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UPPER ATMOSPHERE INTERACTIONS WITH SPACECRAFT*

by

K. M. Foreman
Geo-Astrophysics Section

and

R. A. Oman
Fluid Mechanics Section

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Approved by: Charles E Mack Jr
Charles E. Mack, Jr.
Director of Research

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K. M. Foreman and R. A. Oman

Research Department
Grumman Aircraft Engineering Corporation
Bethpage, New York 11714

INTRODUCTION

Successive generations of larger and more complex Earth satellites will require greater precision in orbital position, attitude and lifetime prediction, especially during the pre-flight planning phase of the program. Current predictive capability is limited by gross uncertainties about the aerodynamic forces and torques, and upper atmospheric structure involved in orbiting above 160 km altitude. In this portion of the atmosphere, Earth satellites may be considered as always in the free molecular flow regime.

Pre-flight calculations of aerodynamic forces, $F = C_F \rho A V^2$, acting on any satellite configuration may have an uncertainty as large as ± 65 percent to 80 percent, with current technology. A major part of this lack of confidence arises from roughly a ± 50 percent uncertainty in the local atmospheric density, ρ, at any given orbital position and time. The effective aerodynamic drag coefficient of the satellite, C_D, passing through the rarefied gas at orbital speeds can be estimated to roughly ± 15 percent, and the magnitude of velocity, V, and effective satellite surface area, A, contribute, for simple shapes, about ± 1 percent and ± 5 percent uncertainty, respectively. As more data become available, from the tracking of the decay of simply-shaped satellites or direct probing by research rockets, our statistics, and hence our knowledge, of the upper atmosphere's aerothermochemical properties improves. Likewise, for any given satellite configuration, once in orbit, we can extrapolate a posteriori its long term positional and attitude characteristics with, perhaps, a "hard core" uncertainty of ± 20 percent. Current determinations of atmospheric density above 160 km usually result from many careful measurements of orbital decay (dependent on $\rho C_D A$). If a consistent value for $C_D A$ is assumed, the computed values of relative atmospheric density will be consistent. But until an independent determination of all elements of $(\rho C_D A)$ is made, the absolute atmospheric density computed will be uncertain by at least the same percentage as C_D.

The influence of uncertainty in gas-surface interaction parameters on satellite drag coefficients has been widely discussed (e.g., Ref. 1). It is generally accepted that errors of the order of 20 percent may be present, but more probable uncertainties for spheres are ± 10 percent. A much more serious problem arises, however, when one examines the question of torques on a stabilized vehicle in a low orbit, or the forces on irregular shapes such as experienced with satellites mounting large solar-cell paddles. Differences in the nature of the gas-surface interaction can alter the relative magnitudes of normal and tangential forces on surfaces at small local angle of attack by dramatic amounts. Predictions by extensive numerical experiments(2-6) under conditions representative of satellite environments routinely show cases which vary in normal force by more than 100 percent of the free-stream normal momentum and streamwise forces which vary by as much as 25 percent of the streamwise momentum. In few cases are the "classical" situations of completely accommodated, diffuse reflection or completely unaccommodated specular reflection relevant to the results, even for simulated engineering surfaces. Experimental data on forces or the features which determine them are not yet available for satellite conditions although there are many extensive programs under way to conduct such experiments.(7,8)

In addition to the effects on forces (energy transfer does not appear to pose an important design problem), we must also face the question of sampling of upper atmosphere constituents. Ignorance of the effects of interactions with surfaces in the sampling process greatly limits our ability to determine, for example, the local ratio of O to O_2. Other effects associated with selective adsorption, desorption, or recombination at surfaces interacting with high energy incident particles may also be important.

The logical action to diminish the uncertainties of the GSI problem lies in:

1. improving our understanding of the process and obtaining good general empirical data, such as momentum and energy accommodation coefficients and reflected molecule density distribution, appropriate to satellite operational conditions; and

2. using the acquired information to compute more precise and meaningful predictions of the aerodynamic behavior of specific satellite configurations in the upper atmosphere.

