JPL PUBLICATION 78-105

Instrumentation Concepts and Requirements for a Space Vacuum Research Facility

Harry N. Norton

(NASA-CR-158423) INSTRUMENTATION CONCEPTS AND REQUIREMENTS FOR A SPACE VACUUM RESEARCH FACILITY (Jet Propulsion Lab.) 49 p HC A03/MF A01 CSCL 14B
N79-20178
Unclas
G3/19 17260

March 1, 1979

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL PUBLICATION 78-105

Instrumentation Concepts and Requirements for a Space Vacuum Research Facility

Harry N. Norton

March 1, 1979

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

PREFACE

The work described in this report was performed by the Systems, Information Systems, and Observational Systems Division(s) of the Jet Propulsion Laboratory (JPL). The following contributed to this effort:

Dr. George W. Lewicki (Program Manager for JPL)

Dr. Joseph Maserjian (Study Manager)

Harry N. Norton (Task Leader)

Dr. Frank J. Grunthaner

Dr. Blair Lewis

Norman Miller

Dr. Mahadeva P. Sinha

Robert J. Wilson

This study was conducted with the assistance of the NASA Langley Research Center team (L. T. Melfi, Jr., R. A. Outlaw, F. J. Brock, J. E. Hueser) which originated and developed the molecular shield concept. The work was sponsored by the Materials Processing Branch of the NASA Office of Space and Terrestrial Applications, under the overall program management of the NASA Marshall Space Flight Center (Mr. Kenneth R. Taylor).

ABSTRACT

An earth-orbiting molecular shield offers a unique opportunity for conducting physics, chemistry, and material processing experiments under a combination of environmental conditions that are not available in terrestial laboratories: microgravity, very-low background gas density, high molecular escape probability for gas released by experiments, and high heat rejection capability. A molecular shield equipped with apparatus for forming a molecular beam from the freestream additionally offers the opportunity to conduct experiments using a moderate-energy, high-flux-density, high-purity atomic oxygen beam in the very-low density environment within the molecular shield.

Instrument concepts and requirements are given based on contacts with potential science users. As a minimum, the following instruments are required for the molecular shield: (1) a mass spectrometer, (2) a multifunction material analysis instrumentation system and (3) optical spectrometry equipment.

The design is given of a furlable molecular shield that allows deployment and retrieval of the system (including instrumentation and experiments) to be performed without contamination. Interfaces between the molecular shield system and the associated spacecraft are given in detail. An in-flight deployment sequence is discussed that minimizes the spacecraft-induced contamination in the vicinity of the shield. Finally, design approaches toward a precursor molecular shield system are shown.

CONTENTS

<u>Figures</u>

Figures (contd)

Figures (contd)

Table

SECTION I

INTRODUCTION

Orbital flight offers environmental conditions from which physics, chemistry and material processing experiments could benefit significantly. These environments include microgravity, solar thermal energy, and high-purity, moderate-energy, high-flux-density atomic oxygen. The range of orbital altitudes in which the Shuttle, as well as free flyers (satellites) that can be serviced by the Shuttle, will typically operate is between 200 and 1000 km. The atmospheric density (see Figure 1-1) is about 10^{10} cm^{-3} at 200 km and 5×10^5 cm^{-3} at 1000 km (Ref. 1). However, a much lower density than the atmospheric density can be made available to experiments by means of a properly designed molecular shield (see Figure 1-2 and (Ref. 2).

At altitudes of 200 km or more, where the molecular mean free path is 0.4 km or greater, local disturbances caused by a molecular shield, and by a spacecraft carrying the shield, are small; therefore, the atmosphere remains in near equilibrium and may be considered a Maxwellian gas drifting at orbital velocity (about 8 km/s) with respect to the shield. In such a gas, only a small fraction of the molecules have the proper combination of spatial location, kinetic energy and momentum components such that they can overtake a surface element whose normal is parallel to the atmosphere drift velocity (-u), provided that $S >> 1$, where $S = u/V_m$ (the speed ratio) and V_m is the molecular mean thermal

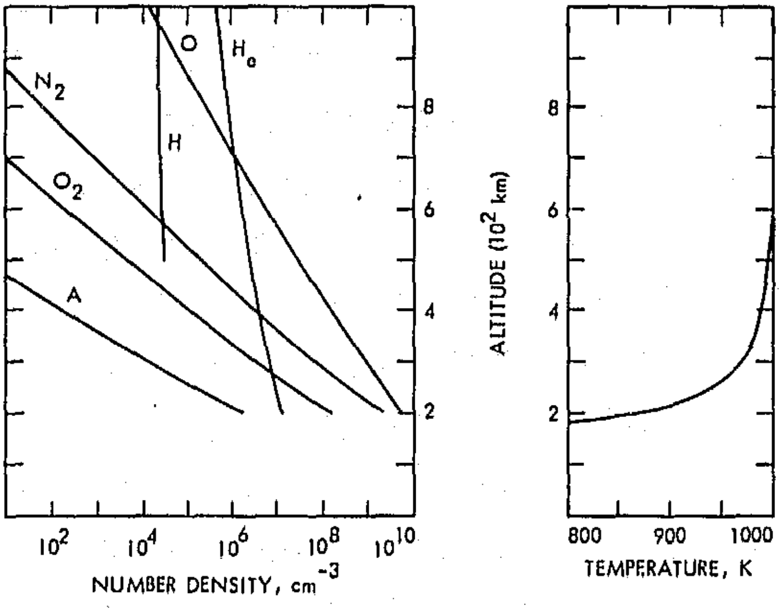


Figure 1-1. Constituent number density and temperature as a function of altitude for a terrestrial atmospheric model with an exospheric temperature of 1000 K (from Ref. 7)

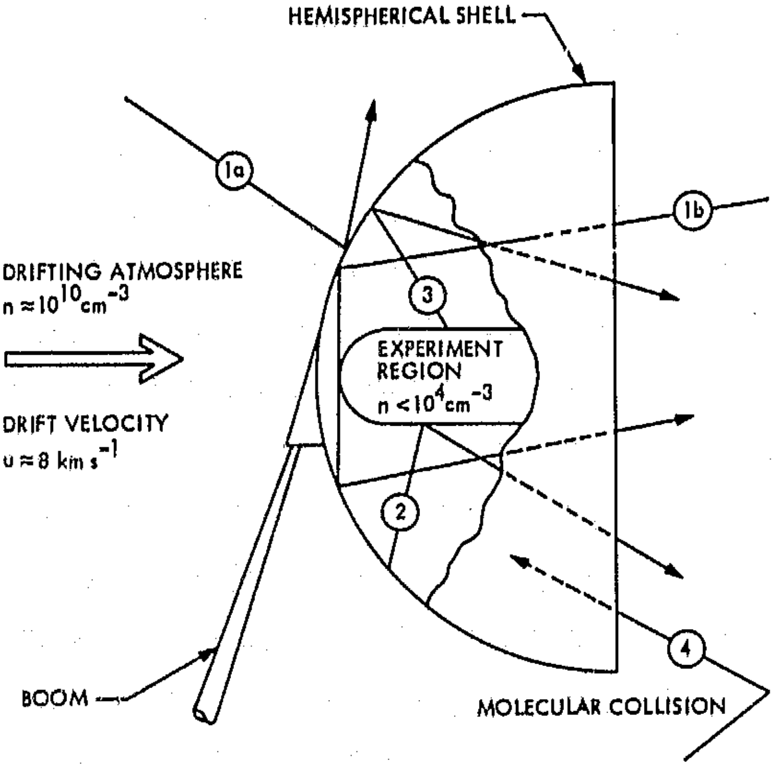


Figure 1-2. Schematic representation of the molecular shield geometry in the drifting gas, illustrating typical molecular trajectories: (1a) and (1b) are free-stream molecules, where the flux of (1a)-type molecules is much greater than the flux of (1b)-type molecules; (2) are desorbed molecules from the shield; (3) are desorbed molecules from the experiment; and (4) are molecules scattered from the Orbiter (from Ref. 3)

speed. Therefore, only a very small fraction of the drifting Maxwellian gas from the aft half space can enter the molecular shield, implying that the atmosphere contribution to gas density within the shield is very low. On the basis of very thorough analyses (Refs. 3 and 4), the density within the shield due to the atmosphere, at 200 km orbital altitude, has been shown to be less than 10^3 cm^{-3}.

As shown in Figure 1-2, there are four principal gas sources (Ref. 3) that may contribute to the density within the shield: (1) free-stream ambient atmosphere, (2) outgassing from the shield inner surface, (3) gas released by experiment and instrumentation elements within the shield (including any gas purposely released for certain types of experiments), and (4) gas emanating from the spacecraft, such as atmospheric gas scattered off its surfaces, outgassing products, and ejection of fluids.

These considerations have obvious implications on the design and materials chosen for a molecular shield and its internal equipment as well as on the choice of a spacecraft, on its design and surface materials, and on its operations. It is also unlikely that any spacecraft could be so "clean" that a molecular shield could be mounted to it directly. A boom or mast would most probably be required to assure adequate separation of the spacecraft from the shield. Two types of spacecraft have been considered for carrying a molecular shield (Ref. 5): the Shuttle Orbiter (see Figure 1-3) and a free flyer (see Figure 1-4). Analyses have indicated that the length of the boom, if mounted to a Shuttle, would have to be about 100 m. If a free flyer is used instead, the boom could be considerably shorter provided that constraints imposed by the molecular shield system are properly implemented in the design and operations of the spacecraft, e.g., if a cold-gas attitude control system were used and external spacecraft elements were designed for minimum outgassing. It should be noted that spacecraft and shield configurations are shown in a preliminary form. The shield, e.g., may have a configuration other than hemispherical in an eventual design based on practical considerations.

Interaction between spacecraft and shield has been estimated to cause the largest contribution to residual density within the shield. This factor will have to be minimized by appropriate selection of spacecraft design and operations, and boom length. The other factors contributing to internal shield gas density are outgassing of internal

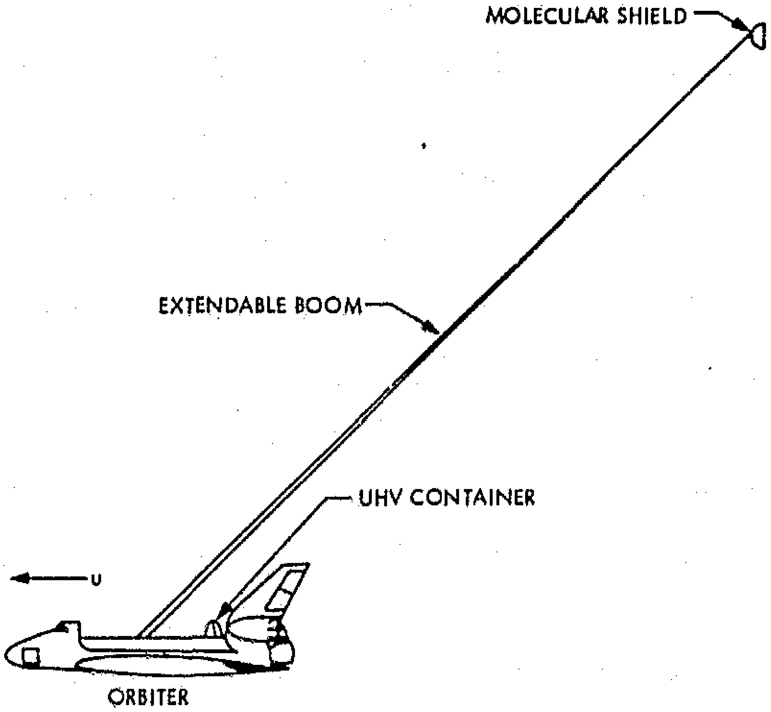


Figure 1-3. Molecular shield deployed from Shuttle Orbiter by an extendable boom; the shield would be kept free of contamination by keeping it in an ultrahigh vacuum container until deployment (from Ref. 5)

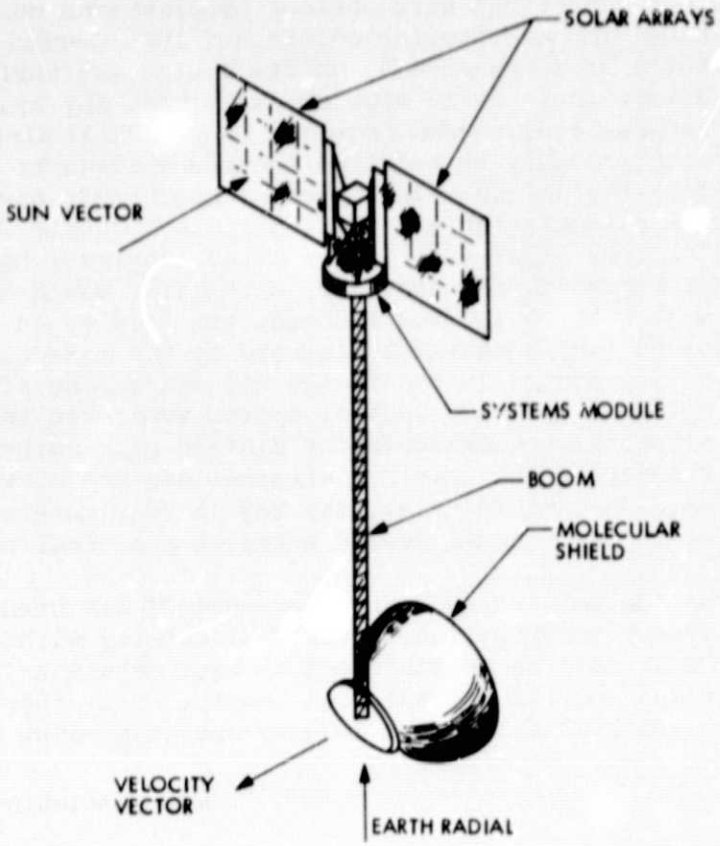


Figure 1-4. Molecular shield deployed from a free flyer retrievable by the shuttle; gravity-gradient stabilization could be used for attitude control (from Ref. 5)

equipment, outgassing of the shield itself, and the ambient atmosphere itself. The effects of experiment/instrumentation equipment on the density distribution within the molecular shield have been analyzed (Ref. 6). Severe constraints must be levied upon the materials and construction as well as the location of such equipment.

Outgassing of the shield itself can be minimized by proper choice of the material and by preassembly and postassembly treatments of the shield. Ultrapure, vacuum degassed aluminum has been suggested as the optimum choice (see Figure 1-5) for the inside surface of a furlable shield as well as for a complete solid shield (material selection and preparation as well as fabrication of a solid shield has been addressed in detail by NASA-LaRC). Presently recognized alternatives are nickel and a sintered gettering material on the internal surface of a metallic shield. Analyses of the contributions to internal density of the ambient atmosphere indicate that the resulting constituents are limited to hydrogen and helium (see Figures 1-6 and 1-7).

The analyses briefly described above, together with their supporting references, show that a molecular shield would provide an extremely

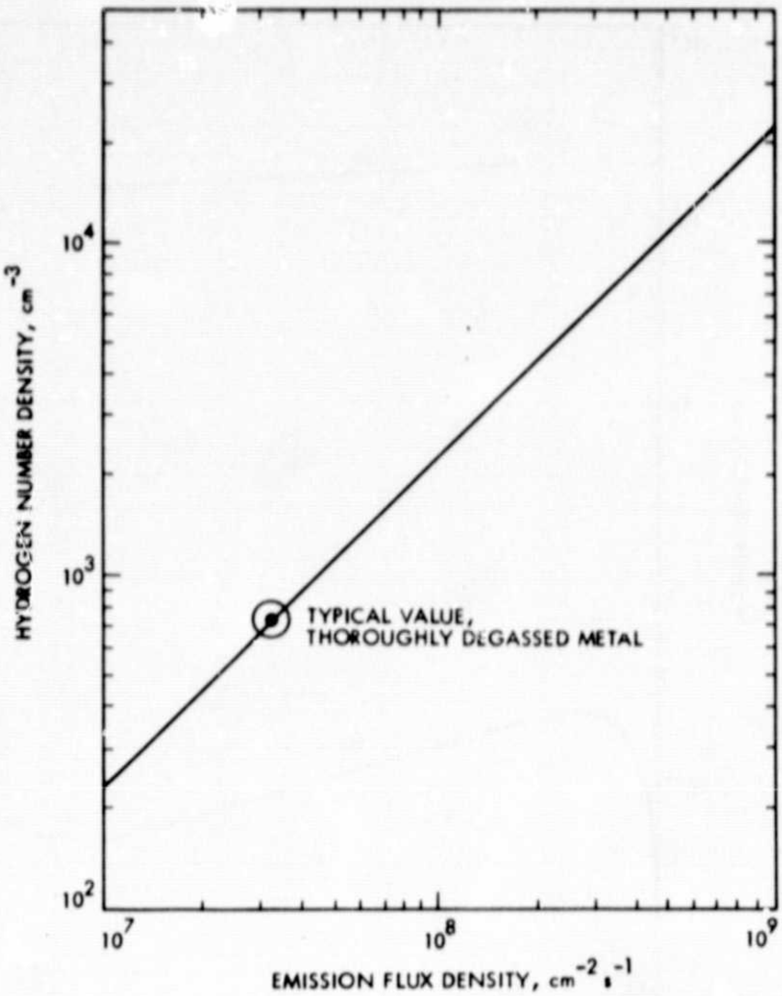


Figure 1-5. Number density at the origin of the hemisphere due to outgassing of the shield as a function of emission flux density. The emission flux is assumed to be H_2, and the surface temperature equals 300 K ($1\ cm^{-2}s^{-1} = 4.14 \times 10^{-18}$ Pa liters $cm^{-2}s^{-1}$)(from Ref. 3)

low density, in the order of $10^3\ cm^{-3}$ (corresponding to an equilibrium pressure of $10^{-12}\ N/m^2$, or 10^{-14} torr, at 300 K) as well as a very-high escape probability for photons and molecules to space (high pumping speed). This allows high-temperature, moderate-outgassing experiments to be performed without compromising the density within the shield. Another valuable attribute of the molecular shield, when flown at typical Shuttle orbital altitudes (regardless of type of spacecraft used) is that a beam of high-purity, moderate-energy, high-flux-density atomic oxygen, from the atmosphere, can be introduced into the shield for molecular-beam experiments (Ref. 7).

