Proton or Delta II launch vehicle without additional upper stages. However, the benefit provided by the launch vehicle stage is likely to be outweighed by a substantially longer trip time (+4 years), the need for additional spacecraft radiation shielding, and additional mission complexities.

The Proton-M has potentially greater performance, thus reducing trip time. The ICE program will maintain the existing Proton baseline until the readiness and benefits of Proton-M are better understood.

4.6 FIRE Mission Description

The FIRE mission, as studied by the team, represents the first mission to combine out-of-the-ecliptic scientific coverage with close solar encounters. The possibility of launching dual spacecraft (one Russian, one US) with differing solar encounter requirements adds tremendous value to the mission science. Several trajectory and implementation options have been considered by the team. The consensus on preferred implementation is a single launch of both spacecraft into a direct Jupiter gravity-assist trajectory resulting in two polar orbits about the Sun, one with a 4 Rs perihelion (the US spacecraft) and the other with a 10 Rs perihelion (the Russian spacecraft).

Requirements: To achieve the required encounter geometry and phasing, trajectory energy considerations must be balanced against launch vehicle performance and implementation scenarios. The key launch system requirement is system payload mass capability at the high launch energy (C_3) for a Jupiter direct launch. This is driven by the launch date, perihelion radius (4 and 10 Rs), Earth location at encounter to ensure acceptable telemetry availability, final orbit inclination, and the duration of the launch opportunity. Launch opportunities from August 2000 to January 2006, recurring approximately every 13 months, have been investigated. A September 2001 opportunity is the reference launch year. Launch energy requirements range from 123.0 to 109.4 km^2/sec^2 over the six opportunities considered. The 2001 requirement is 120.3 km^2/sec^2. The launch system must accommodate a minimum launch opportunity duration of 10 days.

A requirement for a payload system mass of not less than 700 kg is necessary to accommodate both spacecraft, spacecraft adapters, and any airborne support equipment (ASE) required on the launch vehicle upper stage.

Launch System Baseline: Several launch vehicle configurations were assessed for the FIRE mission. While many of these, outlined in the following discussion, met performance requirements, the preferred configuration is a standard three-stage Proton, the Block DS fourth stage, and a STAR 48B solid motor upper stage. This configuration offers development and cost benefits, as well as some upper stage commonality with the ICE mission. A 4.1-m diameter fairing is necessary to accommodate the two spacecraft. This configuration is illustrated in Figure 4-5.

The Proton, launched from Baikonur, injects the Block DS, STAR 48B, and dual spacecraft into a low-Earth parking orbit. A single Block DS burn and the STAR 48B burn occur sequentially to provide injection to the Jupiter transfer orbit. After separation of the two spacecraft, spacecraft propulsion systems provide the propulsive maneuvers necessary to achieve the different Jupiter gravity-assist and solar encounter geometries.

Launch Approval: The FIRE mission plans to launch on the four-stage Proton vehicle and a fifth stage consisting of a US solid motor. Two spacecraft (one Russian, one US) are launched on a single launch vehicle. The Russian spacecraft includes an RTG. The US spacecraft has no nuclear materials. Discussions over the last three months have resulted in better understanding of both the US and Russian launch approval processes.

