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Future Planetary Probes for Jupiter and Saturn

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This paper discusses a study that was conducted to identify the technology developments that would allow deep atmospheric investigations of Jupiter and Saturn to proceed beyond currently planned investigations of the upper atmosphere (above 20 bars). The study considered a deep-probe mission that would provide the capability to scientifically examine planetary atmospheres to the 1000-bar level and 1400 K temperature. Science requirements were established through discussions with selected members of the science community and these discussions established the science objectives. The major thrust of these objectives is to determine the lower atmospheric composition and the measurement of trace constituents down to one part per billion. The study identified that science instrument technology developments would be required to provide the desired sensitivity at these temperatures and pressures. Various technology options were considered for the probe engineering subsystems necessary to support the science requirements during the mission. The major conclusions reached in this study are: 1) a probe designed for Jupiter can be used with minor changes for Saturn; 2) new science instrument technology developments are required; and 3) the only new technology developments required in the engineering subsystem are high-pressure thermal insulation materials and advanced data processing techniques.

Introduction

THE long-range strategy for investigating the physical properties of the outer planets has been developed for NASA by several Science Working Groups commissioned by the National Academy of Science.[1] These groups have established long-range guidelines consistent with investigation of fundamental questions on the origin and formation of the planets and solar system. The first class of planetary entry probes, such as Galileo, applied to Jupiter or Saturn, would provide an extensive homogeneous basis of scientific data that could advance our understanding of the solar system in the next decade. Clearly, any second-generation entry-probe missions must employ scientific investigations that would provide continuity to investigations conducted by Galileo class entry probes, i.e., probes that explore planetary atmospheres between the 1- and 100-bar levels. This study, which considers technology requirements for a second-generation 1000-bar deep-probe mission, was conducted consistent with the requirement to provide science data continuity with Galileo class missions.

The steps used in this study to identify the technologies required for a 1000-bar deep probe mission were: 1) define science requirements; 2) develop and select viable system implementation options; 3) evaluate and establish technology requirements for all viable system options.

The study assumed a technology base derived from the Pioneer Venus, Galileo, and Viking missions.[2]

Science Requirements

The science requirements for a second-generation 1000-bar probe were established through a series of discussions with selected members of the science community. These discussions established the fundamental questions which could be addressed by a second-generation probe. These questions, shown below, provided the framework within which the more detailed scientific investigations can be formulated.

1) What physical processes were responsible for the formation of the solar system and its planets and satellites?

2) What is the internal structure of the outer planets and what processes have been responsible for their present evolutionary state?

3) What are the physical, structural, and compositional characteristics of the outer envelopes of the outer planets, and how have the envelopes evolved?

Recent models of the interior of Jupiter appear to require the existence of a small rocky core surrounded by a nearly solar composition fluid mixture. The rocky core is required to initiate the collapse of the hydrogen-helium envelope of the Proto-Jupiter. Hence, an enhancement of the "rock-bearing" constituents, and possibly the "ice-bearing" constituents, is expected on the basis of cosmogenic considerations.[3] The degree of enhancement ranges from 5 to 10% of the planetary mass, providing approximately a few tens of times the solar abundance of refractory materials. On the basis of these considerations, an actual measurement of the abundance of rock-bearing elements would constitute a severe observational constraint on theoretical models of the outer planets. Hence, a major scientific objective for a deep probe mission would be to measure the composition of deep atmospheres, including trace constituents to one part per billion.

As a guide for future exploration studies, the anticipated composition of Jupiter's deep atmosphere has been studied.[4] Solar abundances compiled by Cameron[5] were employed in chemical equilibrium calculations. The temperature/pressure distribution corresponding to a Jupiter adiabat was used. (The adiabats for Jupiter, Saturn, and Uranus are compared in Fig. 1.) The calculations have been performed for the Jupiter adiabat, but may be used to approximate the data for Saturn and Uranus by selecting the composition data at temperatures adjusted for the different pressures. The calculations yielded equilibrium abundances of over 500 compounds of 27 selected elements. The results have been used to predict the possibility of some constituents which have

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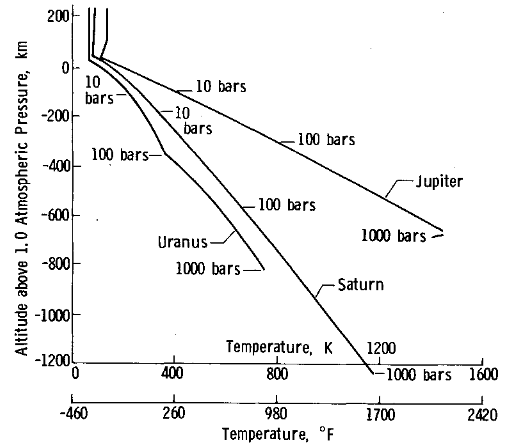