Atomic oxygen is the principal gas species from 200 to 700 km, becoming as much as 90% of the atmosphere at 500 km (see Figure 1-1).

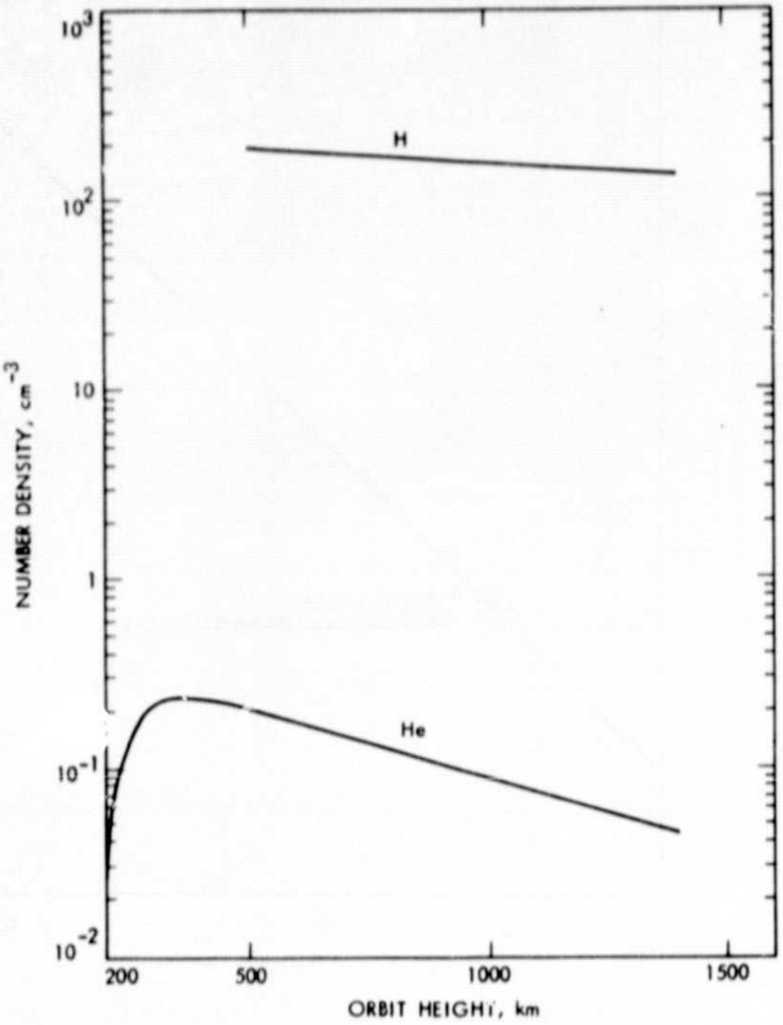


Figure 1-6. Number density at the origin of the hemisphere due to the free-stream atmosphere as a function of orbit height for T_e = 1000 K (from Ref. 3)

The atomic oxygen is formed by the dissociation of molecular oxygen upon the absorption of solar near-ultraviolet radiation. Above 700 km, atomic helium becomes the principal gas species. Figure 1-8 shows the ratio of atomic oxygen abundance to that of the other principal species. Considering only chemically reactive gases, the ratio of atomic oxygen to the next most abundant gas (N_2), at 500 km, is approximately 99 : 1; hence, a high-purity beam of atomic oxygen can be obtained at this altitude. The beam is formed by a pair of concentric, truncated conical shells (collimating apertures), aligned with the velocity vector and placed immediately forward of the molecular shield (see Figure 1-9). The mean energy of this beam would be around 5 eV and could be reduced below this value by, e.g., a surface scattering technique (Ref. 7).

In addition to the extensive research and conceptual work by NASA, especially at its Langley Research Center (Refs. 2 through 7), similar research associated with a molecular shield and the forming and utiliza-

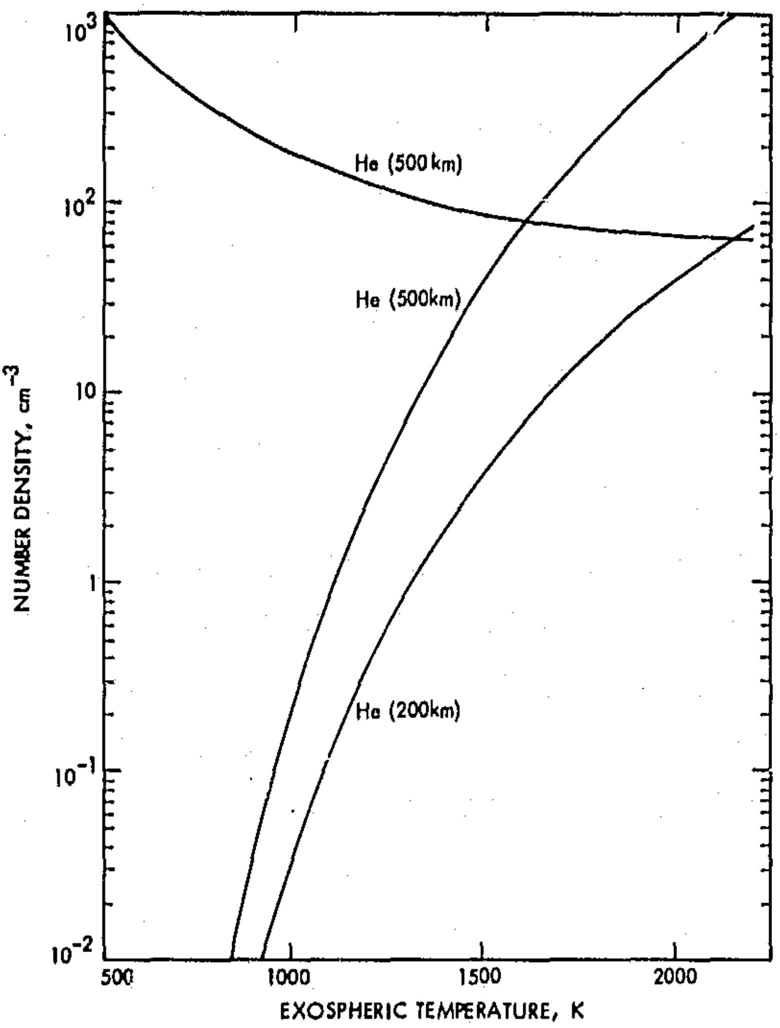


Figure 1-7. Number density at the origin of the hemisphere due to the free-stream atmosphere as a function of exospheric temperature for orbit heights of 200 and 500 km. Note that the local temperature is lower than the exospheric temperature except at very high orbits (from Ref. 3)

tion of an atomic oxygen beam, at Spacelab orbital altitudes, has also been reported by the German Research Society for Aeronautics and Astronautics (DFVLR) laboratory in Goettingen, W. Germany (Ref. 8).

The requirements for ground-based vacuum facilities that could handle experiments of the type foreseen for a molecular shield were addressed in a recent JPL study (Ref. 9). In this study, a system of vacuum-demand indices was defined, and the overall vacuum requirements of 16 classes of experiments were rated on a numerical scale from 1 to 256, in ascending order of facility sophistication.

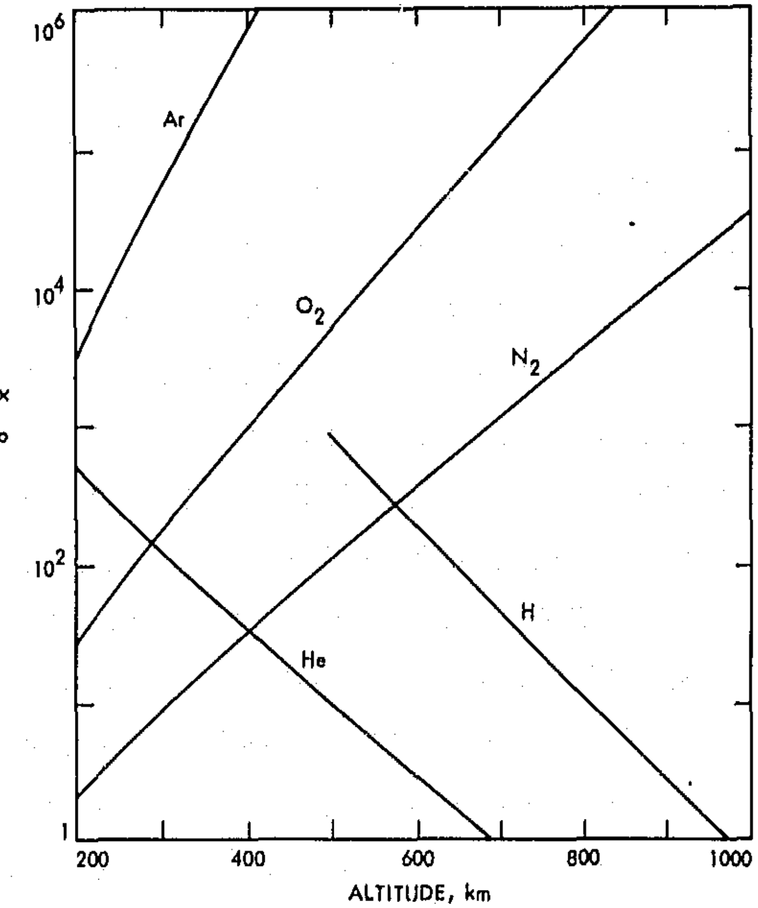


Figure 1-8. Ratio of atomic oxygen number density to the number density of each of the other atmospheric species as a function of oribital altitude (from Ref. 7)

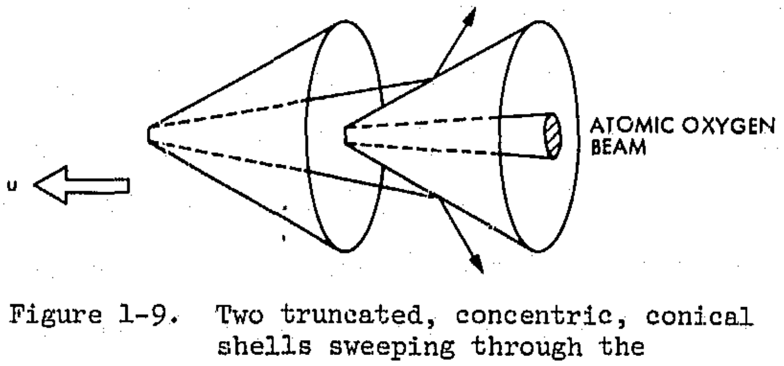


Figure 1-9. Two truncated, concentric, conical shells sweeping through the ambient gas to form a molecular beam. The conical shells are oriented so that their axes are parallel to the velocity vector and their open ends are aft (from Ref. 7)

SECTION II

GENERAL INSTRUMENTATION REQUIREMENTS AND CONSTRAINTS

A. REQUIREMENTS

To establish instrumentation requirements for a molecular shield system, potential science users were contacted and, subsequently, a "miniconference" was held on April 6 and 7, 1978, at the California Institute of Technology, convened and chaired by Dr. J. Mayer. The conference was attended by F. Grunthaner, G. Lewicki, J. Maserjian, and M. Saffren of JPL and the following university and industrial scientists (with area of interest shown in parentheses):

John Arthur, Physical Electronics Corp. (molecular beam epitaxy)

John Fenn, Yale University (free jet expansion and nozzle beams)

E. Kornelsen, National Research Council of Canada (vacuum technology, low-energy ion/surface interactions)

J. Mayer, Caltech (thin films, interfaces)

Robert Merrill, Cornell University (atomic beams, gas/surface interactions)

Gabor Somerjai, U.C., Berkeley (surfaces, catalysis)

John Yates, Caltech and National Bureau of Standards (surface chemistry)

The conferees agreed that an accurate "characterization of the atmosphere in the altitude region between 200 and 1000 km is a necessary prerequisite to the design of experiments for an SVRF." The neutral atmosphere above 200 km contains chemically active gases such as atomic oxygen that recombine on surfaces within the measuring instrument (mass spectrometer) causing inaccuracies in the measurements. Indeed, the newer atmospheric models have increased amounts of atomic oxygen present to compensate for this effect. Measurements made on satellites using a fly-through mode where surface collisions are minimized have confirmed the large concentrations of atomic oxygen. Comparisons of mass spectrometer data taken at nearly the same spatial position and solar time show large differences in reported data, indicating substantial disagreements between various independent experiments.

It has been concluded from theoretical and experimental work that the atmosphere is in thermodynamic equilibrium. However, a direct measurement of kinetic energy distribution (temperature) of the gas at these altitudes has not been made. Temperature is measured indirectly from the ground using Thompson scattering techniques and from satellite drag data. These data have low spatial resolution and are difficult to use directly for local calculations.

The conferees recommended that particular attention be given to measurement of the following atmospheric parameters: "density of significant species; kinetic energy distribution of these species; electronic state and internal energy of significant species with emphasis on neutral oxygen; dayside and nightside variations in these quantities; and analysis of ambient particulates."

The conferees further recommended that experiments be conducted to define the gas dynamics in the vicinity of the shield by "measurements of densities during and after emission of controlled fluxes of gases from the spacecraft as well as from sources within the shield."

The conferees also recognized the following:

(1) "Major instrument development efforts will be required for instrumentation to carry out such measurements. A detector for very-low fluxes and volumetric concentrations is needed. Up to now the available experimental environments have not required development of such detectors. There is a fairly adequate knowledge about how various kinds of detectors behave in laboratory vacuum systems, but the space ambient imposes additional constraints, e.g., the internal environment of the molecular shield involves unusually low densities."

(2) "For the characterization of surfaces and interfaces, the surface science community has developed adequate instrumentation, for ground-based laboratories, to measure surface composition, structure, and the influence of surface preparation and measurement techniques. These instruments include SIMS, Auger, ion scattering, diffraction, ESCA, and sputter sectioning. For a SVRF, a major task will be to develop surface analysis instruments that are space-compatible. A critical feature of such an in-situ measurement system will be sufficient versatility to allow complete characterization of surfaces. In contrast to the case of material processing for ground-based fundamental studies, the surfaces will have to be characterized in the space ambient."

(3) "Optical spectroscopic capabilities will also be needed to characterize the electronic and internal energy states of the ambient species, and to study the interactions of molecular and atomic beams with surfaces and gas phase species would be very desirable. Laboratory instrumentation is available, but space-compatible instrumentation must be developed."

The participants at the miniconference also recommended certain areas of ground-based research to become part of an experiment program, which would include instrumentation research for gas phase detectors and for surface characterization.

On the basis of the above recommendations, the following experiment areas and associated instrumentation requirements and need for conceptual approaches were identified:

(1) Accurate characterization of the atmosphere and residual gas analysis within the shield; a mass spectrometer capable of meeting the stringent performance requirements is essential for determinations in this area.

(2) Surface analysis and other materials processing and analysis; a multifunction material analysis system would have to be developed in a space-compatible version.

(3) Spectroscopy and gas dynamics; space-compatible optical spectrometers as well as a laser source are among the instruments needed for this category of experiments.

B. CONSTRAINTS

A number of significant constraints on the design and characteristics of instrumentation as well as experiment hardware were identified or assumed. Since a high-temperature bake-out is required for the molecular shield and all internal hardware, it is important to minimize the number and size of elements that must be located within this bake-out region. Hence, only such elements as sensors, analyzers, and ion, electron, and photon sources should be mounted within the shield. The associated power supplies and other electronics, as well as such elements as gas containers, if needed, should be located not only outside the shield, but in a package readily detachable from the shield assembly so that bake-out requirements would not have to apply to them. An optimum bake-out temperature must be established on the basis of known outgassing characteristics of materials and time/temperature profiles; however, for the time being, a bake-out temperature of 400°C was assumed. Materials for all hardware within the shield, i.e., within the bake-out region, must be carefully selected so that they not only can withstand the high bake-out temperature for extended periods of time, but also exhibit extremely low outgassing after their installation within the shield.

Other constraints include the usual considerations of launch and flight environmental effects, minimum mass and power requirements, compatibility with the associated spacecraft system, reliability during autonomous operation over relatively long periods of time, compatibility with deployment and retrieval devices and operations, and minimum length of critical wiring.

During the development of instrumentation concepts for some experiment categories, it also became apparent that, in most cases, the experiment hardware will have to be integrally designed and packaged with the associated instrumentation.

SECTION III

INSTRUMENTATION CONCEPTS

Development of, and conceptual approaches to molecular shield instrumentation are described in this chapter. It should be noted, in general, that although the required instrumentation could conceivably be developed and constructed by commercial manufacturers of similar instrumentation for ground-based laboratories, no commercial instrumentation that would be compatible with a molecular shield system and its internal environment is currently available.