In this report we discuss the relevant basic issues of gas-surface interactions. From this point of departure we describe the basis for selecting GSI experiments for a satellite including considerations of the mission plan and upper atmospheric properties profile, which lead to a conceptual satellite-borne GSI experiment package for deployment in Earth orbit.

GSI CONSIDERATIONS

There are several crucial points that must be emphasized in considering the modern view of gas-surface interaction on a satellite's surface, and experiments to determine the nature of these interactions.

First, the type of interaction that can be encountered may range from almost complete adsorption, with accompanying lack of recoil momentum, to a reflection with very nearly the initial kinetic energy, and a normal directional component of momentum as much as 20 percent greater than the initial normal momentum. The point here is that radically different types of behavior are possible for different surface and gas species, even for an initial gas velocity of the order of 10 km/sec (i.e., orbital).

Second, the diagnostic tools available to us are very crude when compared to the need for determining mean momentum coefficients, let alone the states of molecular distributions. Because of this, we must seek to use as many different simultaneous measurements as possible in order to have a real understanding of the results of any one test. For example, one instrument presently available(9) appears capable of measuring the gas density field reflected from a surface. Another concept(10) shows promise of being able to measure velocities of reflected gas particles, but would be useful only for certain species of the atmosphere mixture. There is no a priori relationship between measurements of density and velocity which would enable one to compute momentum exchanges or other quantities of engineering interest without measurement of both or related quantities. The basic decision as to the feasibility of a scattering experiment in an orbiting vehicle currently depends on the successful demonstration, on the ground, of enough workable methods for measuring sufficient related quantities which, when examined together, can be expected to describe the gas-surface interaction. These methods must be mutually compatible, and must possess the necessary sensitivity, signal/noise ratio, and reliability to be acceptable for an orbital mission.

The third major point to be emphasized is the requirement that the test surface either be completely known (a highly improbable situation), or directly related to the kinds of surfaces for which GSI data would be useful. We tend to favor the latter approach in the belief that the former requirement exceeds present technological capability even in ground-based laboratories. Above all, we feel that no single space experiment should be viewed as a panacea for all GSI problems. A more realistic objective is to obtain a sampling of how a few typical surfaces (e.g., tungsten single crystals, nickel, aluminum, solar cell surfaces, thermal control coatings, gold plated structural metals) behave under environmental conditions which previously have been totally inaccessible. If the work is carried out with skill, this information from a single experimental program could be useful for correlating, extending, and generalizing the limited understanding gradually taking shape from the painstaking efforts of many ground-based research centers. What should be avoided, however, is a ready acceptance of excessive compromise which would yield information that is devoid of relatively wide-spread applicability.

EXPERIMENT SELECTION

In view of the obvious costliness of mounting a satellite launch, the inadequacy of ground-based investigations within comparable economic bounds clearly must be shown before an orbital experiment can be justified. In addition, a strong engineering or scientific demand must exist for the type of special information anticipated from an orbital experiment.

Cursory examination of the many alternative GSI experiments possible reveals that an experiment on surface scattering is highly desirable from an engineering viewpoint, while an experiment on environmental alteration of surfaces is indisputably justifiable from the standpoint of inadequate ground-based test capabilities. There remains, however, a certain element of doubt as to whether enough test conditions in an orbital experiment can be defined so that data of permanent scientific value (as differentiated from engineering value) can be obtained.

The one type of GSI experiment that clearly cannot be done adequately on the ground is an investigation of the changes that are produced in the relevant properties of typical surfaces by protracted exposure to an orbital environment. The best laboratory and theoretical treatments of this problem fall very short of realistic simulation of the features essential for reproducing the history of a surface in orbit. The condition of the outermost layers of the surface is known to be a major factor in determining the nature of the gas-surface interaction.(2-7) Atomic oxygen (a major component of the atmosphere in the 200 to 1000 km region) is the most important potential surface contaminant because it has very strong chemical attraction to most of the materials likely to be used, and to itself as well. There is presently no way to determine how often the recombination of two oxygen atoms at a surface will release enough energy into the translational motion of the molecule to allow desorption. If this were to be a favored process, the surfaces exposed to a space environment would be quite clean. If it were not, the surfaces would be covered with one or more layers of adsorbed gas, which would result in very high energy accommodation, and a low exit momentum for reflected atoms and molecules. Coupled with this type of uncertainty are other unknown contributions of the real orbital environment such as solar radiation, bombardment by high energy particles, etc.