Fig. 1 **Comparison of outer-planet atmosphere temperature profiles.**

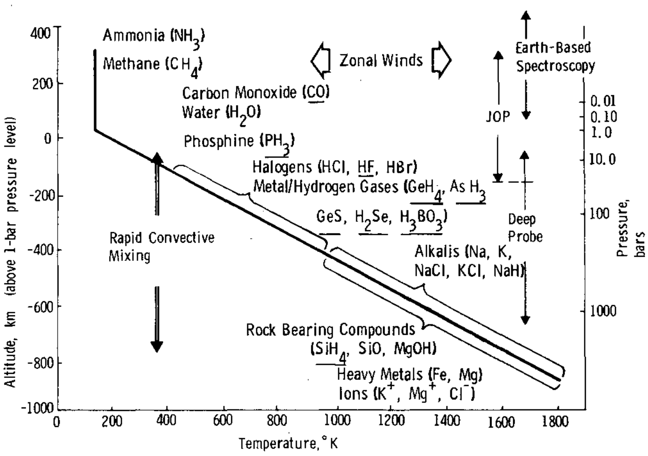

Fig. 2 **Schematic anticipated atmospheric composition of Jupiter (trace components).**

not yet been observed in Jupiter's atmopshere. Anticipated constituents with concentrations in excess of one part per billion were collected from these calculations and summarized in Fig. 2, which illustrates schematically the results of the calculations by Barshay and Lewis.[4] A deep probe ($T \sim 1200$ K) should be capable of making direct observations of the rock-bearing constituents. It may be possible to observe such constituents, either by remote spectroscopy or by a Galileo-type probe, provided adequate instrument sensitivity was available. However, it is not clear if the convective mixing extends sufficiently to transport the constituents upward before chemically interacting with the surrounding environment. These constituents may condense out before reaching observable layers within the atmosphere. The most promising candidates for possible spectroscopic detection are underlined in Fig. 2. In fact, both CO and PH_3 have been observed, and Barshay and Lewis[4] have argued that, since these species are only stable at high temperatures, their existence in spectroscopically observable regions is evidence for rapid convective mixing from layers extending down to temperatures about 1000 K. The observability of the remaining species is dependent on many uncertainties, and a reliable confirmation of the predicted constituents can probably be best observed by a deep probe, particularly for the rock-bearing compounds, some of which are chemically stable at temperatures near 2000 K and pressures of several kilobars.

The calculations performed by Barshay and Lewis also yield predictions of anticipated condensates at various pressure and temperature levels shown in Fig. 3.[4] The actual concentrations of the condensates are not available, but the

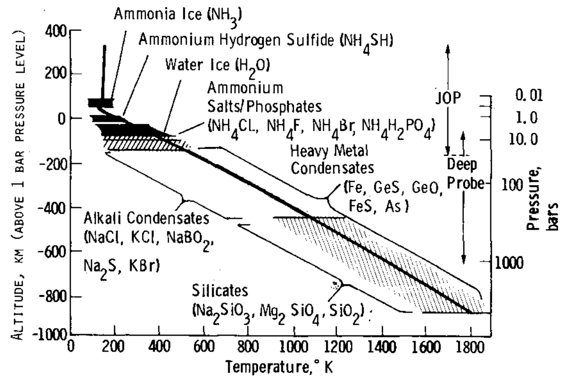

Fig. 3 **Schematic anticipated deep atmospheric cloud structure of Jupiter.**

results may be used as a guide to the possible existence of cloud layers. The situation is extremely complex in the deeper layers, and considerable overlap of condensates is expected. The combined results shown in Figs. 2 and 3 may be used as a guide to understanding Jupiter's deep atmosphere, and have been extremely useful for the development of scientific objectives for a deep-probe mission. The identification and localization of deep cloud layers, the measurement of their vertical structures, and determination of the abundances of trace rock-bearing constituents in conjunction with the atmospheric composition is important for understanding not only the structure, composition, and dynamics of Jupiter's outer region, but also for inferring the prevailing conditions in the deep interior of Jupiter, and obtaining clues to its initial formation from the primeval solar nebula.