A. MASS SPECTROMETER

Of the several basic types of mass spectrometers, the quadrupole mass spectrometer is most suitable for the applications considered here. This instrument employs a mass filter in which the ions pass along a line of symmetry between four parallel rods; an alternating potential, superimposed on a steady potential between pairs of rods, filters out all ions except those of a preselected mass. Different masses can be selected by appropriate adjustment of the potentials. Quadrupole mass spectrometers for ground-based research are available from several commercial manufacturers in the U.S.A. and in Europe. They are widely used in science and industry and are an essential instrument in ultrahigh vacuum systems. Some flight versions have also been constructed and used for determinations of the structure of the terrestrial atmosphere at altitudes above 80 km.

In the early 1970s, a research team at the NASA Langley Research Center (LaRC) developed and partially evaluated a quadrupole mass spectrometer of special design intended for thermospheric density measurements from satellites and high-velocity probes. This design employs molecular beam techniques to reduce gas-surface scattering and gas-surface reactions in the sample, and preserve the integrity of the gas sample during the analysis process (Refs. 10 and 11). Since this design minimizes surface area and uses ultraclean fabrication techniques, the instrument is suitable for the very-low-density measurements within the shield as well as the atmospheric measurements.

The design of the mass spectrometer is illustrated in Figure 3-1. The design contains the usual elements of quadrupole mass spectrometers: ion source, lens system, quadrupole mass analyzer (mass filter), and detector. Unique features of this design, however, include the small-angle conical ionization volume, lens system, and quadrupole entrance aperture, which, in combination, act to reduce gas-surface scattering to a negligible level. The ion source (Figure 3-2) is designed as an extension of the conical support. Therefore, molecules that have external surface collisions are not scattered into the ionization volume. Further, the half-angle of the source is larger than the molecular-beam divergence; this reduces internal surface collisions to a negligible level. Mass spectrometer design considerations are covered in more detail in Ref. 11, pp. 6 through 12.

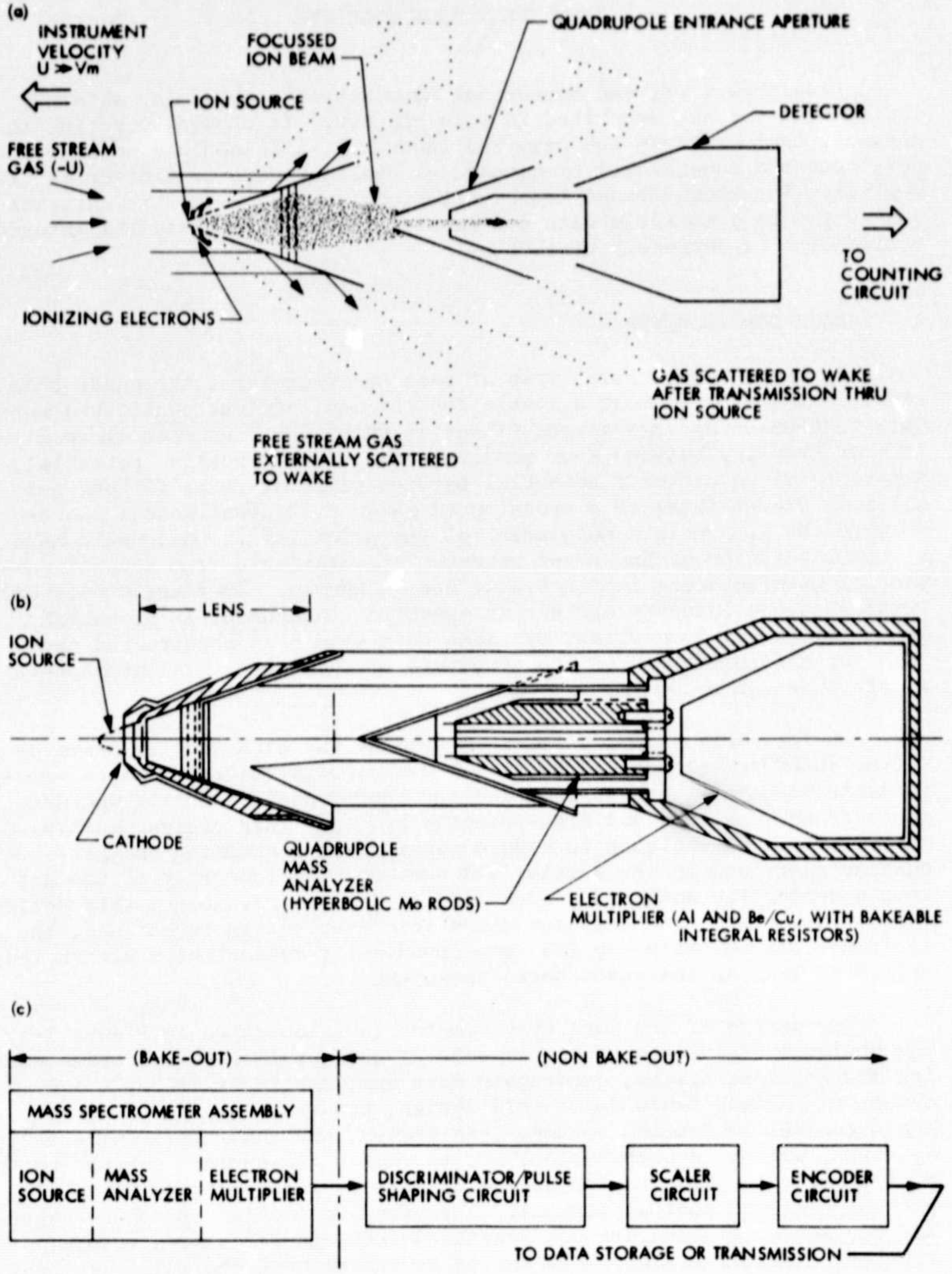


Figure 3-1. Mass spectrometer general design characteristics: (a) schematic; (b) assembly; (c) overall data-flow block diagram

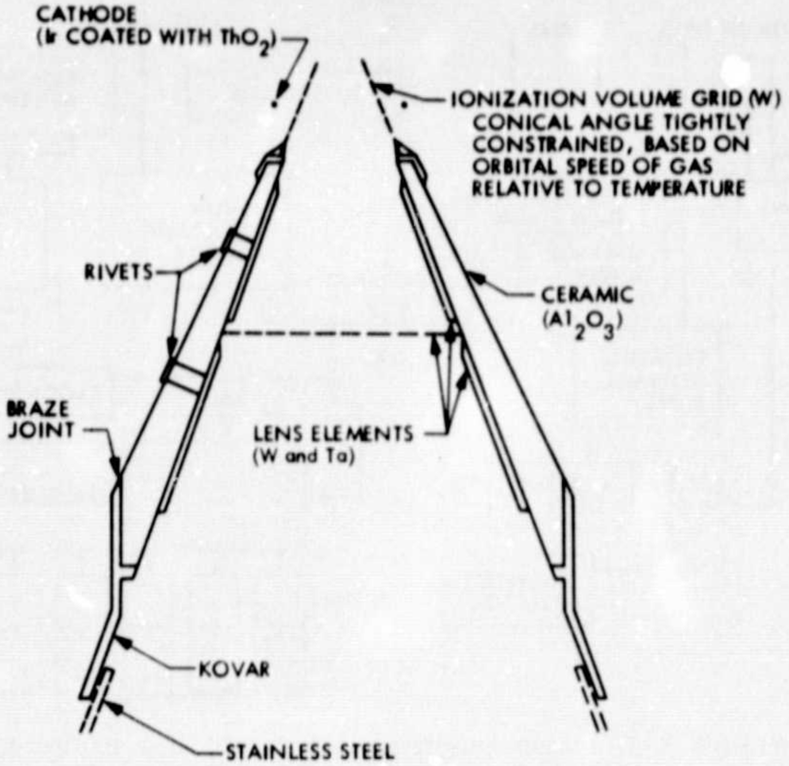


Figure 3-2. Ion source lens details

The functional block diagrams of the mass spectrometer (Figure 3-3) is a simplified representation of the ion source (cathode and grid) and lens supplies and their control, and of the signal and data handling elements of the detector-output electronics that operate in the ion-counting mode. Figure 3-4 shows the elements used for quadrupole control in more detail.

Performance and essential design characteristics are shown in Table 3-1 for the two versions of the mass spectrometer: one for determinations of density within a molecular shield, the other for free-stream density, i.e., density of the atmosphere ambient to the shield. It can be noted that the two designs are identical with regard to mass and dimensions, and differ only slightly in their power requirements. When one or more such mass spectrometers are incorporated into a molecular shield system, the electrical interfaces between each mass spectrometer subsystem (MSS) and the spacecraft are quite simple and would consist of: power (nominally 30 Vdc), digital command data from spacecraft, and digital telemetry data to spacecraft.

B. MATERIAL ANALYSIS INSTRUMENTATION SYSTEM (MAIS)

Significant science user needs for a multifunction material analysis instrumentation system, flight-packaged and space-compatible, were identified through individual user contacts and later confirmed by consensus during the April 1978 miniconference. Concepts for such a

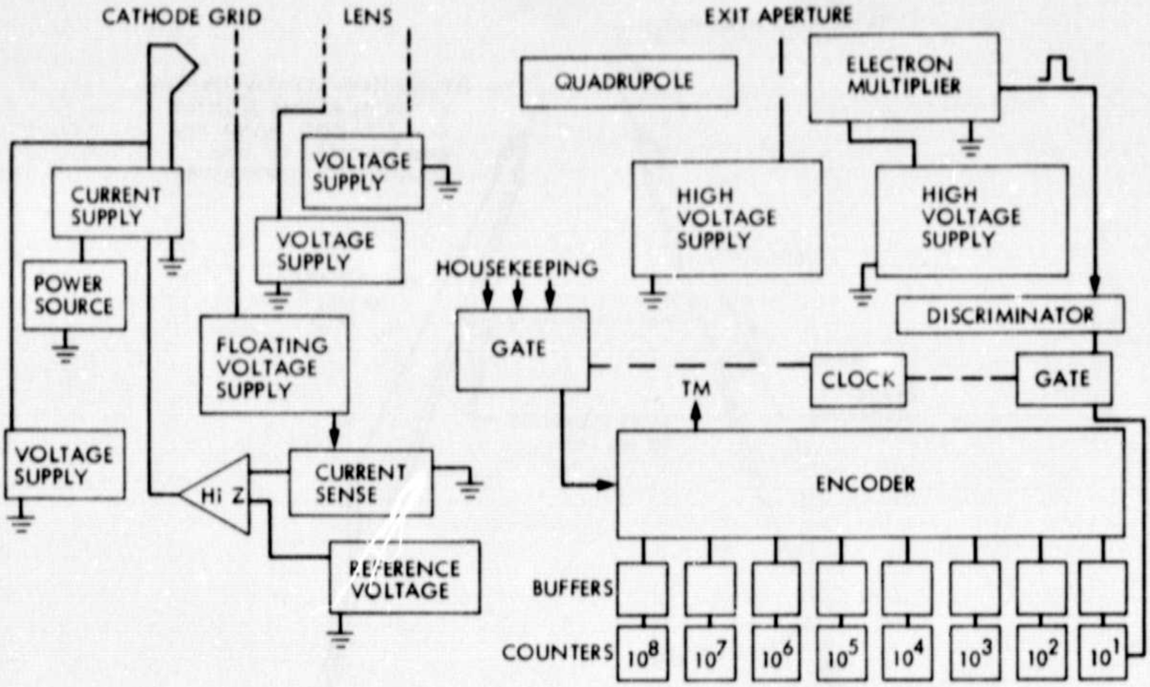


Figure 3-3. Mass spectrometer functional block diagram

system were developed on the basis of a somewhat similar ground-based instrumentation system that has been under development at the Jet Propulsion Laboratory.

The MAIS (Ref. 12) would combine, in a single package, all instrument hardware required for applying essentially all commonly used material (especially surface) analysis techniques to one or more samples whose positioning and processing, if any, would also be handled by the same instrument system. The MAIS, then, would perform the following functions (Ref. 13):

(1) Auger electron spectroscopy (AES); approximate range: 0.1 to 5 keV.

(2) X-ray photoelectron spectroscopy (XPS); approximate range: 0 to 1.5 keV.

(3) Ultraviolet photoelectron spectroscopy (UPS); approximate range: 0 to 50 eV.

(4) Characteristic electron energy-loss spectroscopy (CELS); approximate range: 1 to 500 eV.

(5) Scanning electron microscope (SEM).

(6) Scanning low-energy electron probe (SLEEP).

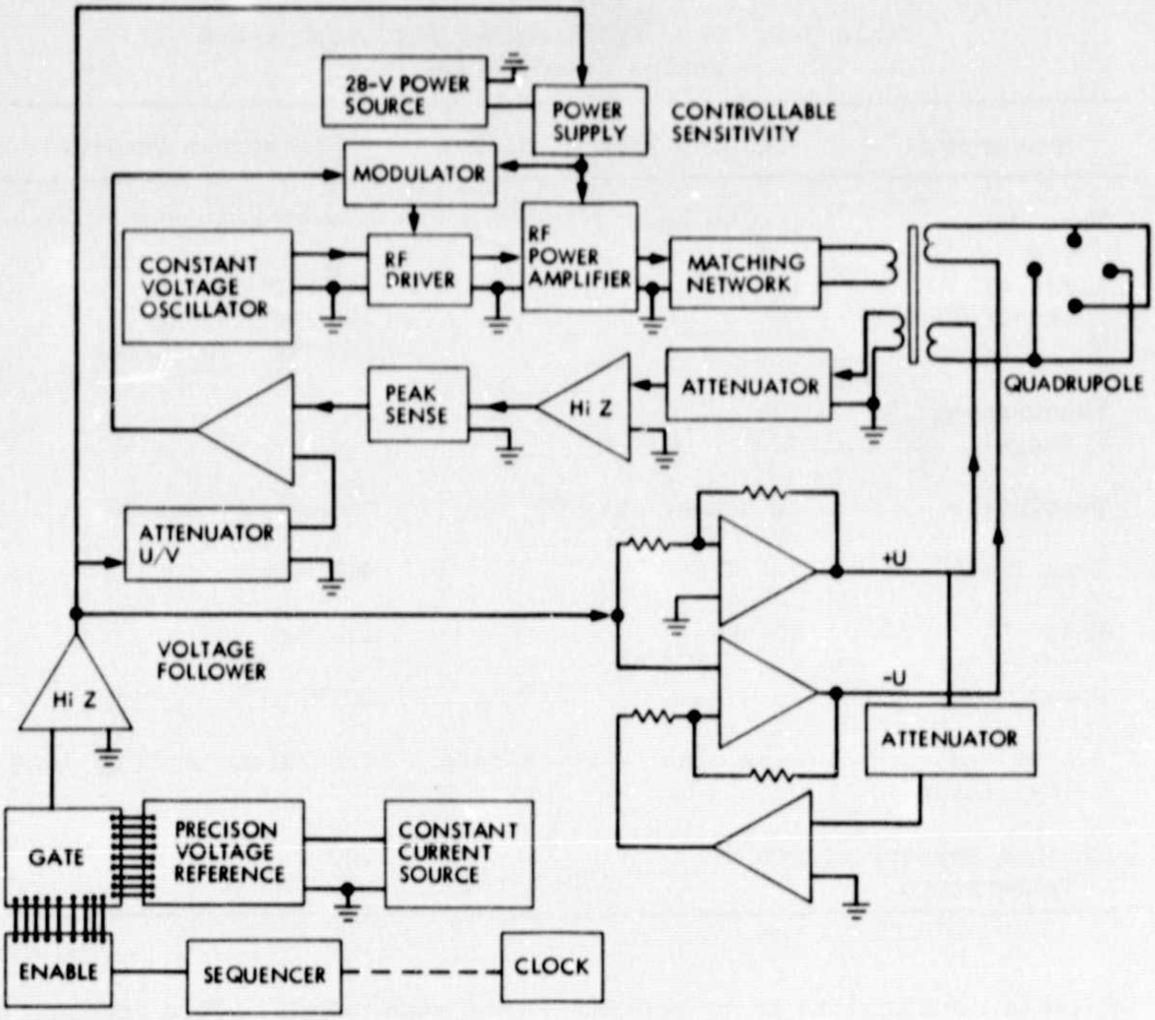


Figure 3-4. Quadrupole power supply and control block diagram

(7) Secondary ion mass spectroscopy (SIMS), including energy-resolved SIMS.

(8) Ion scattering spectroscopy (ISS), including mass-resolved ISS.

(9) Electron-stimulated desorption (ESD).

(10) Residual gas analysis (in sample region).

(11) Certain types of sample cleaning.