A second type of GSI experiment that should prove to be very valuable is a molecular beam scattering experiment. The main advantage of an orbital test over an earth-bound experiment lies in the opportunity to achieve real conditions in the beam source; its species concentration, energy distribution, and over-all density level. The obvious difficulties of a remote-controlled test operation and the data extraction requirements in orbit make this over-all concept somewhat harder to justify in the face of increasing progress in ground-based techniques,(11) but nevertheless it deserves consideration.

MISSION PROFILE

The objective of establishing a mission profile is to prescribe an atmospheric environment which is best suited for gas-surface interaction experiments in orbit. The considerations that influence suitability include:

a) knowledge of the mean atmospheric properties
b) spatial and temporal variations of the atmospheric environment
c) instrumentation characteristics

d) time available for individual measurements
e) time available for entire program
f) special orientation requirements of experiments
g) tracking and telemetry ability
h) launch vehicle capability
i) relevance of test conditions to ultimate usefulness of information

The Atmosphere

For most considerations, the atmosphere above about 120 km exhibits cyclic as well as irregular variations in density profile, temperature, pressure, and composition.(12,13,14) It is sufficient to categorize for this study the following types of observed density variations:

I — At a fixed global location

- a) altitude
- b) diurnal
- c) monthly (27-day cycle)
- d) seasonal
- e) semiannual
- f) solar decimeter radiation (11 year cycle)
- g) solar extreme UV
- h) magnetic storm (irregular)

II — Latitude position

III — Auroral activity (high latitudes)

The changing relation of the earth's orbital position and the sun's activity make it impossible to predict precise atmospheric properties at all times and at any particular altitude. Therefore, model atmosphere profiles are useful primarily as convenient typical values for preliminary guidance rather than a serious attempt to define the actual test situation environment. The distinction is emphasized here because in a rarefied gas-surface interaction the precise properties of the gas (e.g., velocity distribution, composition, number density, etc.), and the concurrent condition of the surface, have an enormous effect on the outcome of the interaction process in progress at that time. It might be added that the surface condition, insofar as it presumably represents the result of the integration of previous GSI processes since initial exposure, also is influenced by short term variations of the atmospheric and radiation environment that are not normally accountable in standardized atmosphere profiles.

It becomes evident once these facts are appreciated that the detailed design of a mission profile must be linked with, at least, the expected solar activity period that the orbital flight is likely to take place. To assure further that the environment conditions of an orbital test are reasonably well known, it appears almost essential to prescribe suitable aeronomy instrumentation in any satellite payload containing primarily GSI experiments. From past experience we know this instrumentation is feasible.(15)

The atmospheric model used in this study for orbital dynamics calculations has been based primarily on recent updated determinations derived from over 50 satellite orbit decay studies.(13,18)

Another atmospheric property important to GSI experiments is the composition of the neutral gas.* Certainly a predominantly atomic oxygen atmosphere will be more reactive than a molecular nitrogen environment. Unfortunately, it is precisely in this area that a great deal of controversy persists; the probable reason for the many contradictory

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*Although ionic species and electrons also exist in the upper atmosphere, and produce important electrodynamic effects, they are smaller in concentration by at least a factor of 10^4 compared to the neutrals. As such, they may be neglected from aerodynamic considerations. Ions can be removed fairly easily, e.g., by an electrostatic field, from the molecular beam created for GSI experiments in orbit.

observations(15,16,17) of atomic oxygen concentrations at altitudes between 120 and about 200 km may lie with GSI processes in the instrumentation, e.g., surface recombination. Thus, it becomes additionally significant to have redundant techniques of determining the local orbital gas composition concurrent with the GSI experiment. Not only would such measures increase the confidence of knowing the environmental conditions under which GSI data would be obtained, but they could be designed to yield correlating data with the primary GSI experimental equipment.