On the basis of the previous discussion, a set of investigations was compiled and is listed in Table 1. The investigations are intended to be carried out by an orbiter-probe mission, with the probe conducting the major portion of the required measurements by in situ techniques. These investigations comprise a comprehensive integrated study of the deeper layers of the outer planets. The desired frequency of measurement is also indicated in terms of the desired spatial scale. Possible instruments are identified, and a significant conclusion from this study was that a major technology development must be made to effect the composition measurements, particularly of the trace species, which are expected to be present at concentrations on the order of one part per billion or less. With the exception of the required composition measurement, extensions of existing techniques

Table 1 Recommended deep-probe measurements

Measurement	Instrument alternatives	Remarks
Composition profiles	GC, MS, GC/MS	
2-3 per scale height, ppm to ppb sensitivity	Absorption spectrophotometer Resonance-fluorescence spectrometer	Instrument technology does not exist
Cloud structure and composition 2-3 per scale height	Nephelometer/particle spectrometer	
Magnetic field and electrical conductivity, 5 per descent	Magnetometer/electrometer	May be adaptable from existing instruments
Pressure/temperature/density, 10 per scale height	Pressure/temperature gage/accelerometer	

appear to be adequate for conducting the required measurements.

Potential Instrument Concepts for Composition Measurements

For a deep probe designed to operate at 1000 bars and 1200-1400 K, a measurement technique is required to determine abundances of constituents at concentration levels of one part per billion or less. Conventional in situ techniques do not appear to be adequate for conducting such measurements under these severe conditions. Several methods have been suggested, but feasibility needs to be considered in greater detail. Several discussions were held with investigators who have developed state-of-the-art instruments for operation in much more severe environments. These investigators felt that both the gas chromatograph and mass spectrometer could be built to meet the deep-probe requirements. The major difficulty with such conventional techniques is associated with the acquisition of the sample and preparing it for analysis without destroying the chemical integrity of the sample. One possible concept for acquiring and handling a sample of hot gas at high pressures would be to inlet the sample into a chamber under rapid expansion to cool the sample quickly. The inlet leaks to the GC and MS could be run off of this chamber and the pressure reduced in several stages to a level that is consistent with the nominal operation of these instruments. A multiple-stage pressure reduction system with the capability for dissipation of large heat loads would be required.

In addition, other techniques were suggested that employ remote optical methods. With emission spectroscopy, an arc discharge within the atmosphere at the measurement location could excite most of the chemical constituents present. A wide spectral coverage spectrometer could then analyze the emission spectrum obtained for abundance determinations; however, the chemical integrity of the species present could be substantially modified by the excitation source, thus leaving the determination of the true chemical state somewhat obscure. Another potential technique involves the use of the resonance fluorescent scattering method developed by J.G. Anderson at the University of Michigan. Several lamps are excited by microwave discharges to produce resonance radiation, which is then absorbed/scattered by constituents in the illuminated sample volume and subsequently detected. This method involves inherently high sensitivity (ability to detect species to one part per trillion), but suffers from the disadvantage that the identity of the gases present must be known. However, further development of the present instrument could provide a search mode with a front-end spectrometer, which could be used in a quasi-exploratory mode.

Figure 4 illustrates the concepts examined during the study. It is not presently clear whether any of these techniques will prove to be feasible for the application considered here. These potential techniques (there may be others not listed here) should be carefully evaluated for feasibility and further development pursued on any that show promise.

System Implementation Studies

Several mission concepts were examined that ranged from staged-fixed-ballistic-coefficient probes to designs incorporating lateral range or hovering and climbing capability. In terms of data return concepts, it is possible to transmit the data from the deep probe directly to the delivery orbiter, or via a second shallower communications relay probe. A second orbiter phased to come into range toward the end of the probe descent was also considered.

All of these techniques were examined, but based on the identified science objectives, it was determined that the simpler mission concepts were adequate. For example, the degree of lateral range that could be achieved after entry by aerodynamic lift or propulsive technique does not afford a sufficiently different sampling region to justify the added complexity in view of the huge scale of Jupiter or Saturn atmospheric features. Likewise, hovering at a given altitude or ascending to a previous altitude turns out not to be of particular interest from a science sampling viewpoint. After preliminary evaluations of various concepts, it was determined that basic science objectives could be met using either a rapid or slow descent mission design approach.

The two-stage rapid descent profile shown in Fig. 5 represents the most rapid descent consistent with achieving all science objectives. The probe is staged from the entry aeroshell at a pressure altitude of about 0.1 bar. Obtaining composition measurements from that altitude to 10 bars takes about 25 min, which corresponds to a probe ballistic coefficient of $\sim 50\ kg/m^2$ (compared to an entry ballistic coefficient of $\sim 150\ kg/m^2$). Staging at 10 bars to a ballistic coefficient of $\sim 1900\ kg/m^2$ produces a descent rate of ~ 400 m/s, which is near the maximum rate compatible with composition measurements. Using this ballistic coefficient, the 1000 bar level is reached in 100 min, at which time the descent velocity has slowed to ~ 80 m/s. Typical rapid descent configurations are shown in Fig. 4 with details of science implementation.