The evolution of the MAIS concept is illustrated in Figure 3-5. Many laboratories still use a variety of separate setups, each with its own vacuum system, and each intended for the use of only one analysis technique (Figure 3-5a). Since each setup requires an analyzer as well as a vacuum system, this type of arrangement is not only very costly but requires more time (e.g., for pump-down and bake-out) when more than one

Table 3-1. Mass Spectrometer Performance and
Design Characteristics

Measurement	Density Within Shield	Freestream Density
Mass Range	1 – 50 amu	1 – 50 amu
Limit of Detectability	10 cm^{-3}	10^4 cm^{-3} for O 10^2 cm^{-3} for H 10 cm^{-3} for trace
Measurement Range	10^6	10^6
Resolution	<1 amu at mass 50	<1 amu at mass 50
Scan Time	10^2 s/amu	0.1 s/amu
Mass	1.5 kg	1.5 kg
Power	15 W	20 W
Dimensions (Cylindrical)	4 cm diam. × 20 cm long	4 cm diam. × 20 cm long
Maximum Bakeout Temperature	500°C	500°C

analysis technique is to be applied to the same sample. More recently a number of commercial manufacturers have been marketing systems that permit more than one analysis technique to be applied to a given sample. Such systems do reduce cost and time, but usually employ more than one analyzer and are still quite bulky and heavy; each piece of equipment (e.g., ion gun, electron source) has its own flange and electrical connector or leads (Figure 3-5b).

The MAIS concept (Figure 3-5c) employs a single analyzer (kinetic energy and mass analyzer) and combines all sources, analyzer, sample transport, and positioning (and heating and cooling) provisions as well as material processing devices such as an evaporator in a single package. The whole package requires only one flange and one electrical connector. This "single flange" concept is, of course, particularly useful for space vacuum research facilities such as a molecular shield. Since there is only one flange and pressure seal that must be capable of withstanding atmospheric pressure on one side and vacuum on the other side, each piece of equipment that is part of the MAIS assembly can be very small and very light. A single pressure-seal electrical connector provides all connections between the equipment assembly and the electronics assembly. This connector (Figure 3-6) is located at the end of a cylindrical recess in the vacuum chamber (which can be the molecular shield) so that one or more preamplifiers can be located as closely as possible to the detector,

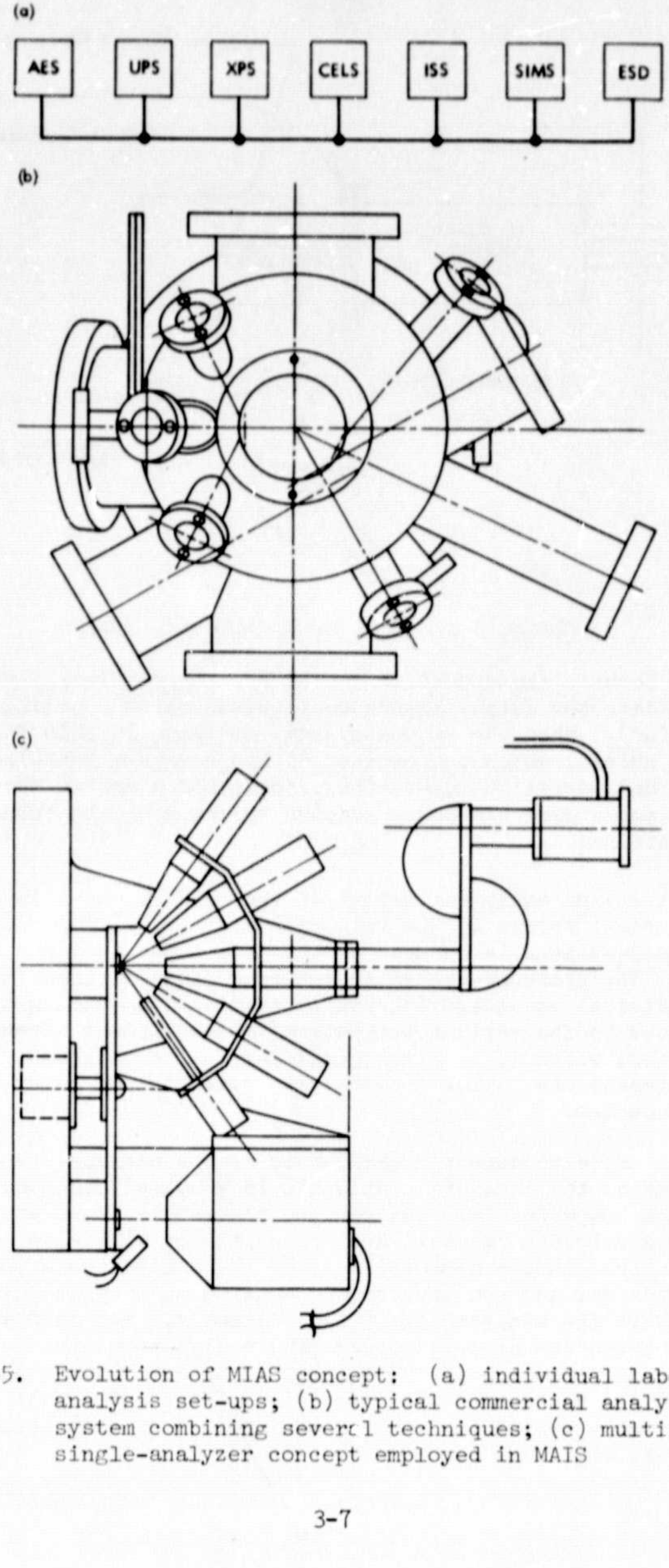


Figure 3-5. Evolution of MIAS concept: (a) individual laboratory analysis set-ups; (b) typical commercial analysis system combining several techniques; (c) multifunction, single-analyzer concept employed in MAIS

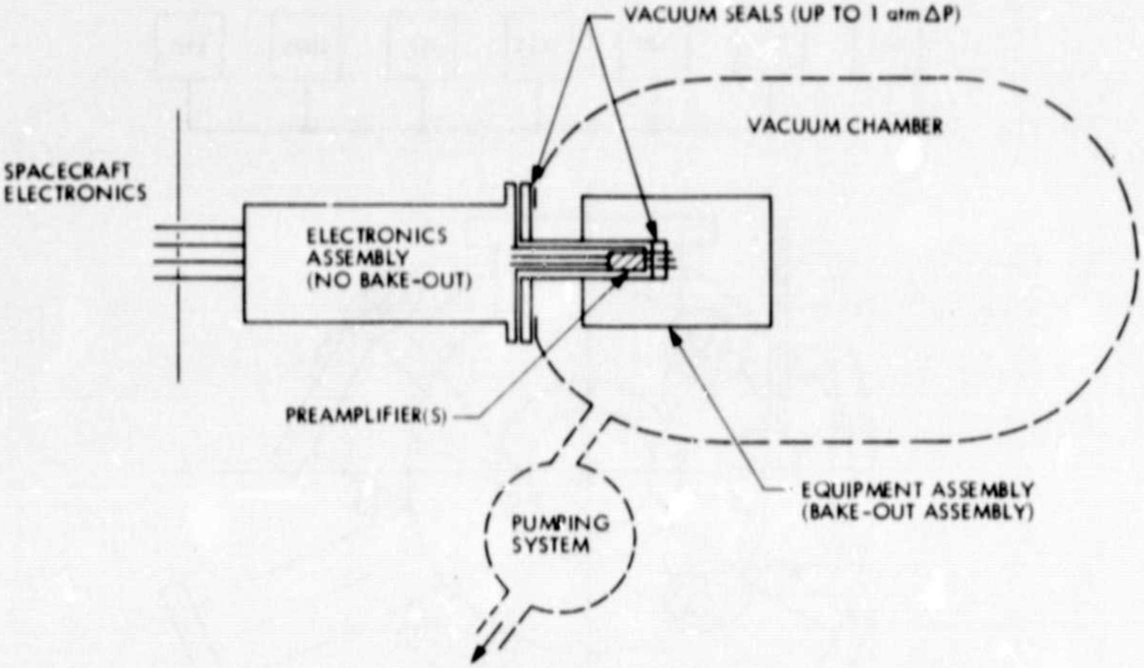


Figure 3-6. MAIS basic packing concept

and leads between these devices can be kept appropriately short (the very-high detector output impedance requires close coupling to the preamplifier). When the vacuum system, as shown in this figure, is the molecular shield, which is retained within a vacuum container during preflight and postflight operations, the pumping system shown would be an ion pump, and a more elaborate pumping system would be tubulated to the vacuum container.

A first-cut equipment layout of the MAIS is shown in Figure 3-7. The cylindrical recess in the vacuum chamber (e.g., solid base of a furlable molecular shield) acts as the main support of the equipment assembly. The pressure-sealed feed-through flange (interface bulkhead) shows electrical connector inserts from which high-vacuum-type wiring would extend to the various elements of the equipment assembly including the detector, which is in close proximity to the bulkhead. Also indicated in the bulkhead are hollow feedthroughs suitable for carrying gas from external sources.

The sample transport mechanism is of the carousel type. When the sample reaches the analysis station it is brought into good thermal contact with a heater/cooler that permits the sample temperature to be adjusted to selected values. A micropositioner will also be available to position the sample appropriately at the analysis station. The UV, X-ray, electron, and ion sources are mounted so they are directed at the sample, as is the analyzer inlet lens assembly. The mass analyzer is mounted between the kinetic energy (KE) analyzer and the detector, whose bake-out requirements point to its being of the electron multiplier type. An evaporator, usable for the deposition of various metals on sample surfaces, and a deposition monitor are located approximately opposite to the analysis station.

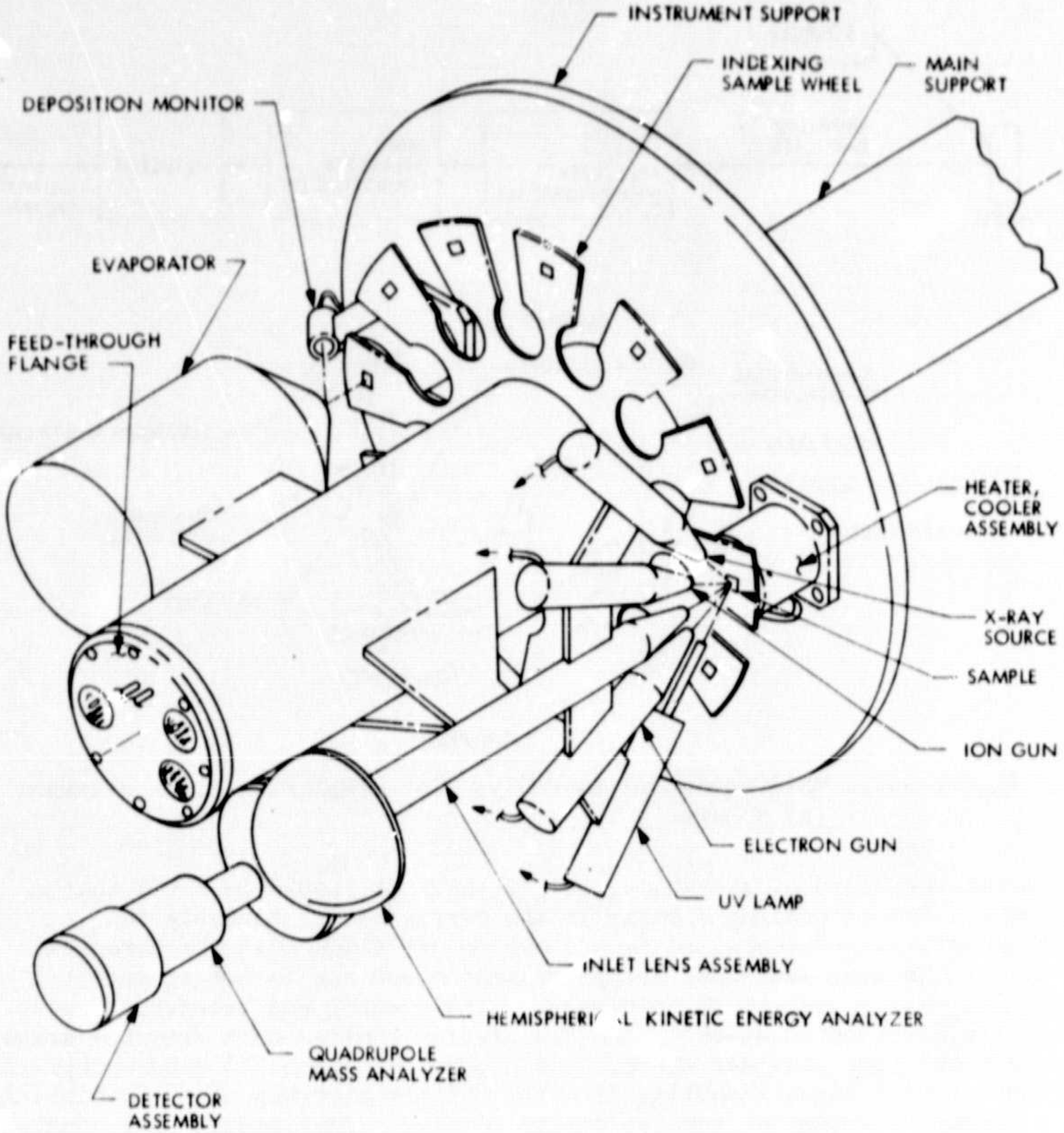


Figure 3-7. MAIS equipment layout

Figure 3-8 shows the MAIS equipment assembly in simplified block-diagram and schematic form. The different analysis functions are obtained by switching on a selected source, selecting its power level, applying selected potentials to the kinetic energy and mass analyzers, controlling inlet and exit lens operation, and energizing the ionizer section (before the exit lens) as required. The Faraday-cup detector is used primarily for calibration purposes.

The simplified functional block diagram (Figure 3-9) shows the major interfaces between the elements of the equipment assembly and the electronics assembly. It also indicates approximate power and potential

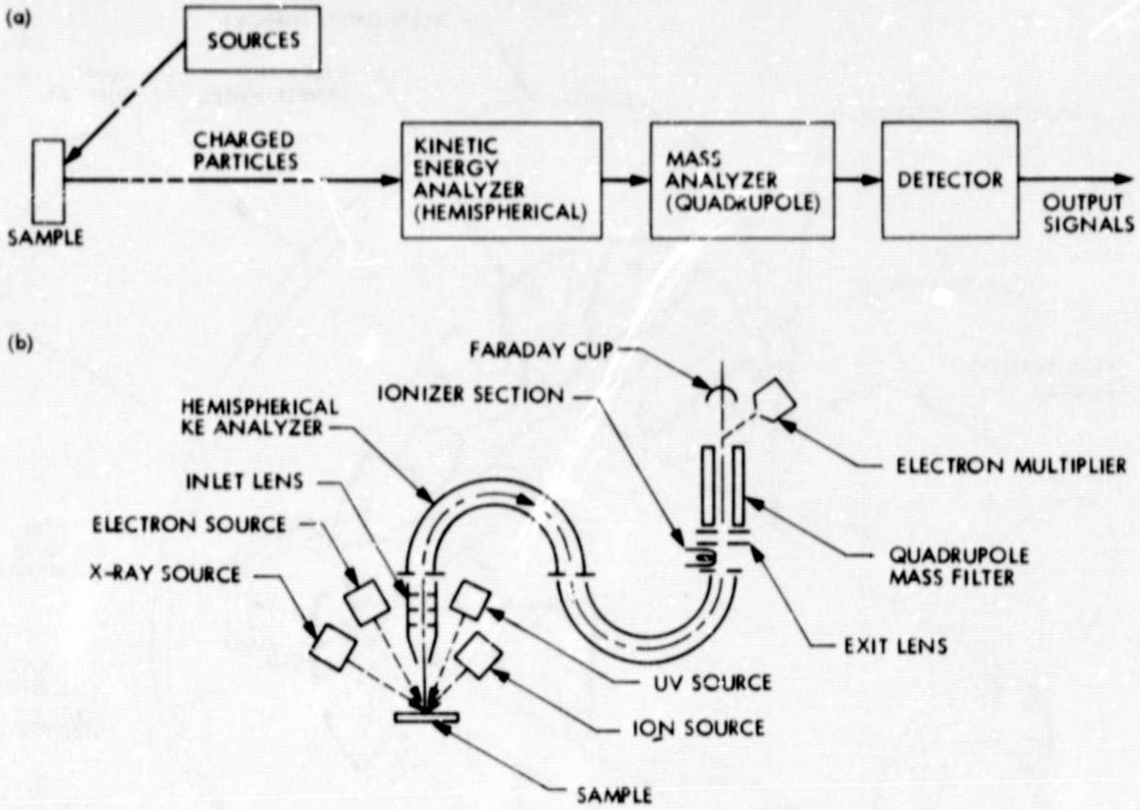


Figure 3-8. MAIS equipment assembly: (a) simplified block diagram; (b) schematic

levels for sources, analyzers, and heater. It should be noted that a thermoelectric cooling element in the heater/cooler assembly can alternatively be energized (not shown on the diagram). The potentials applied to both analyzers are programmable and can be set to selected values within very close tolerances. The control and telemetry module in the electronics assembly decodes digital command data from the spacecraft and then provides appropriate control functions to power supplies and detector signal-handling circuitry either directly or by initiating a prestored sequence from its memory portion. This module also conditions and buffers the signals from the detector and all other sensing devices (e.g., voltage, current, temperature and position sensors), originates status and mode indicator words, and formats all data into a digital data stream acceptable to the spacecraft telemetry system.