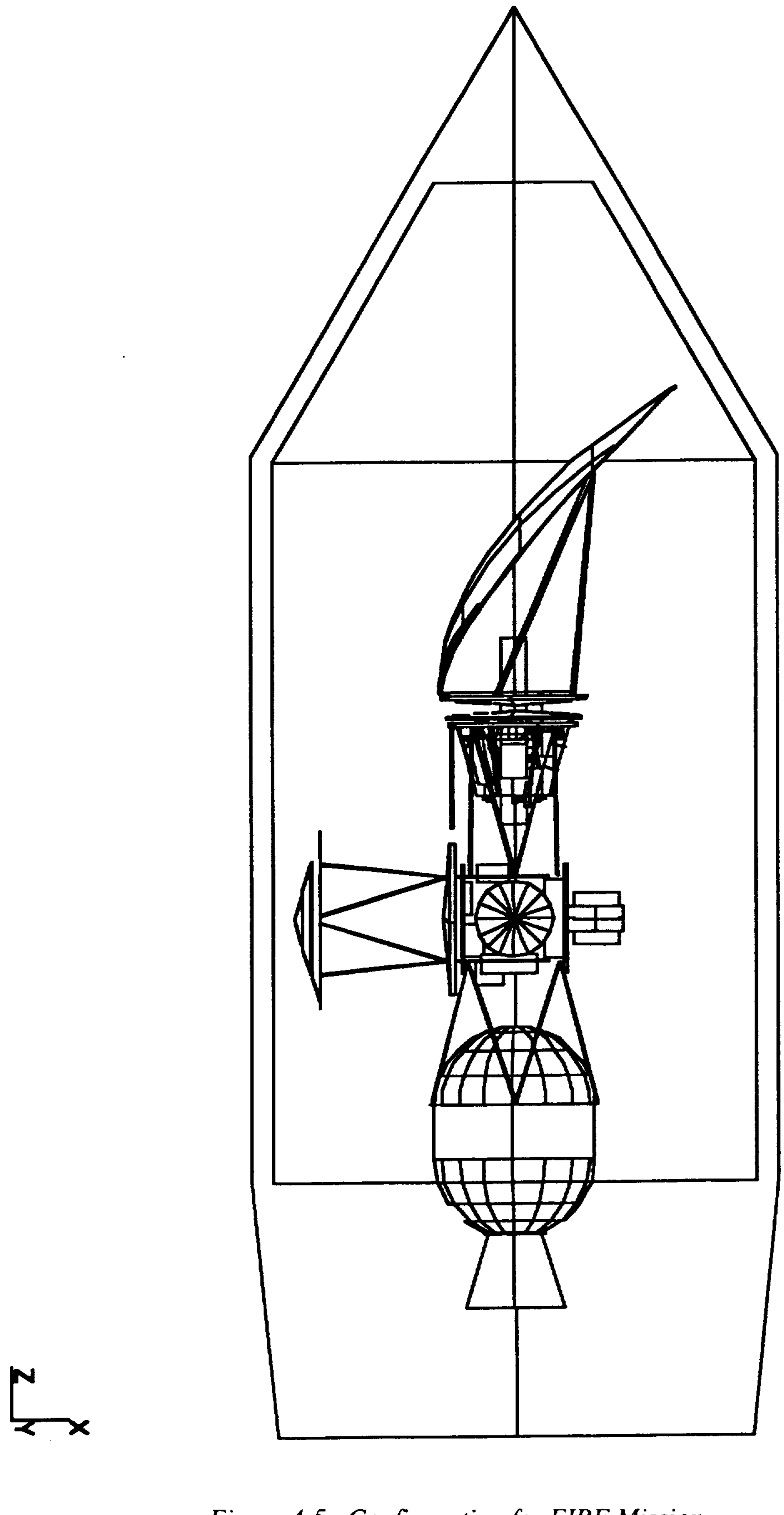


Figure 4-5. Configuration for FIRE Mission

Since the launch includes both US and Russian stages and there is an RTG on the Russian spacecraft, it is probable that launch approval will be required both in Russia and in the US. Each country will require information from the other. The US will need data on the Proton and spacecraft. Russia will require information on the US stage and spacecraft. It appears that the approval procedures are sufficiently similar that the technical challenge of completing the necessary FIRE mission approvals can be met. Further discussions of launch approval procedures are expected to reinforce this conclusion.

Other Options Studied: The team evaluated other upper-stage options as well as the modernized Proton. Stage options included the Block D, DM, and DS versions of the Proton fourth stage, in combination with a Russian liquid propulsion stage, single solid motors, or staged dual solid motors. Many of these options meet performance requirements. A firm selection is not necessary at this time; additional study is warranted to investigate the technical and programmatic benefits of the various systems. While studies to date are not extensive, the fact that there are multiple feasible options greatly enhances confidence in the implementation recommendations.

It is noted that the two spacecraft could be launched independently by their countries. The US spacecraft could be launched on the required trajectory by a Delta II launch vehicle with a smaller solid upper stage. The Proton, or possibly other Russian vehicles, could be used to launch the Russian spacecraft alone.

4.7 Summary, Recommendations, and Rationale

The three proposed cooperative missions pose a variety of requirements for a launch system. As seen, there may be multiple methods, including hardware and trajectory selection, to achieve the end result for any of these missions. The study team has established proposed approaches that clearly demonstrate a basic capability to perform each mission.

Mars Together 98: The standard Proton, the Block D fourth stage, and the Russian spacecraft liquid propulsion module provide the 11 km^2/sec^2 launch energy for transfer to Mars. Launch in December 1998 leads to Mars arrival in October 1999. Various options for the propulsion module lead to flexibility in mission approach.