During the 100-min time period, the orbiter has passed overhead and reached a range of approximately 100,000 km. Because of the high velocity at 1000 bars, the bit rate at which the science data must be transmitted is ~ 150 b/s for the absorption spectrometer. This bit rate, combined with losses due to the 100,000 km range and atmospheric attenuation, dictate the use of the state-of-the-art technology high-gain antenna (HGA) power transmitters or advanced data compression techniques. Developments in these areas were considered, but as an alternative, the use of a relay probe was

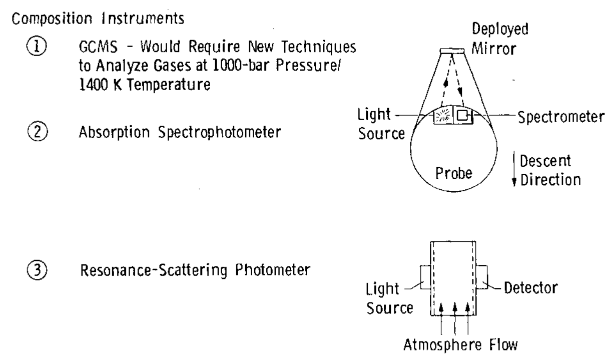

Fig. 4 Science instrument technology development.

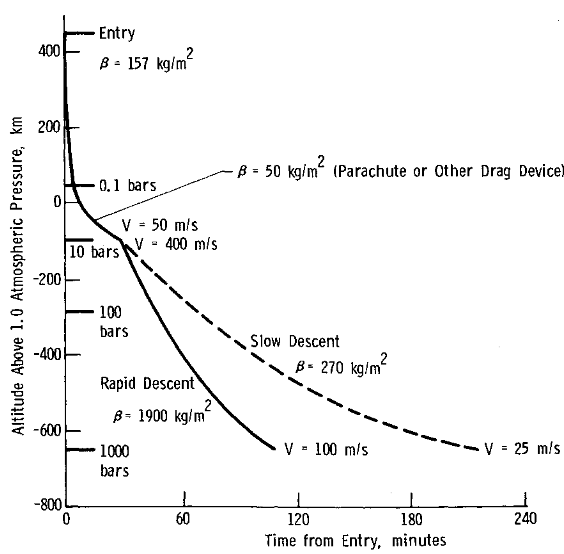

Fig. 5 Example descent time histories.

also considered. In addition to relaying data from the deep probe, the relay probe would also obtain science data to about 30 bars. This approach permits the use of state-of-the-art communications and data systems.

A slow descent probe mission mode was also examined as a method of reducing the data rate below the high rate dictated by the single rapid descent probe. A concept that involved a 200-min descent profile was developed for study. This slow descent profile is shown in Fig. 5. The velocity at 1000 bars was reduced by about one-fourth to 25 m/s and the data rate was reduced by a corresponding amount. The data rate reduction was offset because the range to the orbiter was doubled to approximately 200,000 km near the end of mission, unless a second orbiter was introduced to pick up the probe transmission during the latter part of the descent. Techniques were examined that demonstrated the feasibility of using a dual orbiter approach based on gravity assist from Jupiter and Saturn satellites. This would keep the communication ranges below 100,000 km. Studies also showed that the descent profile could be flown using a relay probe and a single orbiter using the slow descent profile concept.

Figure 6 summarizes the descent profiles and the orbiter/probe relative geometries for the cases considered during the study. Clearly, the disadvantages of the single rapid descent probe concept is a high data rate requirement, while the slow descent concept requires additional hardware and mission complexity to deal with increased communication range and thermal loads experienced during the slow descent. Either of these concepts will work, but the final selection process must consider other factors such as cost, weight, and reliability.

System Technology Studies

The potential for thermal ionization in the deeper layers of Jupiter's atmosphere was analyzed in order to understand the total technologies that migh be required for coping with any breakdown in RF communications which could take place in an ionized atmosphere. The depth at which ionization is likely to become a problem is difficult to predict with any certainty. However, the analysis indicated that ionization is not likely to be encountered until a depth of nearly 1000 bars is reached, and the earliest it could be encountered was at a depth of 600 bars, provided significant vertical mixing takes place. Further analysis of this situation will be required as deep-probe mission designs are developed. This study assumed that ionization would not be encountered prior to the 1000-bar level and that normal RF communication links could be used.