C. INSTRUMENTATION CONCEPTS FOR GAS DYNAMICS AND SPECTROSCOPY EXPERIMENTS

Instrumentation concepts for gas dynamics experiments and, in general, for spectroscopy, were only cursorily addressed during this study. An experiment suggested as being of significant importance by some science users involves the characterization of an atomic oxygen beam entering the molecular shield by means of spectroscopy (in addition to mass spectrometry). A conceptual schematic for such an experiment is

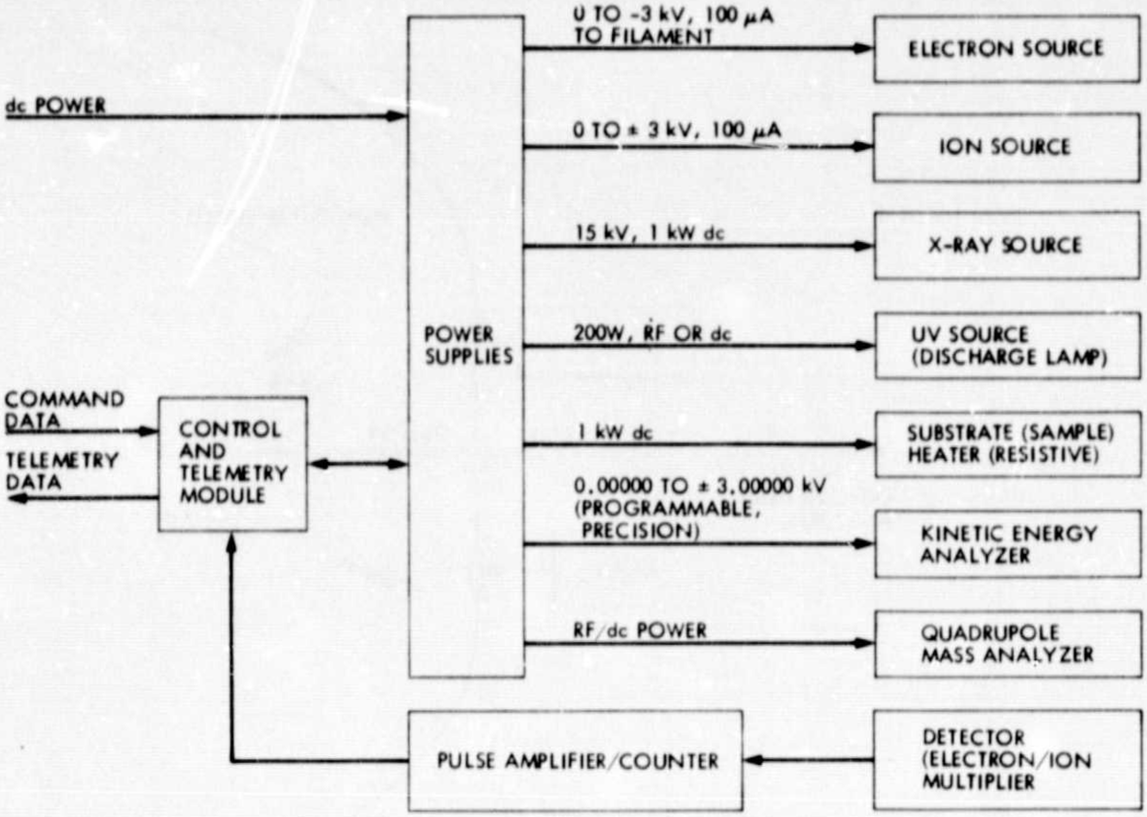


Figure 3-9. MAIS simplified functional block diagram

shown in Figure 3-10. A laser beam is focused at the O-beam at some angle of incidence and the light products of the interaction between the two beams are then collected and focused on the monochromator entrance slit of an optical spectrometer. Fluorescence spectroscopy could be the specific method used in such an experiment. It is possible that the single-flange concept can still be used if windows in the pressure bulkhead are employed. If suitable window materials can be found that minimize attenuation, can be pressure sealed and withstand a differential pressure of one atmosphere, and can withstand the bake-out temperature (the availability of such materials is strongly tied to the wavelength pass-band), then the laser source as well as the spectrometer can be part of the electronics unit which does not need bake-out. Crystal quartz and fused silica could be used as window materials (they also would not outgas significantly after bake-out), but their wavelength pass-band is limited to about 0.18 (0.4 for quartz) to 4 µm.

Concepts for more generalized instrumentation set-ups in a molecular shield were also attempted and are illustrated schematically in Figure 3-11. Free-jet expansion and cross-beam experiments were considered in these applications of emission and absorption spectroscopy. The considerations of the single-flange concept with windows would be the same as for the O-beam characterization setup. A vacuum feed-through in the electrical connector bulkhead could be used to feed gas from an

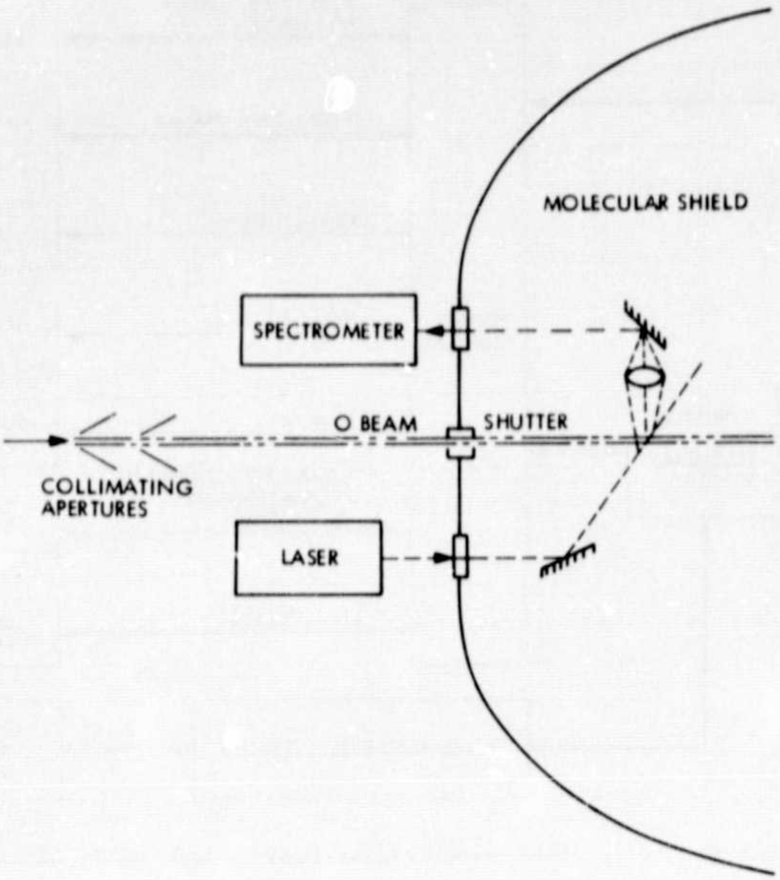
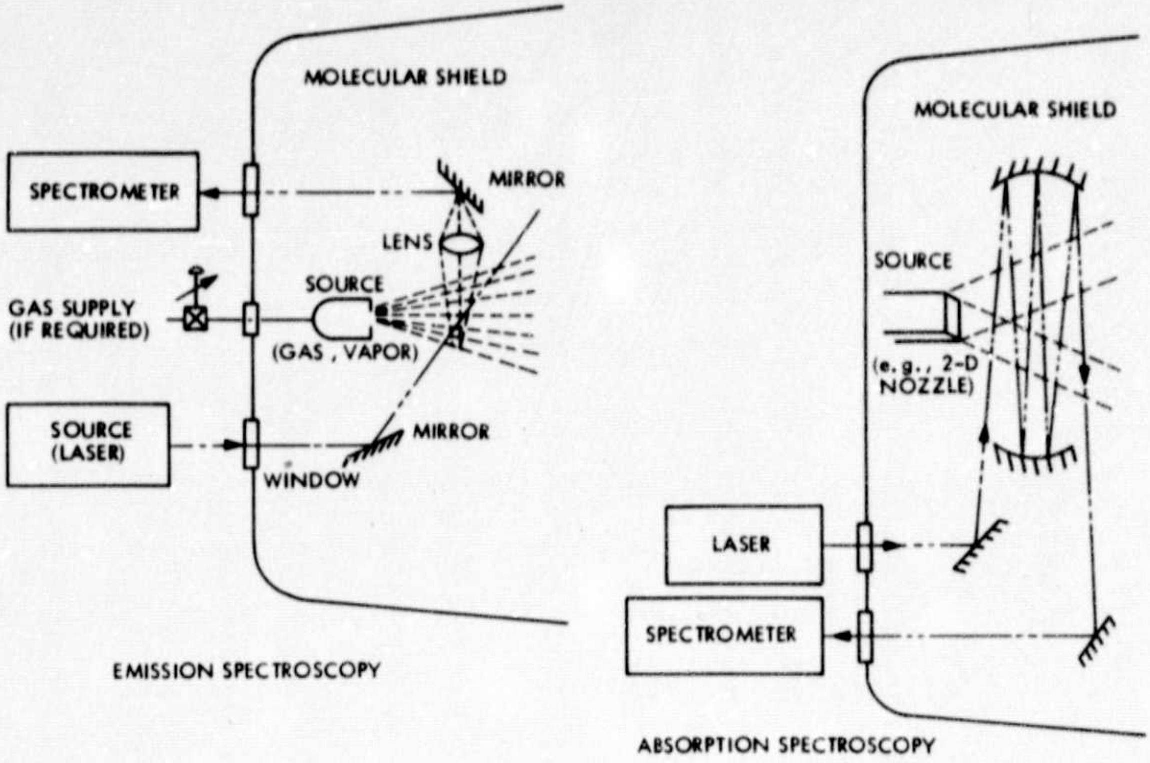


Figure 3-10. Characterization of atomic oxygen beam by spectroscopy - conceptual schematic (refer to Figures 4-6 and 4-7 for possible practical configurations)

externally-located (not baked-out) gas source into the experiment region. Instrument types and arrangements and optical devices within a molecular shield can be addressed in more detail once specific experiments in this category have been defined. It is believed, however, that at least some such experiments could be performed successfully in a molecular shield.



EMISSION SPECTROSCOPY

ABSORPTION SPECTROSCOPY

Figure 3-11. Conceptual schematics - instrumentation for gas dynamics and spectroscopy

SECTION IV

DEPLOYMENT AND RETRIEVAL CONCEPTS

A. SYSTEMS CONSIDERATIONS

A number of different approaches were considered by JPL to develop conceptual designs for a molecular wake shield assembly that could be deployed as well as retrieved with a minimum amount of contamination introduced into the experiment region. Such concepts would be aimed at a combination of design and operations whereby the molecular shield itself as well as the instrumentation and experiment hardware within the shield could be baked-out and thoroughly degassed on the ground, whereby the absence of contamination can be maintained until the shield is in its final operating location and position, whereby the vacuum seal can then be broken without introducing contamination inside the shield, and where the shield, experiment, and instrumentation can be resealed prior to retrieval, again without introducing contamination into the shield.

While it is probably true that some experiments may not levy all of these requirements on a molecular wake shield system, the above set of assumptions constitute a worst case, and it was decided to develop concepts to fit such a case. In the process of working out such designs it became apparent that a systems approach would be helpful. In such an approach there would be two major systems to be considered: the spacecraft system, whose subsystems would include a boom, and the molecular shield system, within which the various subsystems are properly integrated so as to best meet science objectives and interface with the spacecraft system (see Figure 4-1). Some of the molecular shield subsystems (e.g., a mass spectrometer subsystem) will be comprised of two major assemblies: the portion within the shield, which could be termed the sensing assembly, or perhaps the bake-out assembly, and the portion outside the shield, the electronics assembly.

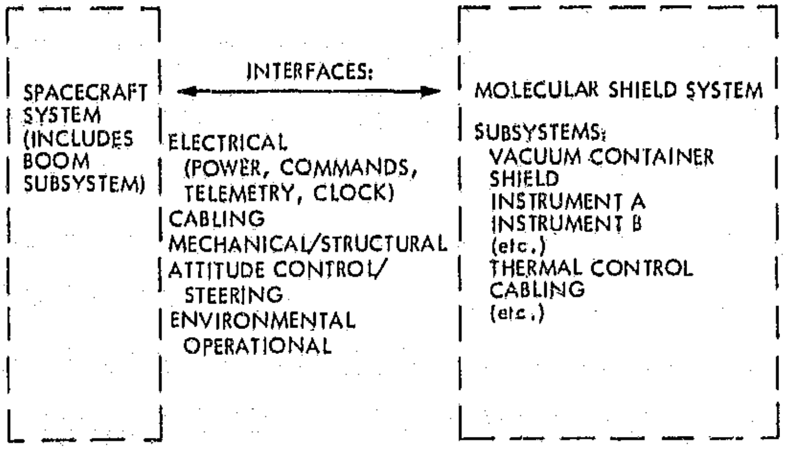


Figure 4-1. Systems arrangement

B. A BASELINE DESIGN CONCEPT FOR A MOLECULAR SHIELD SYSTEM (WITHOUT O-BEAM PROVISIONS)

An earlier concept, involving a vacuum container on the spacecraft, which would be unsealed just before boom erection and molecular shield system deployment, was addressed at first, but was discarded because too much contamination would be introduced during both the deployment and the retrieval operations. Efforts were then directed at a "flyable" vacuum container that could be unsealed as well as resealed in the final deployed position.

The impacts on size and mass of a "flyable" vacuum container for a solid 3-m-diameter shield were then addressed, and it became apparent that use of a furlable shield in lieu of a solid shield would offer significant size and mass reduction advantages. The 3-m diameter of the shield was chosen during earlier work on the basis that a shield of this size, and its surrounding vacuum container, would be the largest that could be accommodated within the cargo bay of the Shuttle. Solid shields could be smaller than that, but not be larger unless a later derivative of the Shuttle could offer a roomier cargo bay, or unless it were assembled in space. JPL has worked extensively with commercial manufacturers on furlable structures, primarily for use as spacecraft high-gain antennas, and had actually built and tested a furlable antenna of the "umbrella" type for possible use on an outer-planets spacecraft. The Galileo spacecraft (Jupiter orbiter with probe), managed by JPL, will use a 4.8-m furlable, high-gain S/X-band antenna of the same type that will fly on the Tracking and Data Relay Satellite (TDRS), which is related to the Space Transportation System (STS).

Preliminary layouts indicated that a vacuum container for a 3-m-diameter furlable shield would be only approximately 2.25-m long by 0.75-m diameter, and that shields (not necessarily of hemispherical shape) ranging in size up to 25-m could probably be accommodated within the existing dimensional limitations of the Shuttle cargo bay. The essential elements of a furlable shield are the ribs, attached or hinged around a central hub, which would be external to a thin, flexible web. When the ribs are fully deployed, such as by spring force or a motor drive, the shield is "unfurled" and assumes its final shape. A detailed design and material selection was not attempted (although some of these are suggested in Section 5); a sandwich construction of the web, consisting of pure, degassed aluminum foil (inside surface) bonded to a molybdenum web (external surface) was considered as a first-cut approach.

An initial design of a molecular shield system capable of meeting the "worst case" system requirements involved a vacuum container that after unsealing, was pushed forward over the associated (and not baked-out) electronics unit, by means of a centrally located jackscrew. This design had one undesirable characteristic: it required a rotary (sliding) high-vacuum seal. A different design was then created that overcame this problem.

In this design, the molecular shield system comprises two major assemblies (see Figure 4-2):

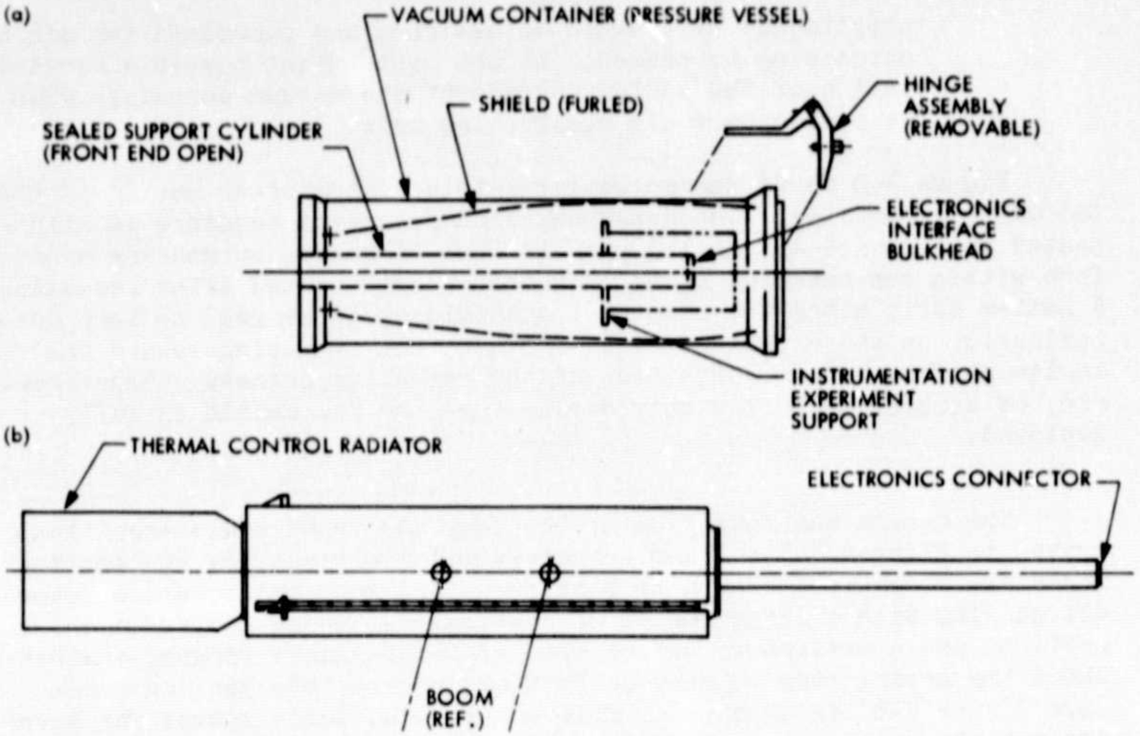


Figure 4-2. The two major assemblies of the molecular shield system: (a) bake-out assembly; (b) electronics unit

(1) The bake-out assembly, which includes the vacuum container, the furlable molecular shield with a sealed support cylinder intruding from its base plate, the instrumentation/experiment support that is mounted to the cylinder, and a motor-driven hinge assembly, which is removable so that it does not need to go through the bake-out process; the entire assembly can be baked-out and pumped-down (the pumping port is not shown).