The apparent diurnal variation of atomic oxygen to molecular nitrogen concentration ratio(16,19) and total local number density may yield different GSI results as the orbital perigee precesses from the daylight to night regions. However, for guiding GSI instrumentation measurement threshold and dynamic range, the adopted atmospheric density and composition model profiles should encompass the maximum and minimum extremes likely to be encountered during the lifetime of the program. This objective is achieved by using the highest density atmosphere model (i.e., 1400 hours, active sun) at the lowest altitude for which the mission could be conducted, and the lowest density atmosphere model (i.e., 400 hours, quiet sun) at the highest likely altitude of testing (see Table 1). Any departure from these assumed models during an actual orbital mission would represent enhanced instrumentation capability that might be used for greater measurement accuracy and/or greater trajectory variability.

TABLE 1

ASSUMED ATMOSPHERIC CHARACTERISTICS FOR GSI INSTRUMENTATION PERFORMANCE REQUIREMENTS (AFTER REF. 12)

	Maximum Density Atmosphere					Minimum Density Atmosphere				
Alt.	ρ gm/cm^3	n_{TOTAL} cm^{-3}	$n(N_2)$ cm^{-3}	$n(O)$ cm^{-3}	$n(O_2)$ cm^{-3}	ρ gm/cm^3	n_{TOTAL} cm^{-3}	$n(N_2)$ cm^{-3}	$n(O)$ cm^{-3}	$n(O_2)$ cm^{-3}
		$\times 10^{10}$	$\times 10^{10}$	$\times 10^{10}$	$\times 10^{10}$		$\times 10^{9}$	$\times 10^{9}$	$\times 10^{9}$	$\times 10^{9}$
140	3.5×10^{-12}	7.9	5.6	1.4	.88					
160	1.5×10^{-12}	3.6	2.4	.77	.35					
180	9.0×10^{-13}	2.2	1.4	.54	.19					
200	5.8×10^{-13}	1.4	.88	.40	.11					
220	3.8×10^{-13}	.95	.57	.31	.07	4.6×10^{-14}	1.4	.40	.97	.03
240	2.6×10^{-13}	.67	.38	.24	.04	2.3×10^{-14}	.74	.16	.57	.01
260						1.3×10^{-14}	.42	.07	.35	$< 10^{-2}$
280						7.0×10^{-15}	.24	.03	.21	$< 10^{-2}$
300						4.0×10^{-15}	.14	.01	.13	$< 10^{-3}$
350						1.1×10^{-15}	.041	.001	.04	$< 10^{-4}$

A point might be made about the control of satellite outgassing which is a source of local atmospheric composition anomaly and randomly occurring surface contamination. The outgassing burden should, preferably, be minimized prior to launch by attention to the design selection of primary and secondary structural materials, by care in the manufacturing and assembly of the satellite systems, and by prelaunch conditioning in a proper thermal-vacuum facility.

An additional point should be introduced concerning manned spacecraft. An obvious application of better GSI data would be to improve orbital position and lifetime prediction of manned satellites. Such applications inherently introduce the reality of never achieving a fully outgassed vehicle. In addition, there is the likely situation that certain gaseous contaminants such as H_2O, CO_2, H_2S, NH_3, and hydrocarbon-halogen compounds may be emitted at random intervals during the flight. Under such contamination conditions, the spacecraft surfaces are likely to behave differently than for identical unmanned vehicles. It thus becomes of interest to conduct at least some GSI experiments in conjunction with scheduled manned flights of the Apollo and MOL programs. These special tests could be of value despite the ultimate need for comparative GSI data employing a specially designed unmanned satellite.