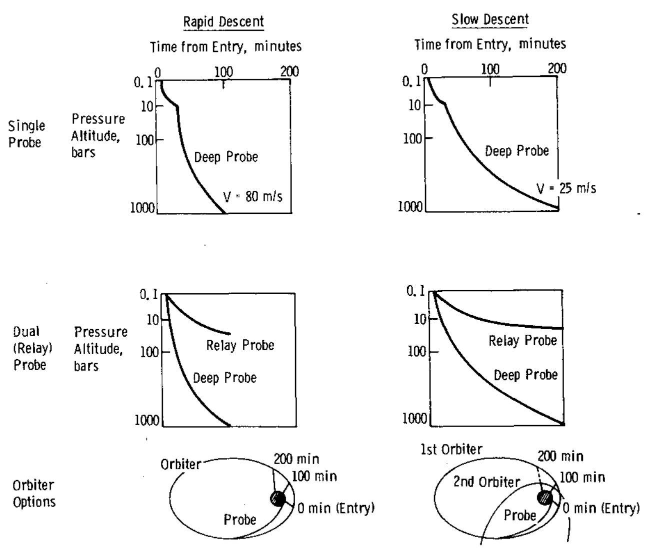

Fig. 6 Example descent profiles.

A number of alternative mission, system, and subsystem concepts were studied and identified as candidates for accomplishing the science and mission objectives. These studies are summarized in matrix form in Fig. 7. A detailed discussion of the studies performed in each area can be found in the final report (see Ref. 2). The matrix can be used to evaluate the relationship of technology developments that are required for various program development criteria when synthesizing various deep-probe missions. Fox example, one can examine the technology relationships where a minimum new technology development deep-probe concept is desired. Other probe concepts such as minimum mass or cost can also be evaluated using the matrix. Two such examples are discussed in the following paragraphs.

The matrix shown in Fig. 7 identifies the mission and system concepts considered in each area to implement a deep-probe mission. Those concepts that appear to require only existing state-of-the-art technology, or relatively straightforward applications of existing technology, are indicated by an open box. Those involving new or beyond the state-of-the-art technologies are indicated by shaded boxes. Certain options fall somewhere in between these extremes, e.g., the use of a shallow probe for relaying data from the deep probe appears to be a straightforward application of Galileo technology, but will add complexity and has no flight history. Options that fall in between the extremes are indicated by a dash-lined box.

Looking at the first column in Fig. 7, it would appear that with the exception of science instrument development and pressure vessel penetration development (high pressure/temperature feedthroughs, inlets, etc.), it would be possible to synthesize a deep probe with state-of-the-art (SOA) probe subsystems. This is not quite true, since the SOA options in the various areas are not all mutually compatible. For example, direct transmission from the probe to the orbiter, a state-of-the-art technique, results in a data rate that is too high when using a SOA medium-power transmitter that employs conventional data handling techniques. Thus, either advanced data compression techniques, advanced high-power transmitter technology, or the introduction of a relay probe would be required for this probe concept. A similar situation exists with regard to combining all SOA subsystems in the thermal/structural area. Combinations of subsystem options which are compatible and satisfy specific objectives are identified and discussed in the following sections.

Probe Technologies

The "minimum" paths indicated by solid and dashed lines through the matrix illustrate two different ways in which the mission and system concepts can be combined to provide a probe capable of achieving the recommended science objectives. The dashed-line path presents a combination requiring minimum new technology development. The solid-line path identifies combinations which should provide a minimum mass probe. The latter combination involves several options in certain subsystem areas as indicated. The concepts requiring advanced technology development are again identified by the shaded boxes.

Minimum Technology Development Probe

The new or advanced technology items in this group include, in addition to the science instruments, a separate relay probe, a refractory metal pressure vessel, a high-temperature antenna, and feedthroughs, windows, inlets, etc., capable of withstanding the high-pressure differential and high temperature. The use of a relay probe to alleviate the high data rate is believed to require less technology advancement than the development of data processing techniques that would provide the large degree of data compression required. The refractory metal pressure shell was required. The refractory metal pressure shell was found to be the minimum technology (albeit heavy) solution in the thermal/structural area, since