(2) The electronics unit, which is attached to the bake-out assembly after completion of all degassing and bake-out operations; when this unit is attached, the electrical connector at the end of the cylindrical protrusion mates with a connector (pressure-sealed) in the electrical interface bulkhead of the bake-out assembly; the main purpose of this arrangement is to permit one or more preamplifiers to be located near the electrical connector, without needing to be baked out, and then be in close proximity to detectors in the bake-out assembly; it is essential that wiring between detectors and preamplifiers be kept as short as possible; the electronics unit also contains the three jackscrew assemblies (motor-driven) which engage with (or are coupled to) the forward flange of the vacuum container; thermal control provisions are, for the time being, shown in the form of radiator fins; all external surfaces of the (sealed)

electronics unit would be designed and processed for minimum outgassing to prevent, to the best extent possible, contamination of the inside surface of the vacuum container when it is pulled over the electronics unit.

Figure 4-3 shows the molecular shield system after mating of the two major assemblies. The deployment and retrieval sequence is illustrated in Figure 4-4. An ion pump is used to remove outgassing products from within the bake-out assembly before unsealing and after resealing. A getter strip along the edge of the shield could be used to keep contamination on the external shield surface from migrating toward the inside surface before completion of the resealing process. Experiments are, of course, performed only during the time the shield is fully deployed.

The design and operation of the rear and front seals are illustrated in Figures 4-5 and 4-6. The essential elements of the sealing/unsealing mechanism, common to both front and rear seals, are a motor-driven ring with a large number of cam-fingers, wedge-shaped in cross section, and a stationery set of similar wedge-shaped fingers against which the moving ring rotates so that the appropriate sealing force (see Figure 4-6) is obtained. This compression force pushes the cover against the seal. A molybdenum sulfide lubricant could be used, between the rotating and stationery fingers, to prevent a diffusion bond between them, or a freely rotating ball could be placed between the faying surfaces of the fingers for the same purpose. The seal itself has not yet been defined in detail; it can be envisioned as a gold-plated copper O-ring for the time being. A large amount of knowledge about high-vacuum seals is available and the optimum type of seal, as well as the power required by the (geared-down) seal-drive motors would probably best be established by laboratory work.

C. DESIGN MODIFICATIONS TO INCLUDE O-BEAM PROVISIONS

After completion of the design described in the previous section of this report, some cursory studies were initiated to determine the

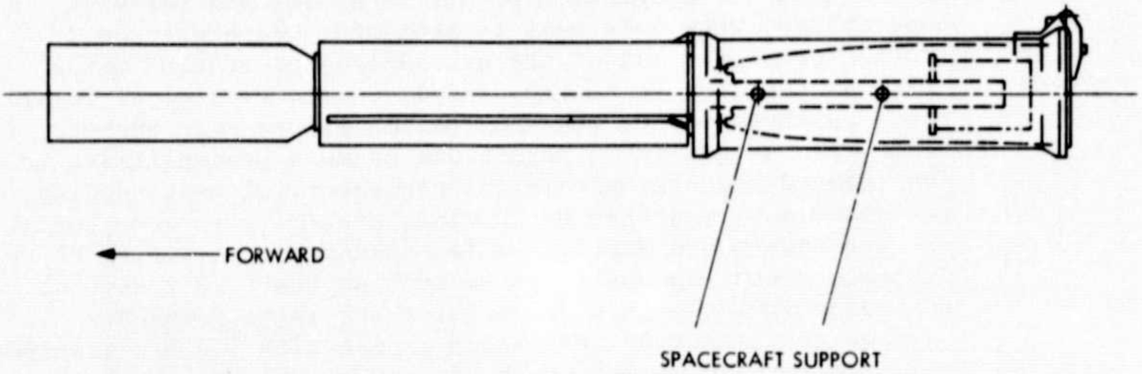


Figure 4-3. Molecular shield system fully assembled and in operating position

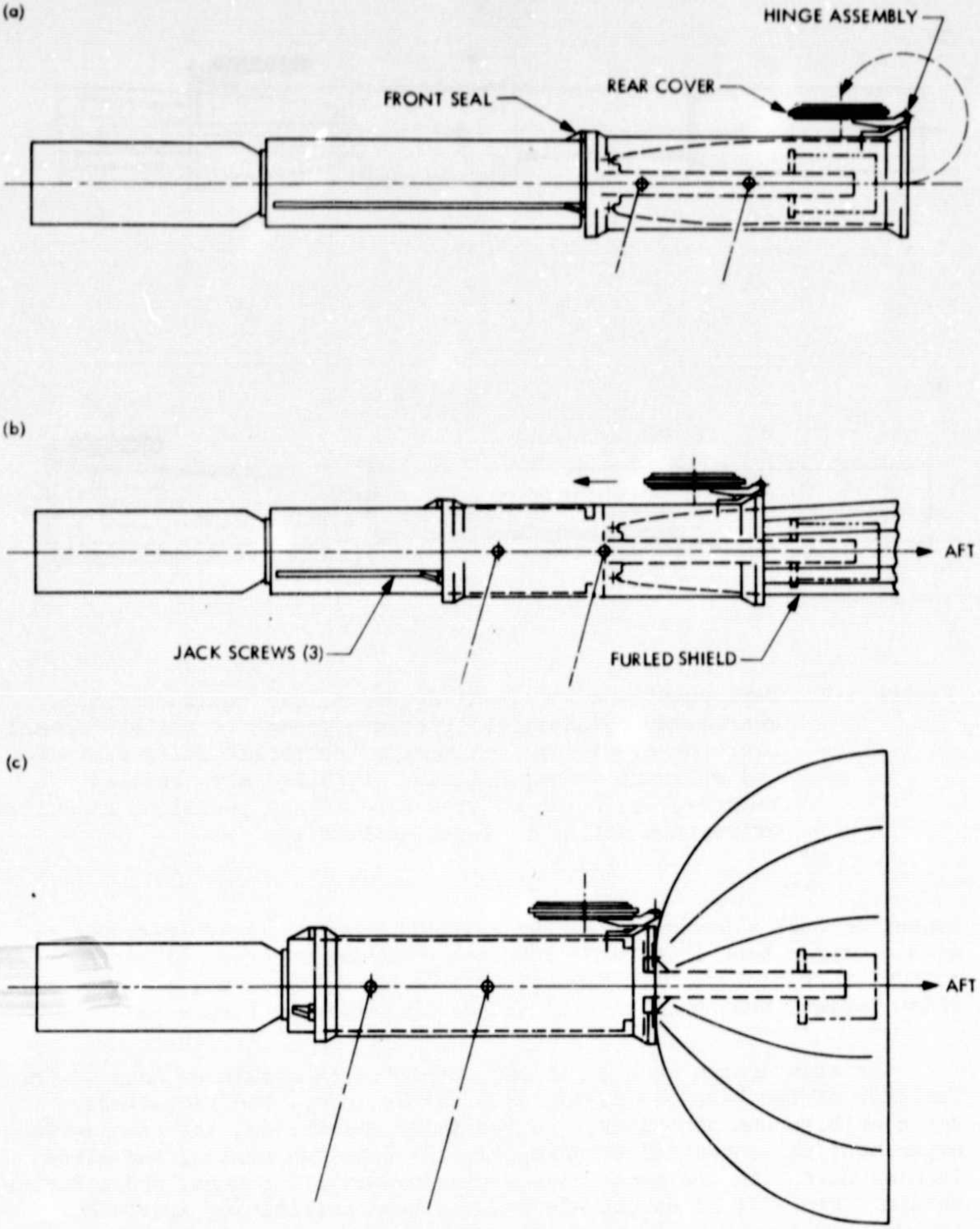
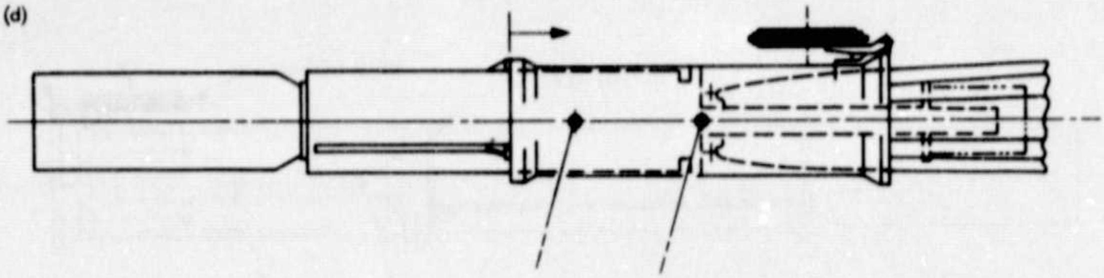


Figure 4-4. Deployment and retrieval sequence: (a) seals released, rear cover rotates; (b) pressure vessel is pulled forward over the electronics assembly; (c) shield fully deployed; (d) pressure vessel cylinder is pulled aft, shield refurls; (e) cover rotates into closed position, resealing drives are activated

(d)



(e)

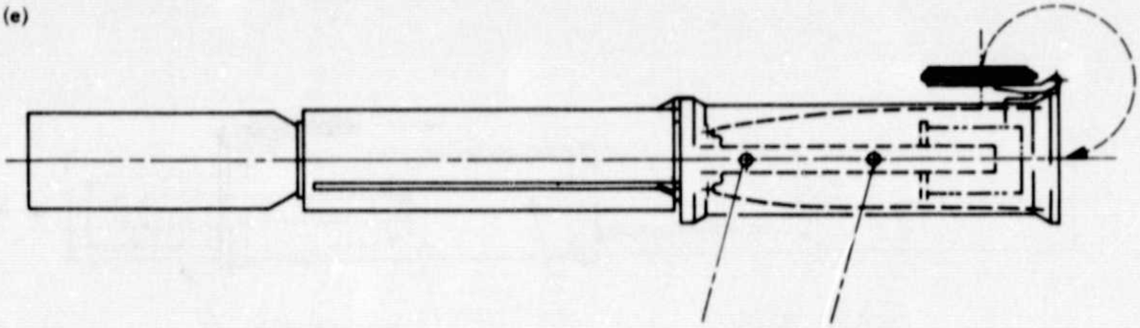


Figure 4-4. Deployment and retrieval sequence: (a) seals released, rear cover rotates; (b) pressure vessel is pulled forward over the electronics assembly; (c) shield fully deployed; (d) pressure vessel cylinder is pulled aft, shield refurls; (e) cover rotates into closed position, resealing drives are activated (continuation 1)

impact on such a design of adding suitable provisions to introduce an atomic oxygen beam ("O-beam") into the experiment region within a molecular shield system. Several options were looked at, and the one which appears most promising is the design shown in Figure 4-7.

In this design concept it was attempted to retain as many of the features of the baseline design as possible, e.g., the retractable, resealable vacuum container, the two major assemblies, the single-flange experiment/instrumentation package in the bake-out region, the electronics unit with its protruding wiring/preamplifier tube, and a furlable shield. Since it is essential that the beam collimating apertures (shown only sketchily in this illustration) are aligned with the velocity vector, it became apparent that a simple solution would be to fly the complete molecular shield system vertically, i.e., with its centerline normal to the velocity vector. The shield would be hinged at two points on the apex plate of the aperture assembly (see Figure 4-7), and would be unfurled as well as refurled by a draw cable through the ribs, which would probably have to be spring-loaded toward their fully deployed position. A secondary set of ribs (not shown), not attached to the web, and located midway between primary ribs, could be added to force the web to fold inward properly during refurling (this could also be done for the

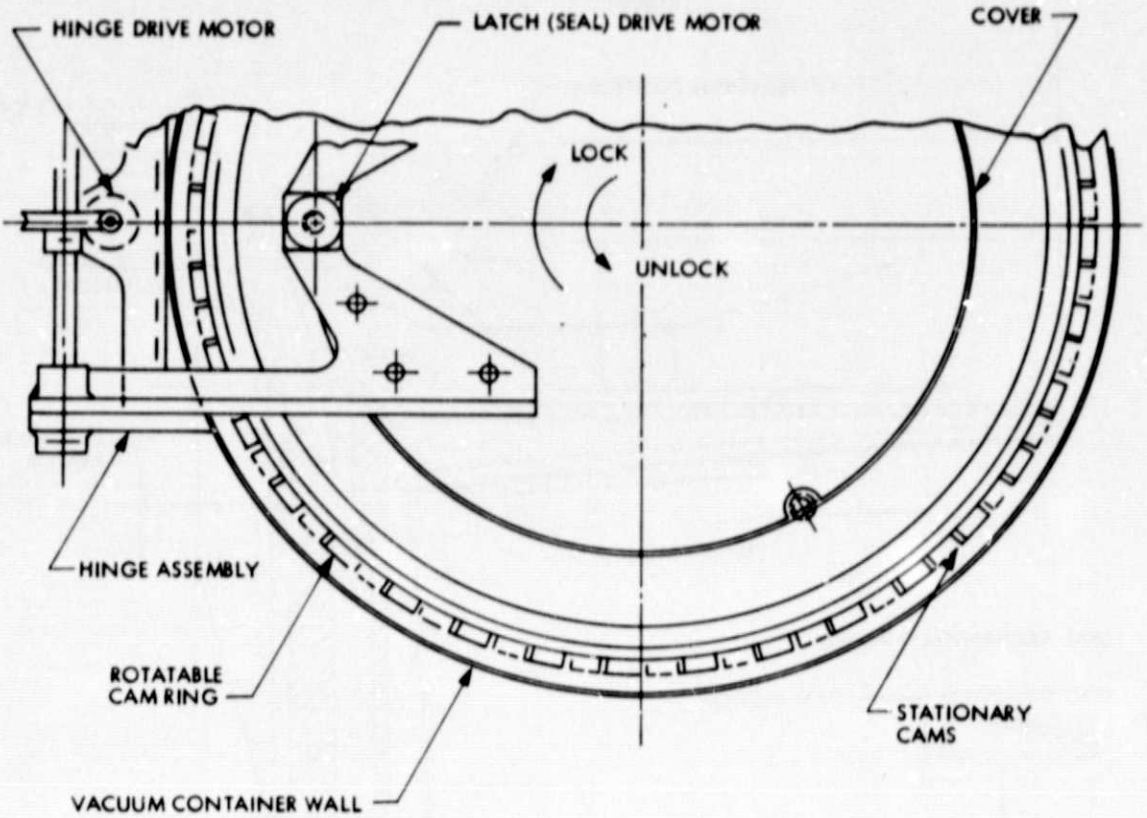


Figure 4-5. Aft seal and hinge assembly (front seal employs the same principle)

baseline design version). A possible design concept for the cable reel mechanism is shown in Figure 4-8. Other options could be considered for elements of this design, such as the use of a pair of solenoids in lieu of the motor and cranks, or use of a second crankshaft in lieu of the catch-and-pawl drive for the drum (bellows can also move laterally. It is also very probable, with reference to Figure 4-7, that the shield, when deployed, would be shallower (so as to bring the apertures closer to the experiment region) and that it may not be hemispherical but closer to conical.

The aperture arrangement is shown more properly in Figure 4-9. It shows the two apertures: the forward aperture (large truncated cone) and the aft aperture (small truncated cone); the latter is connected to the apex plate by a (cylindrical) tube; the apex plate (which then becomes the apex of the molecular shield) can be of conical or curved shape. The ribs of a furlable shield would be hinged at points along the aft edge of the apex plate and the web would be welded to the apex plate.