ICE: Two separate launches, in early 2001, of the standard Proton, the Block DM fourth stage, and tandem US solid rocket motors accelerate separate 180-kg spacecraft/Zonds on direct trajectories to Pluto with launch energies in excess of 206 km^2/sec^2. The availability of the modernized Proton and optimization of the upper stage complement allow trip times to Pluto of significantly less than 10 years.

FIRE: A September 2001 launch of the standard Proton, the Block DS fourth stage, and a US STAR 48B solid motor inserts the dual Russian/US spacecraft into a trajectory leading to Jupiter flyby gravity assists and subsequent simultaneous solar encounters in May of 2005. Flexibility and spacecraft mass margin are provided by upgrade options for various elements of the launch system that are likely to be available in time for launch.

While the study team is confident of the top-level feasibility of these approaches, detailed discussions regarding launch system/spacecraft integration were extremely limited. In many cases, the basic spacecraft and mission concept are affected by the capabilities and interface characteristics of the launch vehicle. Both launch vehicle and payload representatives need to understand capabilities and limitations from the start of the design process. Greater technical information exchange will ensure success in developing the proposed missions.

International nuclear safety approval for the launch of each mission is a key milestone that must be accomplished in order to continue these cooperative missions. Each mission has a unique combination of US or Russian upper stages, spacecraft, and RTGs. Each must therefore be considered separately within the framework of general agreements in this area. Progress has been extensive and must continue through the next stages of mission definition.

The Proton launch vehicle is the mainstay of the launch system proposals. The Proton is a highly reliable, high-performance, cost-effective vehicle with a proven record of interplanetary missions. The proposed missions impose a set of straightforward requirements on the Proton, similar to those within its extensive flight experience and which will be expanded by upcoming launches of Western payloads. A variety of upper stages can be selected, each satisfying mission performance requirements and further increasing confidence in launch system feasibility.

It appears that the future of the exploration of space lies in joint activities. Indeed, the level of international cooperation has been steadily increasing over the last twenty years. The pace and scope of that cooperation are expected to increase as tight budgets favor joint missions to reduce costs. Joint activities will encompass many types of arrangements, including international complements of scientific instruments on spacecraft and the sharing of data. An opportunity is now available, in sharing US and Russian launch system resources, to expand the nature and scope of international science missions. In this case, the possibility of launching US and Russian spacecraft on the Proton is under consideration. The future undoubtedly will include the launch of Russian spacecraft on US or other non-Russian launch vehicles. In these joint activities, the opportunity exists to engage the public in a shared vision of international exploration of the solar system, abandoning an outdated paradigm of space competition.

4.8 Open Issues and Recommended Next Steps

The following recommendations are made to the US and Russian space agencies. To the extent possible, it is recommended that activities in these areas continue beyond the duration of the joint study team. It is expected that these activities would be formalized on the approval of these missions by the respective governments.

The overriding issues associated with a Proton launch of the proposed joint missions are in maximizing the probability of a safe and environmentally clean RTG launch and establishing a joint process under which that safety can be certified. It is highly desirable that a launch approval forum be established to allow technical specialists from all involved parties to continue expanding understanding of both countries' requirements and existing processes, and to begin developing an approach to accomplish launch approval for each of these unique missions. In the case of the Mars Together 98 mission, the short time available drives the need for agreement on a launch approval process as soon as possible. The FIRE and ICE missions, with the unique use of US stages, spacecraft, and RTGs (for ICE only) will likely require a more complex combination of Russian and US launch approval processes. Initial work in developing a joint approach should not be delayed as experience has shown that the US approval process takes a very long time.

A number of basic concerns remain regarding integration of US upper stages and spacecraft with the Proton launch vehicle and launch processing system. Each mission has unique integration issues that should be addressed soon. For example, the potential need for a spacecraft escape system (to possibly facilitate launch approval) on the ICE mission may be a critical element that drives long-term activities. The time and resources available to the study team did not permit in-depth investigation of these detailed technical issues. The team recommends a forum be established to allow technical specialists from each side to exchange the detailed integration data necessary to define the launch systems for each of the joint missions. Initially, this forum would support a general exchange of launch vehicle, upper-stage, and spacecraft information applicable to all three missions. Emphasis on Mars Together would allow initial definition of interface requirements and design. As each mission reaches an appropriate state of program maturity, separate mission-unique study teams would be formally established.