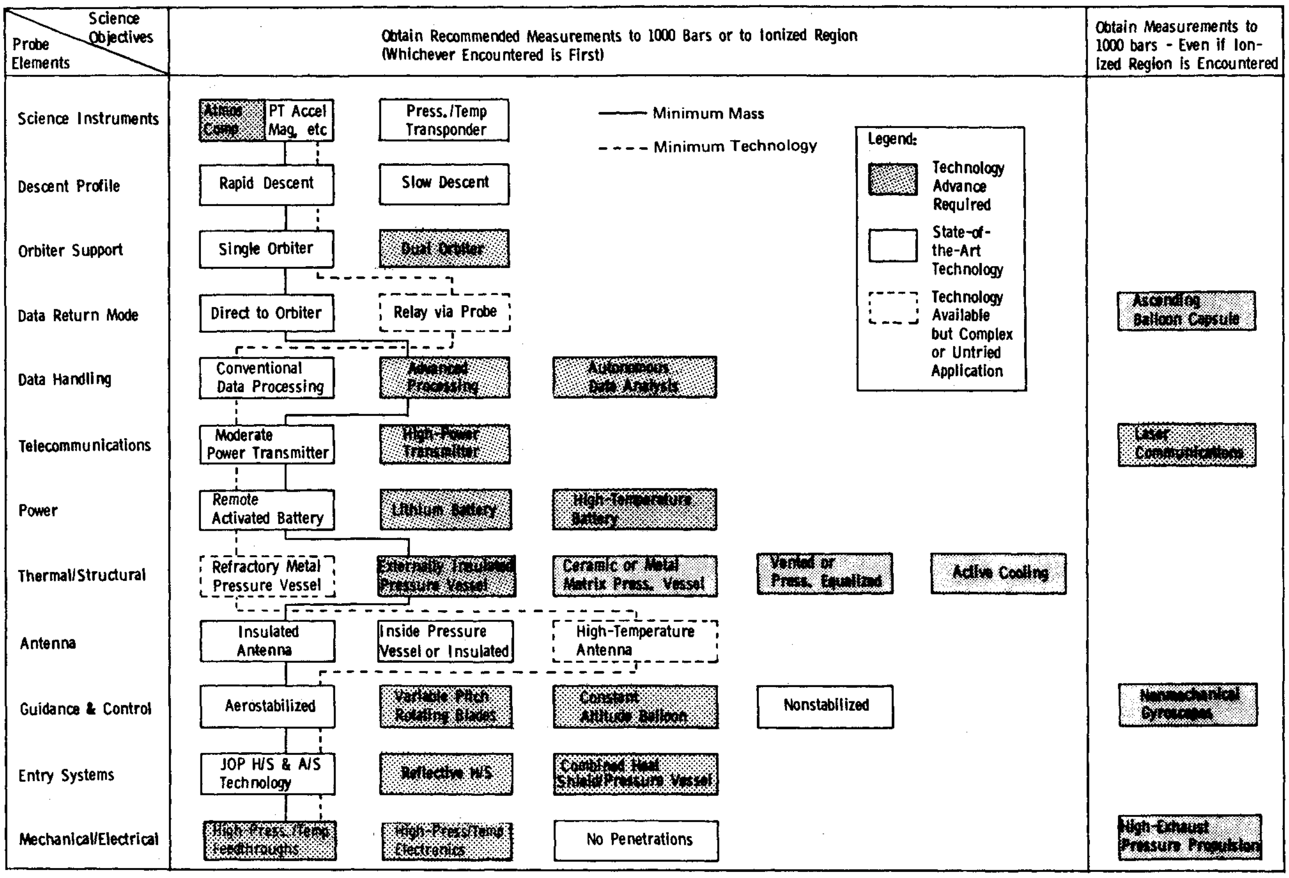

Fig. 7 Probe technology matrix.

off-the-shelf refractory metal alloys are available that can withstand the crushing loads in the 1400 K (2100°F) environment. The use of a metallic pressure shell involves the use of an external antenna which must be capable of operating at the 1400 K temperature. Suitable materials exist from which designs could be developed.

Pressure shell penetrations must be developed, i.e., feedthroughs for electrical wires and coax cables, and inlets and windows for instruments that are beyond current experience (Pioneer Venus probes).

The choice between an external hot structure pressure vessel using "off-the-shelf" refractory metal materials vs the development of an external insulation system that could protect the pressure vessel to temperatures consistent with existing structural alloys was considered. An April, 1971 study reported the evaluation of existing structural alloys for operation at 1400 K (2100° F) and concluded that a refractory metal could be used, for example, B066 Columbian.[2] A significant amount of even a very efficient insulation material, such as multilayer, would be required inside the pressure vessel to keep the equipment compartment at normal equipment operating temperatures, along with some phase change material. This dictated a large pressure vessel diameter relative to the external insulation approach (50.8 cm vs 38.1 cm), to contain a 1 ft^3 volume payload. The weight of such a system was found to be quite large compared to the externally insulated approach, approximately 450 kg vs 100-150 kg.