The dimensions of the apertures are related to the desired diameter of the beam (D_2) at a given point behind the aft aperture (L_2) by:

$$\frac{D_1}{L_1} = \frac{D_2}{L_1 + 2L_2}$$

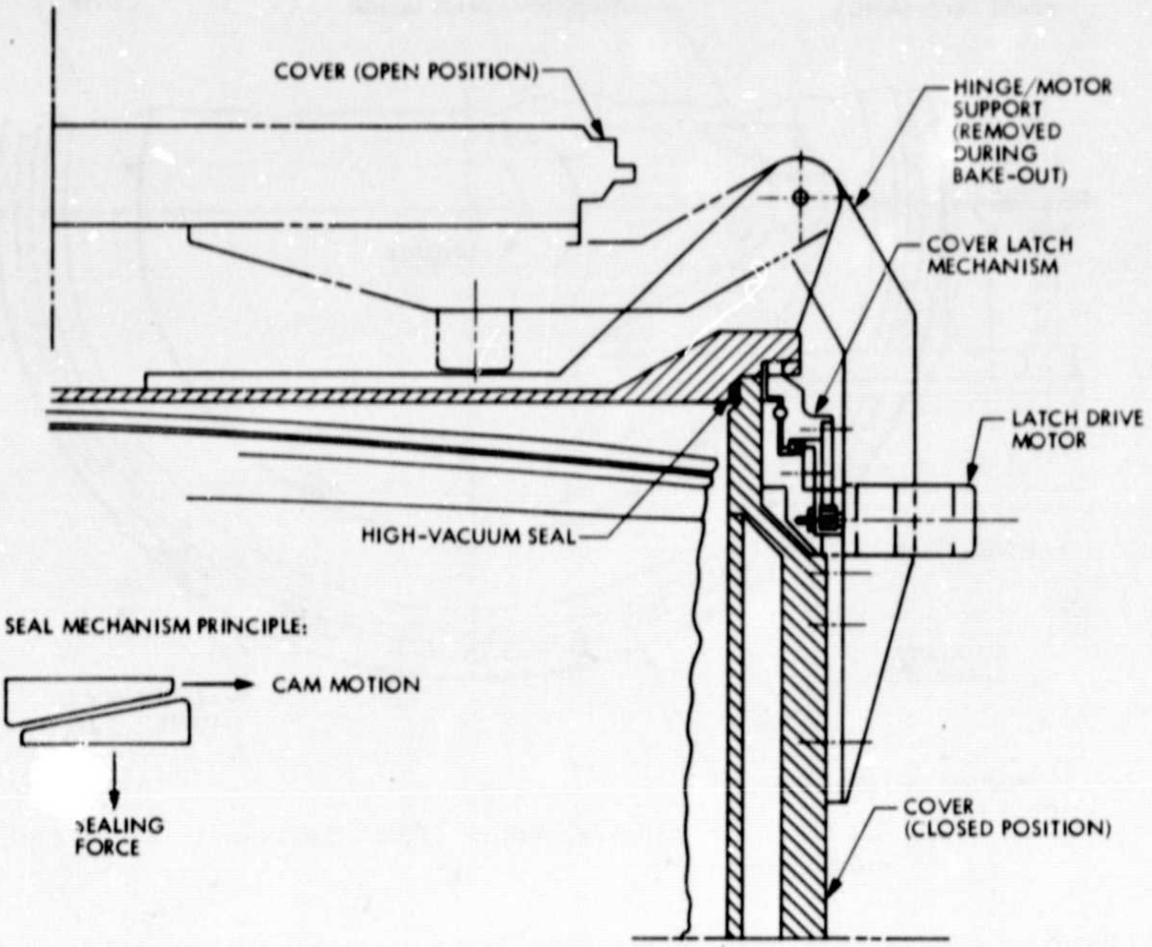


Figure 4-6. Cover, hinge, and seal elements

The following could be typical dimensions: let us assume that a sample, with which the atomic beam is to interact, is located 50 cm aft of the opening of the aft aperture; let us further assume that it is desired that the beam diameter, at the sample location, is to be one centimeter. If we choose 0.25 cm as a reasonable aperture opening diameter, then L_1 would be 33 cm.

The structural configuration is not shown in the illustration. However, the forward aperture cone would be attached to either the aft cone, or to its tube, or to the apex plate by thin, rigid struts, e.g., knife-blade-shaped struts spaced 120 degrees apart.

The atomic beam intensity was calculated for the typical dimensions shown above (1-cm-diameter beam at a distance of 50 cm aft of the aft aperture) (Ref. 14). At the sample location, the cross-section of the beam would have a central region (0.25 cm in diameter) of high intensity and a second region, extending from this central region to the perimeter of the beam, in which the intensity would decrease until it reaches zero at the perimeter (see Figure 4-10). At typical orbital altitude and velocity the ambient (incident) atomic oxygen flux would be 2×10^{13} atoms cm^{-2} s^{-1}. At the sample location, the flux in the high-intensity

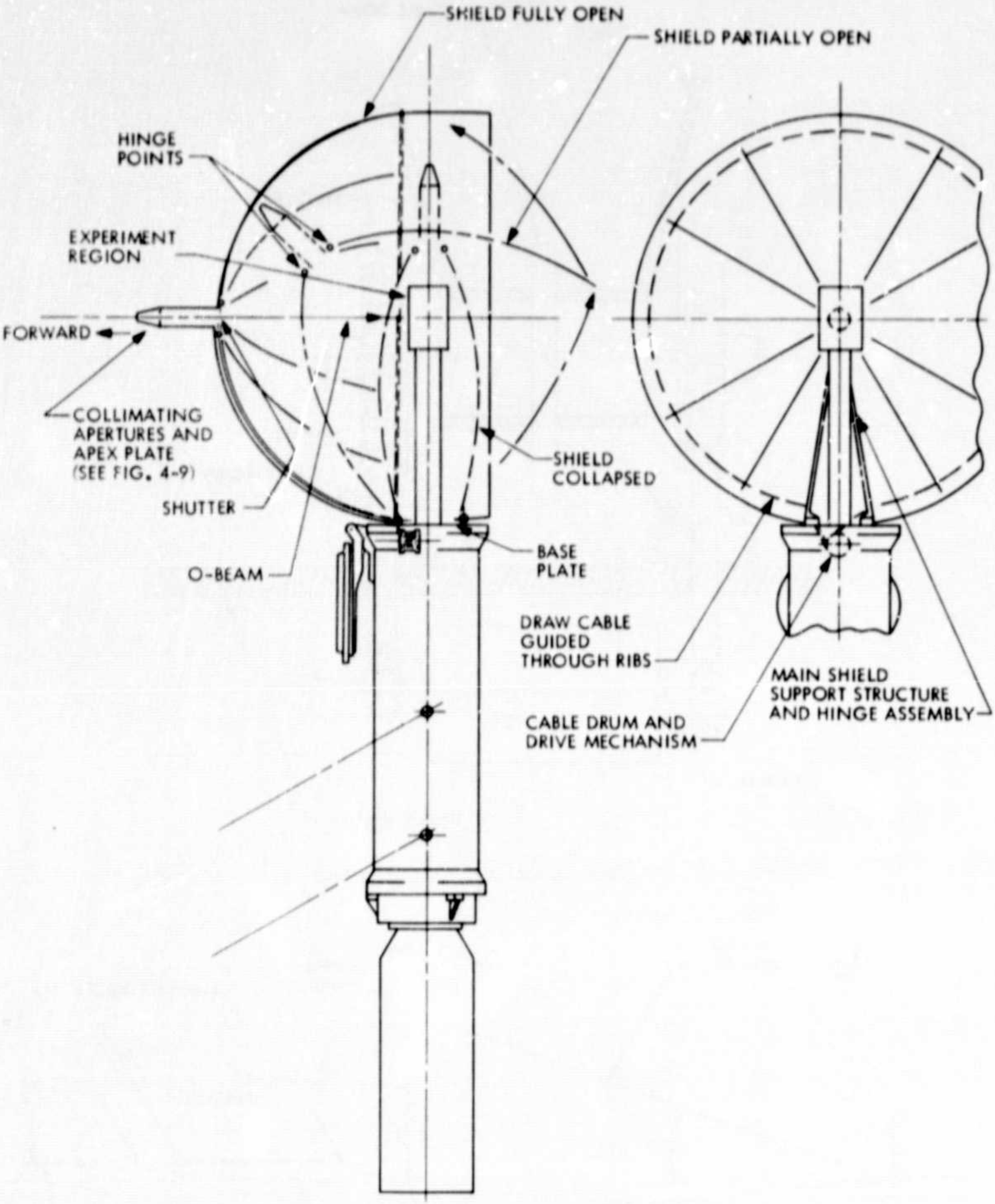


Figure 4-7. Deployable/retrievable molecular shield system concept with O-beam provisions

(A-A) region would then be 1.3×10^{11} atoms cm^{-2} s^{-1}, and in the regions of decreasing intensity (A-B) it would be $1.3 \times 10^{11} \times 2.638 \times (0.5 - x)$, where x is the radius at which this intensity is to be determined. It can be seen that, when $x = 0.5$, i.e., the perimeter of the beam has been reached, the intensity at that point would be zero.

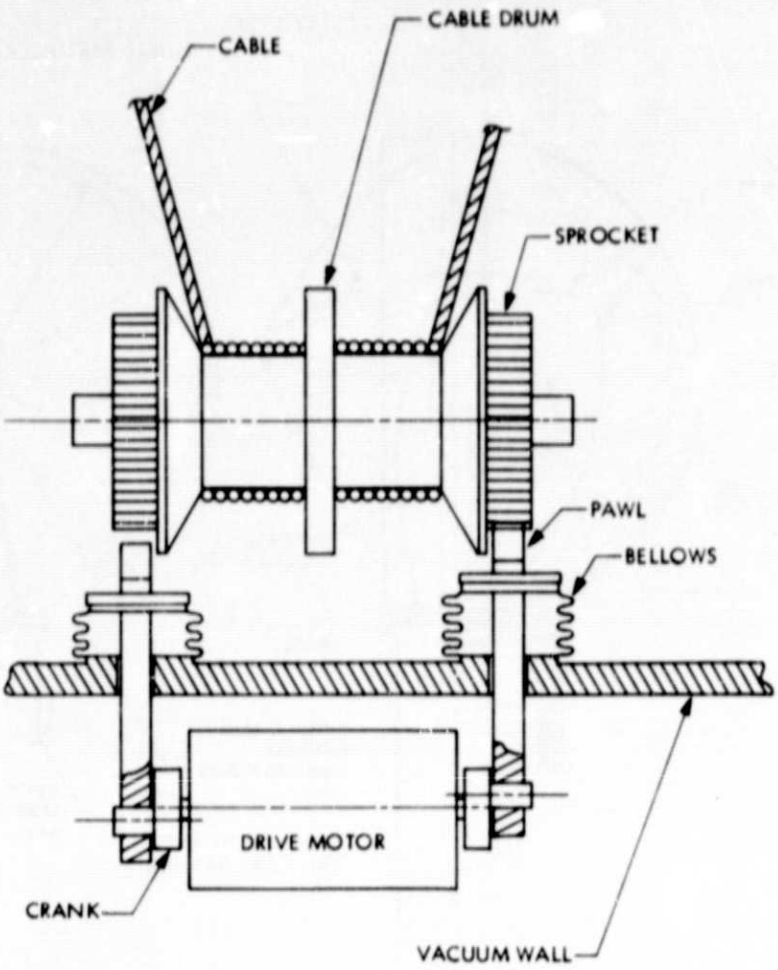


Figure 4-8. Cable drum and drive mechanism concept

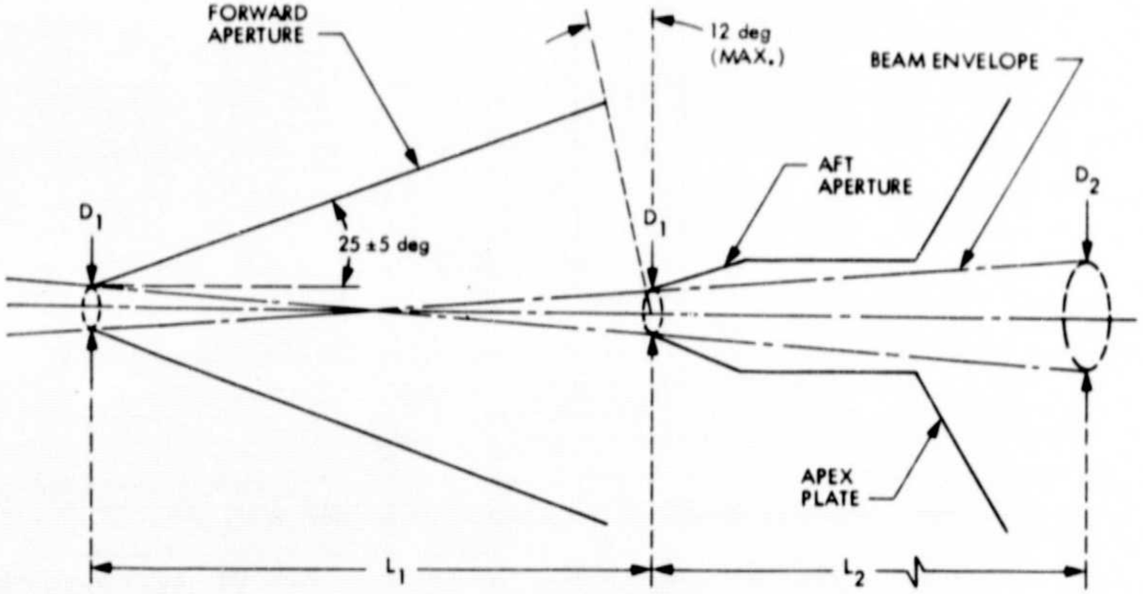


Figure 4-9. Atomic beam aperture arrangement

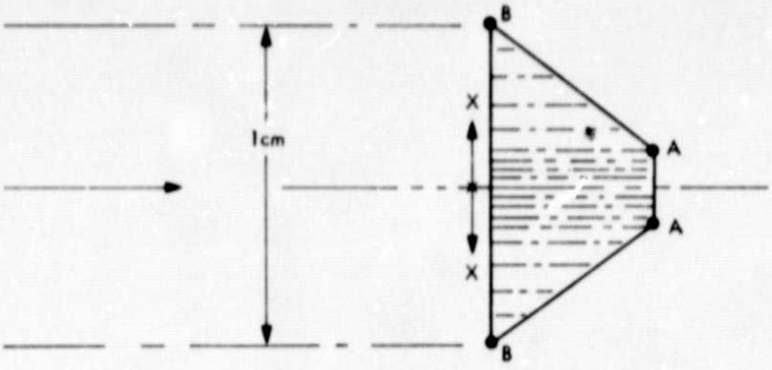


Figure 4-10. Cross-sectional profile of atomic beam intensity at sample location

The conceptual shield design with O-beam provisions was not carried out to the level of detail of the design without such provisions. Among areas to be addressed are: avoidance of contamination introduced into the shield as it unfurls (since it now would no longer unfurl while pointing aft) general rib and web configuration and sealing of the now double-hinged web to the base plate (without necessitating a "hole in the web" to accommodate the tubular instrumentation/experiment support).

SECTION V

DESIGN CONSIDERATIONS FOR A MOLECULAR SHIELD SYSTEM PRECURSOR

It had been suggested by a number of science users that a precursor molecular shield flight be considered before work on more ambitious experiments and shield system designs is undertaken. It is felt that one, or perhaps more than one, precursor missions would be a very desirable beginning of what would then be a phased program during which increasingly complex experiments could be performed. Such a precursor mission could possibly be flown on one of the earlier Shuttle Orbiter missions. The first precursor mission would most probably be primarily an engineering verification flight.

Several design approaches were suggested by NASA MSFC and LaRC, some involving use of the Shuttle's Remote Manipulator System (RMS) as the boom for a relatively small solid shield. Different flight attitudes of the Shuttle were also considered. The approaches taken by JPL are described below.

The major elements of the precursor design would be:

(1) A furlable molecular shield (TDRS 4.8-m high-gain antenna design base).

(2) Although not part of the molecular shield system, an extendable/retractable 115-m long boom (Voyager magnetometer boom design base).

(3) Two quadrupole mass spectrometers, one external, the other internal to the molecular shield; multiple fields of view, or multiple viewing angles, selectable by remote command, were also considered for these instruments.

The furlable shield would be provided with ribs of elastic metal so that the energy stored as spring force is used to attain the final shield geometry, which, for the time being, is assumed to be hemispherical. Means for damping the spring-force-activated unfurling would be provided to avoid damage to the web. The ribs would be external to the web (and a secondary set of external ribs could be added to assure proper refurling, if such refurling is part of the requirements on the precursor).

The inside surface of the web could be pure, de-gassed aluminum foil; alternatively, it could be a sintered getter material applied to an aluminum, nickel, or stainless-steel substrate (Ref. 15). Either of these inside surfaces could then be bonded to a metal mesh (probably molybdenum), which could also be plated or coated to help provide desired temperatures, e.g., elevated temperatures, while exposed to solar radiation. The getter material could be type ST-171, essentially a Zr-Al (Ta-Ni) alloy, commercially available from Westinghouse. The getter material would reactively pump such active gases as H_2, O_2, and CO with increased efficiency at elevated temperatures. If the getter material is used, the web when fully open could assume a corrugated pattern to maximize getter area and provide a rough surface to enhance random scattering of gas molecules. It is realized that use of getter material instead of pure metal foil as the inside shield surface radically modifies the original molecular shield concept. A selection of either of the two alternatives would have to be preceded by a thorough materials testing program.

The characteristics of the boom were also addressed while assessing precursor designs. A boom extensible to a total length has been studied in considerable detail by JPL, as part of studies on solar-sail spacecraft (Ref. 16). The design of this boom (see Figure 5-1) is similar to that of the "Astromast" design. A 13-m Astromast is currently flying on Voyagers 1 and 2 to carry the magnetometer sensors. The 115-m "solar sail" boom, proposed here, uses a motor drive assembly to extend and retract the boom (the Voyager boom is not retractable). This drive assembly is suitable for incremental extensions and retractions to selectable lengths, up to 115-m; this could be a useful attribute to a precursor mission, such as for determining the minimum acceptable length of a boom. The triangular boom is made up of three hollow titanium tubular longerons, 0.8 cm in diameter. The longerons are stowed in a coiled configuration within a cylindrical canister. A motor-driven (two redundant motors) mechanism operates the jackscrews that extend and retract the boom. Analyses have indicated the following characteristics of this boom assembly:

(1) A total mass of about 145 kg (0.3 kg for the boom plus about 100 kg for the canister and 10 kg for the drive assembly).