Orbital Parameters

One of the prime concerns for orbit selection is the assurance that the GSI experiment will be exposed to a free-molecular gas flow regime. This establishes an altitude of about 160 km as the lower limit for any practical GSI experiment. However, for all but a highly eccentric orbit, the satellite lifetime is very short (i.e., on the order of a day) at this altitude and yields a mission with low cost effectiveness.

As the design perigee altitude is increased, two important trends start competing. The orbital lifetime increases with perigee increase but the measurement capability rapidly approaches a sensitivity threshold because of decreasing atmospheric density. The determination of maximum perigee for a GSI experiment, then, represents a compromise of these considerations biased to the best estimate of instrumentation performance. Some flexibility in obtaining a desired lifetime may still be exercised by suitable design of the satellite ballistic coefficient, (M/C_DA), where M is the satellite mass, C_D is the average drag coefficient at near-perigee conditions, and A is the effective cross-sectional area of the satellite.

The instrumentation currently in use in the Grumman molecular beam apparatus(9) is capable (with some modification) of measuring scattered density distributions formed from a source corresponding to an altitude slightly in excess of 230 km for a minimum density atmosphere at night. The day-to-night density ratio is approximately 1.5 for quiet sun(13) so that an initial operational altitude of 240 km may be associated, during daylight, with a minimum density atmosphere. Therefore, an initial perigee of 240 km is just compatible with existing density measurement technology for incident mass flow, under minimum, quiet-sun atmospheric conditions. Development of more sensitive instrumentation than current state of the art similarly would permit higher perigee or an increased signal level to be employed. Lifetimes of 30 or 300 days would necessitate ballistic coefficients of 1.63 slugs/ft^2 and 16.3 slugs/ft^2, respectively. The orbital period would be approximately 90 minutes.

Longer lifetimes can be achieved also by establishing low eccentricity orbits to reduce the time of atmosphere-induced orbital decay near perigee. Additional benefit can be derived from gas venting opportunities possible in the greatly reduced atmosphere surrounding the apogee position.

One constraint on the apogee consideration is the Van Allen radiation belt located beyond about 1000 km altitude. The large concentration of energetic particles in this belt presents potential environmental hazards to GSI electronic instruments that may result in distortion or even complete frustration of any measurements.

A reasonable criterion for minimum apogee selection is that a monolayer of atmospheric species would take about 1000 seconds to form on a clean surface. This rule links the apogee (through the atmospheric density) to the prevailing atmosphere profile at the time of the mission. For conditions similar to a low density atmosphere model, the apogee should be at least at 400 km; for a medium density model the apogee should be at least at 550 km, and for a high density model atmosphere the apogee should be at least at 700 km.

Table 2 shows some typical orbit characteristics and requirements resulting from the three apogee possibilities discussed above, and an initial perigee of 240 km.

TABLE 2

SOME TYPICAL ORBITAL CHARACTERISTICS FOR A GSI EXPERIMENT SATELLITE

Condition	Initial Perigee, km	Initial Apogee, km	Eccentricity, %	Satellite Lifetime, days for $M/C_DA = 1.0$	M/C_DA Required for Lifetime of	
					30 days	300 days
1	240	400	1.20	~ 20	1.5	15
2	240	550	2.29	~ 45	.75	7.5
3	240	700	3.37	~ 75	.40	4.0

If it is assumed that the launch site will be at Cape Kennedy (28.5° north latitude), with a maximum inclination angle of 30°, the bulk of the experimental data will be obtained for equatorial atmospheric conditions (assuming no complex in-flight trajectory changes by on-board propulsion).

Thus, major orbital perturbations caused by earth oblateness, seasonal variations of the atmosphere, and high latitude auroral or magnetic storms phenomena are virtually eliminated as areas of concern. The molecular beam produced by transit through the perigee atmosphere is more likely to be repeatable in the equatorial zone than at high latitudes. This is a highly desirable situation for the basic GSI experiments. However, many anticipated applications of earth satellites are likely to have initially high inclination orbits. Eventually, orbital precession should expose these future satellites to the same latitude environments projected for the GSI experiments. Therefore, the mission profile test conditions have relevance, although not complete, to the ultimate application of the GSI data to be obtained.