This approach, however, would permit a more direct extrapolation of Pioneer Venus probe technology since the Venus probe design uses a hot 750 K (900° F) external pressure vessel (titanium) and multilayer internal insulation. The Venus probe is exposed to a 100-bar pressure environment. Solving the differential expansion problems at penetrations in the higher temperature environment of Jupiter, as well as the spherical shell fabrication problems with the less ductile material, are modest technology advances

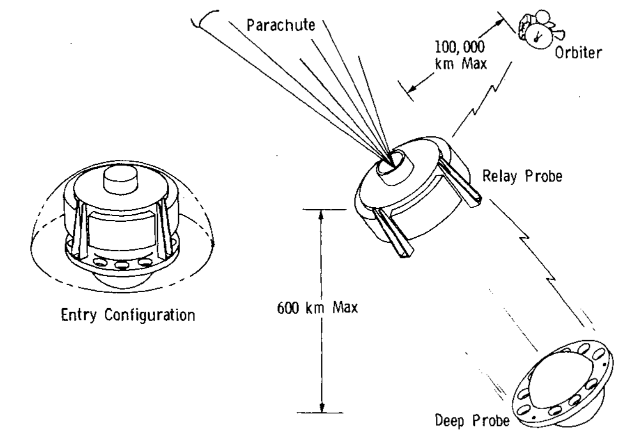

Fig. 8 Relay probe operational concept.

that would have to be addressed even in this "minimum technology" approach.

Relay Probe

The relay probe approach, shown in Fig. 8, allows the use of SOA transmitters since the range from the deep probe to the relay probe does not exceed 600 km (1000 km in the case of Saturn). Therefore, it is possible to transmit the desired 150 b/s with a low-power transmitter and a low-gain antenna, i.e., less than a 1 W transmitter at a frequency of 0.4 GHz. The relay probe then transmits the deep-probe data to the orbiter, along with an additional 150 bits/s of data from the relay probe's own instruments, with an SOA 50-W transmitter (2.3 GHz).

The disadvantages of this approach are the added mass and system complexity introduced by the additional vehicle. From a volume standpoint, however, it appears that the relay probe

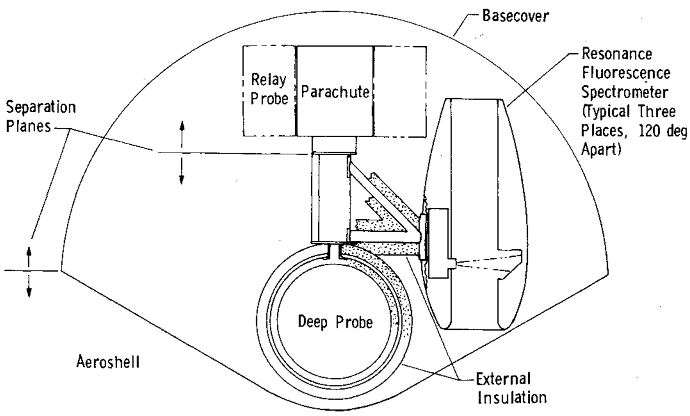

Fig. 9 Relay probe concept—aeroshell configuration.

can be accommodated within the same diameter entry aeroshell as is required by a single deep probe as shown in Fig. 9. The staging operations and parachute subsystems will not require any new technology; hence, the relay probe approach, although untried, would appear to be a straightforward application of Galileo class technology.

The total mass of the deep probe and the relay probe is estimated to be about 1.5 times a single deep-probe mass. This would require either an increase of 20% in aeroshell diameter over the single-probe case, or a moderately more severe entry heating and deceleration environment over that experienced by the single probe.

Minimum Mass Probe

A second combination of options that will yield a more compact and lighter weight probe than the minimum technology probe group is shown in Fig. 7 by a solid-line path. This group involves more new technology developments but would not necessarily prove to be more expensive to implement, depending on the payload dollars per pound relationship at the time the mission is flown.

The new technologies involved in a minimum mass probe concept, in addition to the science instrument and pressure shell penetration technologies, are: 1) an advanced data encoding and error correction encoding system; 2) the development of an external insulation material to limit the temperature of the pressure vessel so that a lightweight alloy can be used for the pressure vessel; or 3) the development of a more efficient high-temperature pressure vessel design for external use other than the refractory metal design, e.g., a design employing a ceramic or metal-matrix-composite material.

An externally insulated pressure vessel concept (see Fig. 9) allows the use of efficient, conventional metal alloys for the pressure shell, but exposes the insulation to the extreme atmospheric environment. The risks associated with this concept involve the extrapolation of the behavior of the known insulation materials at these extremes of pressure and temperature. To date, the test data only covers up to 120 bars at 600° F; data would have to be obtained up to 1000 bars and 1400 K (2100° F).

Free convection within the insulation at high-pressure levels is a distinct possibility. If present, the free convection has a serious degrading effect on the insulation performance. The material selected should have as small a permeability as possible.