(2) Dimensions (while stowed) of 1.4-m diameter by 3-m long for the canister and 30-cm diameter by 15-cm high for the drive assembly (next to bottom of canister)..

(3) The boom would be able to withstand bending strains up to 50 N·m and axial loads to about 140 N; the boom would be capable of lifting a 14-kg mass, vertically, at Earth gravity.

Two companies have stated their willingness to construct such a boom: Astro Research (Carpinteria, Calif.) and AEC-Able Engineering Corp. (Goleta, Calif). Reference 15 also includes suggestions for boom installation and deployment, and for boom steering that may involve a gimballed, two-axis-articulable canister support and may additionally require articulation of the molecular shield assembly at its attachment to the boom tip. Such boom steerability also implies possibilities for flight test plans in which the shield could be tilted to selected angular positions other than alignment with the velocity vector.

One molecular shield system design considered by JPL was the concept illustrated in Figure 5-2 (Ref. 15). The concept is based on use of a furlable shield (with gettered inside surface), a vacuum container for the system, which remains on-board the spacecraft, and a jettisonable, thin, gettered cylinder around the furled shield; this cylinder remains in place until the shield is ready for unfurling. Retrieval

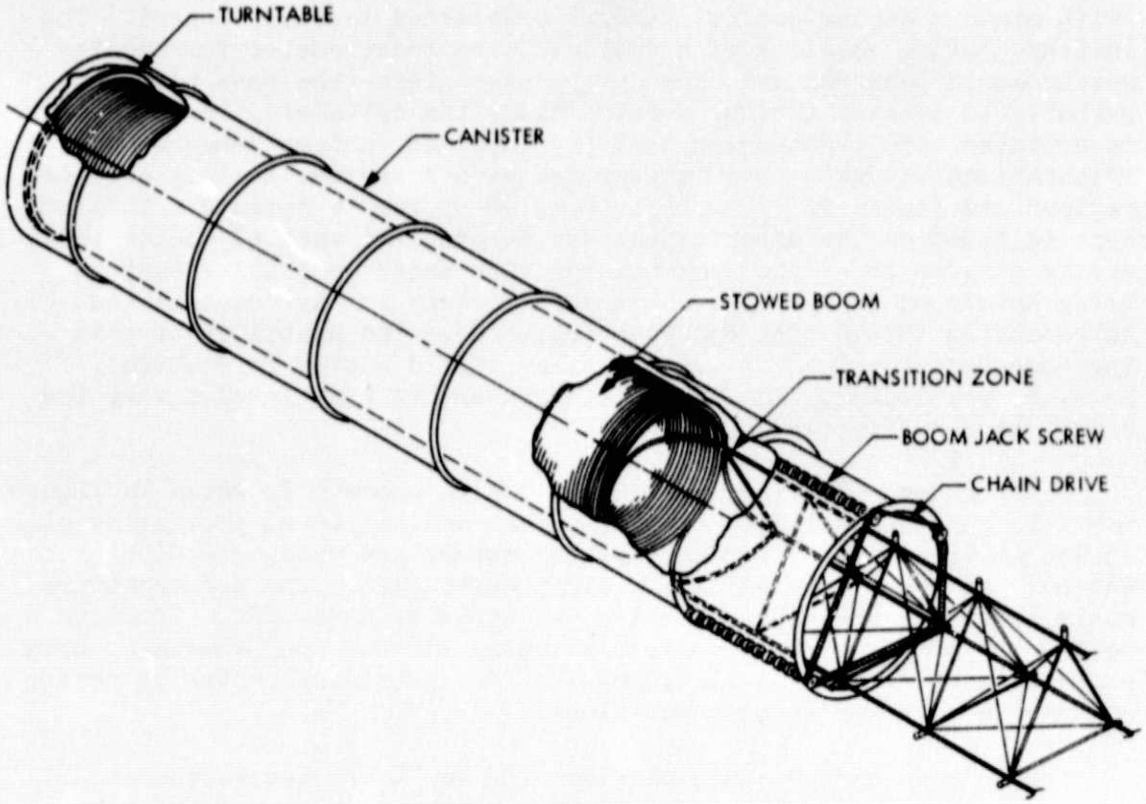


Figure 5-1. 115-m boom and canister assembly

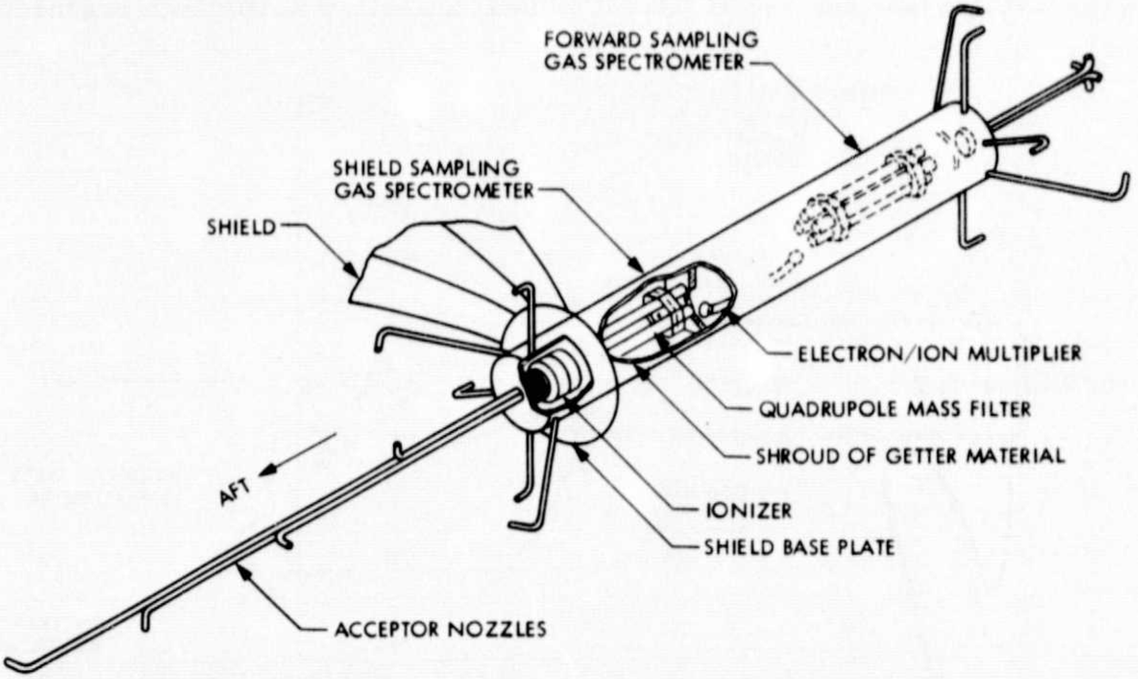


Figure 5-2. Dual gas spectrometer with acceptor nozzles

(with minimum contamination) was not considered in this concept. The instrumentation consists of a dual gas mass spectrometer for density measurements internal and external to the shield (the base plate would probably be located further forward along the cylinder). Each ionizer is equipped with right-angle sampling tubes of various lengths and orientations and each tube is provided with a shutter so that selected regions and fields of view can be sampled by remote command. This concept is based on the experimental and theoretical work of Kleber (Ref. 17) and is similar to a mass spectrometer with acceptor nozzles that is being developed by the German Research Society for Aeronautics and Astronautics (DFVLR) for Spacelab (Ref. 18). The usability of this Spacelab-based design for the molecular shield system is doubtful, however, particularly for internal measurements that involve very low densities and reactive gases.

A perhaps more viable precursor design concept is shown in Figure 5-3. This design utilizes the deployment and retrieval provisions discussed in Section IV. Two mass spectrometers are used, one within the shield, the other forward of the electronics unit. The spectrometers could be of the type that is being developed by NASA-LaRC. If it is desired to obtain different viewing angles for the spectrometers, they could be mounted on tilt platforms that could then be driven by remote command to selected angular positions.

Such a precursor could be flown for an "ambient-atmosphere characterization" mission, a desire for which has been expressed by a number of science users. When flown in conjunction with an extendable/retractable, steerable boom, gas species and their density could be determined outside and inside the shield for varying shield-system attitudes and shield-to-spacecraft proximities; it would also act as proof-of-concept for the molecular shield and allow a thorough engineer-

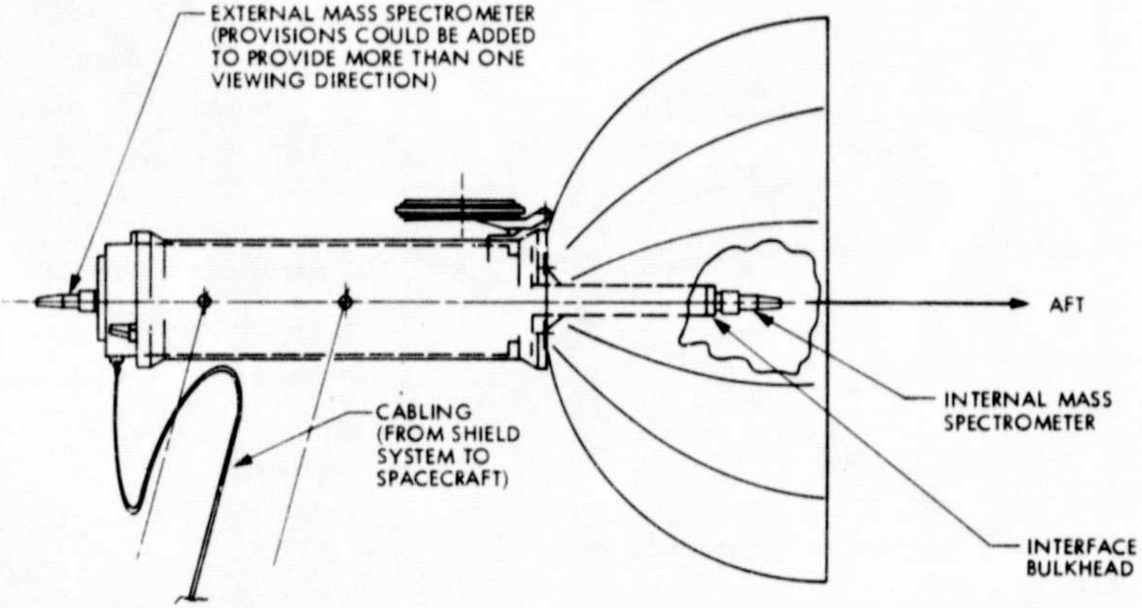


Figure 5-3. Molecular shield system precursor concept

ing validation of this design. This concept does not, however, allow for admitting an atomic-oxygen beam into the shield. A shield system, perhaps of the type discussed in Section IV, and of a considerably more complex design (possibly even including optical spectrometry instrumentation for a more complete characterization of the beam) could be substituted to supply these provisions, or, better, be designed and flown on a follow-on precursor mission. An early Shuttle flight of the simpler system (see Figure 5-4) may well be a desirable first step to a possible molecular shield program.

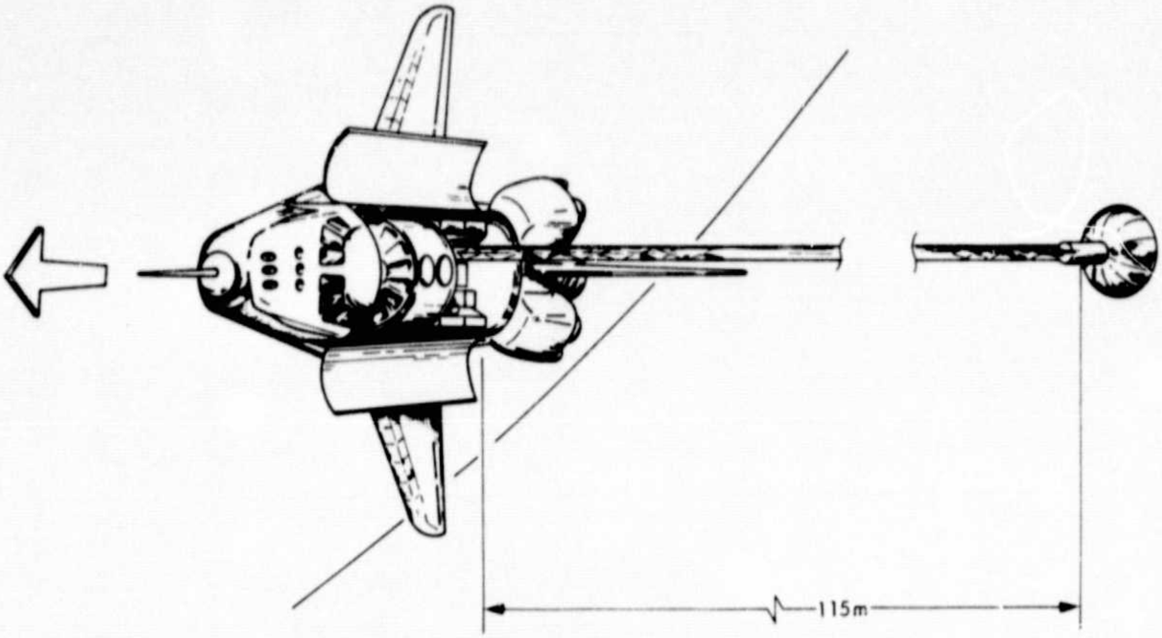


Figure 5-4. Precursor flight concept

REFERENCES

1. "CIRA 1972, COSPAR International Reference Atmosphere"; Akademie-Verlag, Berlin, 1972.

2. Youngblood, J. W., Outlaw, R. A., Melfi, L. T., Jr., and McIlhaney, J. R., "An Orbiting Molecular Shield Vacuum Facility: A Materials Laboratory in Space"; Am. Astron. Soc. Paper No. 75-248, 1975.

3. Melfi, L. T., Jr., Outlaw, R. A., Hueser, J. E., and Brock, F. J., "Molecular Shield: An Orbiting Low-Density Materials Laboratory"; J. Vac. Sci. Technol., Vol. 13, No. 3, May—June 1976.

4. Hueser, J. E., and Brock, F. J., "Theoretical Analysis of the Density Within an Orbiting Molecular Shield"; J. Vac. Sci. Technol., Vol. 13, No. 3, May—June 1976.

5. Melfi, L. T., Jr., "Characteristics and Potential Applications of Orbiting Ultrahigh Vacuum Facilities"; paper presented at XXVIIth Internat. Astronaut. Congress, Anaheim, Calif., 1976.

6. Hueser, J. E., Park, S. K., and Brock, F. J., "Effect of Experiments on the Density Distribution in a Molecular Shield"; J. Vac. Sci. Technol., Vol. 14, No. 5, Sept.—Oct. 1977.

7. Outlaw, R. A., "Orbiting Molecular-Beam Laboratory"; J. Vac. Sci. Technol., Vol. 14, No. 6, Nov.—Dec. 1977.

8. Buetefisch, K. A., and Koppenwallner, G., "An Orbital Research Facility for Rarefied, Reactive and Plasma Flows (Orbitaler Stroemungsversuchsstand)," paper presented at Rarefied Gas Dynamics Conference, Cannes, 1978; DFVLR-AFA, Goettingen, W. Germany, 1978.

9. Chuan, R., "Vacuum Environment for Scientific Studies"; Report 2000-39, 1978. Jet Propulsion Laboratory, Pasadena, Calif. (JPL internal document).

10. Melfi, L. T., Jr., and Brock, F. J., "Molecular Beam Techniques Applied to Mass Spectrometric Thermospheric Density Measurements"; Rev. Sci. Instrum., Vol. 44, No. 10, Oct. 1973.

11. Melfi, L. T., Jr., Brock, F. J., and Brown, C. A., Jr., "A New Approach to Mass Spectrometer Measurements of Thermospheric Density"; NASA TN D-7711, NASA, Washington, D.C., Sept. 1974.

12. Grunthaner, F. J., Lewis, B., and Norton, H. N., "Material Analysis Instrumentation System for Vacuum Research Facilities"; New Technology Transmittal No. NPO-14702, NASA Pasadena Office, CA, 1979.

13. Czanderna, A. W., Editor, "Methods of Surface Analysis"; New York: American Elsevier Publishing Co., Inc., 1975.

14. Interoffice Memo dated 11/11/78, M. P. Sinha to H. Norton IOM No. 382-1-78, Jet Propulsion Laboratory, Pasadena, Calif. (JPL internal document).

15. Maserjian, J., Grunthaner, F. J., and Norton, H. N., "A Molecular-Wake-Shield Precursor Design"; New Technology Transmittal No. NPO-14598, NASA Pasadena Office, Calif., 1978.

16. "Final Report on Conceptual Analyses of Extensible Booms to Support a Solar Sail," prepared by AEC-Able Engineering Co. under JPL Contract 954700; AEC-R-7715/1064, 20 Oct. 1977; NAS 7-100.

17. Haefer, R. A., and Kleber, P., Le Vide (Vacuum — French) No. 181, Jan.—Feb. 1976.

18. Joo, F., "Measurement of Molecular Flow Fields in Spacelab Pallets," in Proceedings of the 7th Internat. Vacuum Congress, Vol. I, p. 337, R. Dobrozemsky, Vienna, 1977.

NASA–JPL–Coml., L.A., Calif.