In addition to technical integration factors, the implementation of the integration process has a direct effect on launch system costs in both countries. The roles and responsibilities of each of the affected organizations within each country should be established to permit efficient start-up of mission definition and integration activities.

4.9 Membership

The Membership of the launch vehicle group is shown below:

Frank Spurlock	Oleg Papkov
Tom Shaw	Vladimir Karrask
Scott Benson	Boris Martinov
Irene Shaland	
Doug Abraham	
Sandra Dawson	
Ed Mastel	

GLOSSARY

AB	accumulator battery
APS	autonomous propulsion system
ASC	Automatics and Stabilization Complex
ASE	airborne support equipment
ASW	antenna switcher
BF	buffer
C–C	carbon–carbon
C/D	manufacturing phase of a project
CDU	command data unit
CI	command instruments
CNES	Centre National d'Etudes Spatiales
CPU	central processing unit
DACP	digital array control processor
DAS	digital array source
DSN	Deep Space Station of the Deep Space Network
DZ	Drop Zond
EP	electric propulsion
FC	functional commands
GCC	Gore–Chernomyrdin Commission
GRS	gamma-ray spectrometer
HGA	high-gain antenna
ICS	Information Collecting System
IG	input generator
IKI	Russia's Institute for Space Research
IR	infrared
IRU	inertial reference unit
JGA	Jupiter gravity assist
JPL	Jet Propulsion Laboratory
JWG	Russian/American Joint Working Group on Solar System Exploration
LGA	low-gain antenna
LILT	low-intensity low-temperature
LTSM	long time storage memory

MCC	multiplexer interchanging channel
MGS	Mars Global Surveyor
MIPS	million instructions per second
MLI	multilayer insulation
MS-2	Mars Surveyor 2
MT-98	Mars Together 1998 Mission
NASA	National Aeronautics and Space Administration
NRA	NASA Research Announcement
OCRC	onboard control radio complex
OGCC	onboard guide control complex
OPSWG	Outer Planets Science Working Group
ORS	onboard radio system
PCA	Pluto closest approach
PFF	Pluto Fast Flyby
PJSSG	PFF Joint Science Steering Group
PMIRR	pressure-modulated infrared radiometer
PSS	propulsion subsystem
RAS	Russian Academy of Sciences
RC	radio complex
RCC	radio channel control computer
RCCP	radio complex control computer
RDB(S)	fourth stage of the Proton launch vehicle
REC	receiver
RF	radio frequency
RHU	radioisotope heater unit
R_S	solar radius
RSA	Russian Space Agency
RTG	radioisotope thermoelectric generator
S/C	spacecraft
SRC	Space-Rocket Complex
SRM	sample return mission
SRM	solid rocket motor
SSAC	Space Science Advisory Committee
SSES	Solar System Exploration Subcommittee
SSPA	solid-state power amplifier
TCM	trajectory correction maneuver

TMU	telemetry modulation unit
TRS	transmitter
UDMH	unsymmetrical dimethylhydrazine
UV	ultraviolet

ACKNOWLEDGMENT

This report was jointly sponsored by the Russian Space Agency, the Russian Academy of Sciences and the National Aeronautics and Space Administration.

Publication support was provided by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. 94-29	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle: Mars Together and FIRE & ICE Report of the Joint U.S./Russian Technical Working Groups		5. Report Date: October 1994
		6. Performing Organization Code
7. Author(s): The Joint U.S./Russian Technical Working Groups		8. Performing Organization Report No.
9. Performing Organization Name and Address: JET PROPULSION LABORATORY, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, California 91109		10. Work Unit No.
		11. Contract or Grant No. NAS7-1260
		13. Type of Report and Period Covered: JPL Publication
12. Sponsoring Agency Name and Address: NATIONAL AERONAUTICS AND SPACE ADMINISTRATION, Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The Cold War's end opened an opportunity for greater cooperation in planetary exploration for the United States and Russia. Two study groups were formed, Mars Together and FIRE and ICE. The Mars Together team developed a concept for a flight in 1998 that merged one U.S. Mars Surveyor 98 mission with the former Russian Mars 96 mission to further understanding of the Mars surface and atmosphere. The FIRE and ICE team developed concepts for a dual-spacecraft mission to the solar corona and for a mission to Pluto. The missions, scientific potential, and open issues are described.

17. Key Words (Selected by Author(s))	18. Distribution Statement
Mars Surveyor Pluto Solar Probe	Unclassified; unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	118	

JPL 0184 R 9/83