EXPERIMENT PACKAGE CONCEPT

A consequence of the establishment of several GSI experiment requirements and the design features for two principal experiments,(18) is the formulation of a conceptual experimental package for a satellite (see Fig. 1). Although certain elements of the

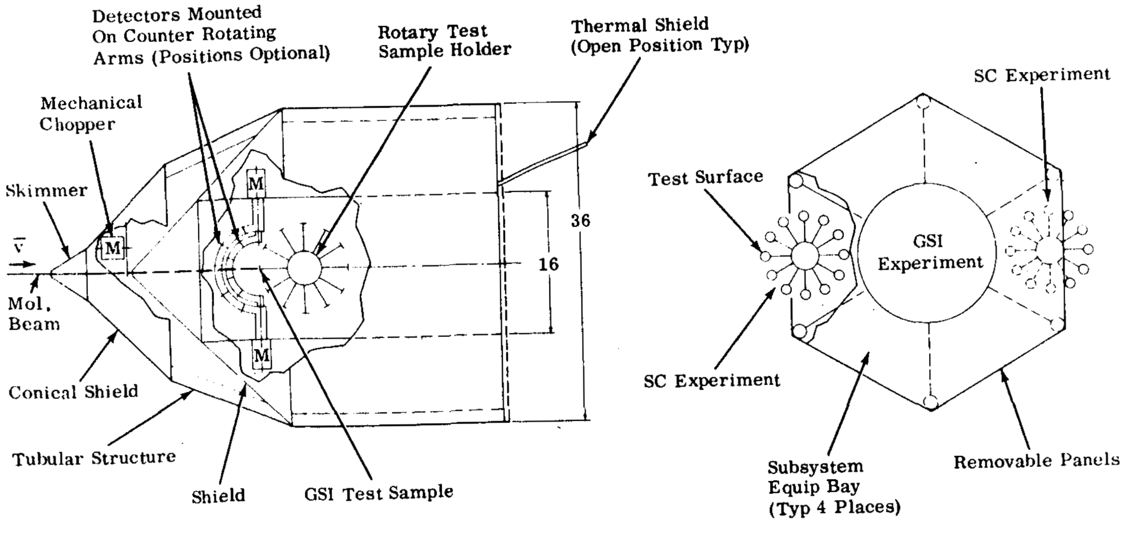

Fig. 1 Two-View Schematic of Gas-Surface Interaction (GSI) Experiment Package Concept for Orbital Flight

experiments must still be developed, this package concept becomes a first step in providing direction to a future satellite system involving several complimentary experiments. It is assumed (with reasonable substance) that eventual technological development, to provide certain currently unfilled measurement capability, will be accommodated within the geometric constraints of this package concept. A description of the features of this package concept is given in Appendix A.

Attitude Control System

A satellite containing GSI experiments must be able to align the beam-forming orifice within ± 2 degrees of the orbital velocity vector during the data-taking period (i.e., near perigee). The conventionally used technique of reaction jet attitude control is inappropriate in this instance because the exhaust gas products would very likely contaminate the test surfaces and compromise the investigation of natural GSI processes. Helium jets might be acceptable if extraordinary contamination control were exercised and they could provide sufficient total impulse for the mission. To meet these alignment and contamination-free requirements, the active control moment gyro system and the passive gravity gradient with aerodynamic damping hybrid system both hold promise. However, more analysis of acquisition or capture dynamics is needed before a judgment based solely on performance is possible.(18)

CONCLUSIONS

Design engineering requirements of future Earth satellite systems establishes a demand for better than currently available gas-surface interaction data, under satellite operational conditions. Laboratory and analytical treatments of the GSI problem will require orbital confirmation, especially in the environmental effects on surface conditions. An orbiting GSI research facility would overcome many of the current obstacles frustrating the resolution of this problem. We conclude that:

1. The condition of the solid surface is a vital factor in the interaction process. It is important, and presently appears to be feasible to conduct experiments in orbit to examine the changes of surface characteristics brought about by exposure to the orbital environment.