Two external insulation candidates which show promise for this mission are MIN-K and LI-900. The MIN-K has excellent properties over the total range of temperatures and pressures tested to date and appears to exhibit acceptable permeability. The LI-900, to be used on the Space Shuttle, has excellent properties and is used on external surfaces of the Space Shuttle which experience high shear forces associated with turbulent flowfields.

Pressure vessel penetrations must be designed for any deep-probe concept considered. These are divided into two categories—electrical and mechanical. Within these categories there are two general types, bulkhead and feedthrough. Optical windows would fall under the bulkhead type. The extreme pressure differential of 1000 bars at the extreme temperature makes each penetration through the pressure vessel a major consideration. Pioneer Venus probe penetrations have been designed and tested for each of the above types; however, the environment is almost an order of magnitude less than a deep probe would experience. The petrochemical industry has developed high-pressure, high-temperature pressure vessel penetrations and appears to offer a satisfactory basis from which these developments can originate.

Two other material classes considered for the pressure vessel structure are ceramics and metal matrix composites. Some forms of both exhibit strength/weight ratios at 1400 K (2100° F) which would result in a reasonable structural weight.

Ceramics, such as alumina oxide, would require extensive development testing to demonstrate the ability to design around its inherent sensitivity to holes and attachment loads induced by vibration, pyrotechnic, and thermal environments. Methods would have to be derived to ensure that the design reliability not be excessively degraded by the low tensile allowable of the ceramics. This basic class of materials has had little or no application for spacecraft primary structure in the past, and would definitely appear to present a high risk design without some development test breakthroughs. Several high-temperature metal matrix composites are currently being investigated within industry and appear to show satisfactory promise, for example, the M200 superalloy.

Deep Probe Technology Assessment

The study results identified several alternative approaches that could be employed in developing a 1000-bar probe for use in second-generation exploration missions to Jupiter or Saturn. It is worth noting that the science objective of such missions would be to extend and supplement data gathered on earlier missions using Galileo class probes at the upper levels. The most significant scientific measurement required is that of atmospheric trace elements that occur only at part per billion levels. This requirement places a formidable technology development challenge in the science instrument area. Several methods of measuring atmospheric composition at the one part per billion level was suggested by this study. An extensive study of these and other concepts should be initiated early, well in advance of any deep-probe mission systems studies, because it represents the "hinge-point" for the science mission. That is, in order to meet the science objectives, atmospheric trace elements must be measured at the one part per billion level.

During the study, several alternative concepts were developed, requiring varying degrees of new technology developments. Figure 7 shows two of these concepts which were found to represent the extremes of the practical concept range, provided ionization is not encountered prior to reaching the 1000-bar level. By using the basic data shown in Fig. 7, a large number of alternate concepts can be formulated based on various program constraints. Technology developments were found to fall into two general classes—enabling technologies or enhancing technologies.

Enabling Technologies

The major potential obstacles to deep-probe missions and the related technology developments appear to be:

1) Science instrument technology does not exist for making the sensitive composition measurements needed. Instrument conceptual studies should be conducted to define development approach.

2) Efficient temperature control will necessitate either the development of flow-resistant external insulations or much improved high-temperature structures. Alternatives involve solving a number of other problems induced by very heavy probes.

3) Thermal ionization may produce a conducting atmosphere that would preclude normal telecommunications. Early tests are required to determine ionization levels.

Enhancing Technologies

Below are examples of technologies that would enhance the mission. Some would become enabling technologies if advances above are not realized.

1) Improvements in source data encoding and error-correction technology.

2) Adaptive science techniques.

3) High-power transmitters.

4) Improvements in energy storage technology.

5) High-temperature parachutes.

6) Advanced heat shield materials.

Conclusions

Several detailed study conclusions are mentioned within the technical section of the paper. The major conclusions reached as a result of the study are:

1) The mission has scientific merit if atmospheric composition can be determined, including trace elements.

2) Technology advance required to develop composition instruments, such as resonance fluorescence spectrometer to operate in lower atmosphere.

3) Probe system can be developed (brute force) with present technology concepts, but resulting probe is large, heavy, and complicated.

4) Advanced onboard data analysis can enhance deep-probe mission.

5) Externally insulated pressure vessel design is the lightest approach with moderate technology advancement.

6) Probe designed for Jupiter with minor changes can satisfy the Saturn and Uranus missions.

7) Further analysis and testing should be undertaken to evaluate the possibility of ionization at the 0.6-kbar level.

These conclusions are, of course, based upon the assumption that thermal ionization does not exist above the 1000-bar level.

It is difficult to identify specific technology developments without first establishing any program constraints, e.g., low cost, minimum mass, or other pertinent program driving functions. However, the science instrument technology development is common to any probe concept and, therefore, should precede any further program development studies.

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