2. A molecular beam scattering experiment in orbit is highly desirable but we do not feel it is currently feasible. The principal deterrent is the lack of a demonstrated time-of-flight velocity measurement technique for the reflected molecules, under orbital conditions. A method of measuring molecular density distribution under these conditions appears feasible with no major additional technological advances.

3. It is desirable and feasible to have aeronomy instrumentation accompany any orbital GSI experiment in order to obtain a concurrent in situ definition of the atmospheric properties under which the interaction experiment is conducted.

4. A nominal initial perigee of 240 km and orbit initial eccentricity of between 1.5 and 3.5 percent is indicated for proposed GSI experiments. The exact mission plan will depend largely on the launch date relation to solar activity since the latter profoundly influences the density profile of the upper atmosphere.

A gas-surface interaction experiments package concept has been devised as a first step toward defining a future satellite system configuration. Although we believe it is presently premature to implement the entire package, it is reasonably certain that additional work to develop instrumentation and techniques can soon change this status. When this occurs, we can look forward to some enlightening satellite experiments that could have a far-reaching influence on our future aerospace programs.

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APPENDIX A

DESIGN FEATURES OF THE GAS-SURFACE INTERACTION EXPERIMENT PACKAGE CONCEPT

The reflected beam experiment of the package (see Fig. 1) features a beam-forming skimmer, with auxiliary shield, that permits the upper atmospheric molecules, traveling at an orbital speed of about 8 km/sec to enter through the orifice and intermittently impinge upon the target surfaces after passing through a chopper. The conical shield acts to deflect misaligned molecules away from the experimental equipment, as well as to protect against radiation and micrometeoroid penetration. The measurements are made during near-perigee conditions. A moderate-to-low speed (i.e., ~ 100 Hz) chopper behind the skimmer provides suitable fiduciary signals to allow density measurements of reflected gas molecule distributions. Venting of the initially deflected molecules occurs through the open section immediately following the front conical shield. The rotary test sample holder is to be indexed after a predetermined period of exposure, or number of orbits. The detectors, on the other hand, are mounted on two movable yokes that can be rotated to different angular poiitions for reflected beam measurements. The counterrotating yokes also can serve to support other diagnostic devices such as mass spectrometers.

The 16-inch diameter, cylindrical inner passage provides an exit for the continuous outflow of unreflected beam molecules as well as randomly directed background gas. Surrounding the passage are four subsystem equipment bays and two additional bays containing other surface contamination experiments. Three movable panels hinged at the rear of the package and activated by a rearward facing sun sensor will be used to shield the GSI experiment from solar rays when the rear of the satellite faces the sun. This design would function either with or without internal cryogenic pumping. The added weight of cryogenic equipment would result, however, in a reduction of background noise for instrumentation.

The second,or surface contamination, experiment consists of two arrays of specially prepared test surfaces mounted on diametrically opposed indexing mechanisms which rotate on axes parallel to the package centerline. A sector of each array is exposed to the total orbital environment (i.e., not just perigee conditions) for a predetermined time interval before being rotated into an analytical chamber for examination of their surface properties. In one chamber, a portion of each exposed surface may be desorbed by one of several techniques. The efflux would be monitored by a scanning mass spectrometer as a means of assessing relative surface absorptivity characteristics during the satellite lifetime. The second analytical chamber provides the opportunity for independent measurements of surface potential and/or surface reflection characteristics for a thermal energy helium gas beam after increasingly longer periods of surface exposure to the orbital environment. As a new test surface moves into the analytical chamber, another is rotated outside the experiment bay to join those exposed to the natural environment.

Structural support of the experiment package is provided by six longitudinal tubular members and cross-members to the internal cylindrical passage. The outside panels for each of the equipment bays are removable for ease in subsystem preflight checkout and servicing. The 36-inch maximum cross section dimension provides a reasonably small projected area in comparison to any of the Saturn class launch vehicles and should be a minor disturbance to the rocket's flow field.