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A STUDY ON GAS MOLECULE-SOLID SURFACE INTERACTION SATELLITE EXPERIMENT FEASIBILITY

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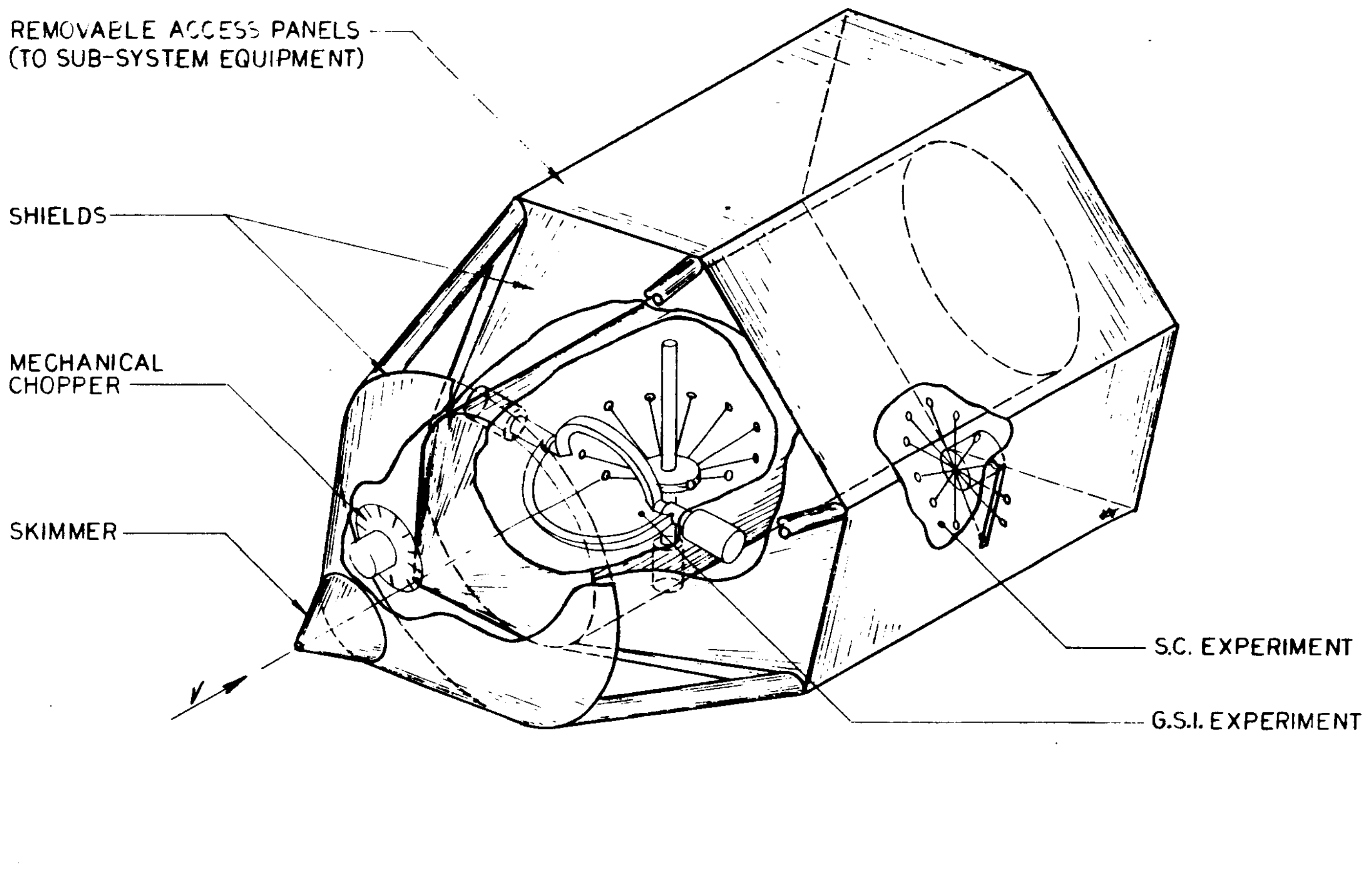

SATELLITE PACKAGE
FOR RAREFIED GAS-SURFACE INTERACTION EXPERIMENTS

Frontispiece

ACKNOWLEDGMENTS

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FOREWORD

As we progress through successive generations of larger and more complex earth satellites, the demands for greater precision in orbital position and lifetime prediction become more compelling. The accuracy of these determinations is a difficult hurdle, particularly where atmospheric drag assumes importance, because of our uncertain knowledge of the atmosphere's properties. Compounding the problem is our current inability to compute with accuracy the effective drag of a satellite passing through the rarefied gas at orbital speeds. One key to better prediction of satellite drag lies in improving our understanding of the rarefied gas-solid surface interaction (GSI) process and having reliable general empirical information with which to apply to specific satellite configurations.

This report results from a feasibility study, of the ability to conduct GSI experiments in orbit, sponsored by NASA, George C. Marshall Space Flight Center under Contract NAS 8-21090. Mr. Robert E. Smith and Mr. James O. Ballance have been the technical monitors for NASA under this contract.

ABSTRACT

The feasibility of conducting two types of gas-surface interaction (GSI) experiments in an earth satellite is examined. The primary point of view is the ability to determine the angular distribution of reflected gas molecule density, momentum, and energy accommodation.

The engineering need and feasibility are established for experiments designed to examine the changes in solid surface properties arising from exposure to the natural orbital environment. Surface condition is considered a vital factor in rarefied gas interaction processes. Some laboratory development effort is still needed, however, to standardize techniques for characterizing various kinds of surfaces and to demonstrate long term storage of clean surfaces in orbit.

A satellite-borne experiment of the molecular beam scattering type is highly desirable. However, this experiment cannot be considered feasible until a suitable technique is demonstrated for measuring the velocity of reflected molecules at orbital conditions. It should be added, in contrast, that measurement of molecular density distribution appears feasible within current technology, although demonstration of a proposed innovation to improve the sensitivity of an existing instrument is still needed.

An examination is made of recent data on profiles of atmospheric density and its influence on the design of a mission plan. Although details of the plan will be influenced by ultimate choice of the launch date, a nominal orbit of 240 km initial perigee with 1.5 to 3.5 percent eccentricity is indicated for the GSI experiments. It is recommended that a supporting aeronomy experiment be conducted concurrent with the GSI experiment to define the precise properties of the atmosphere during test.

To aid in defining a future satellite system configuration, a GSI experiments package concept is presented, although it is recognized as presently premature for implementation.

Recommendations are made for a four part development program to resolve several important questions revealed by the study and to make possible the expeditious exploitation of future technological advances in measuring gas molecule velocity distribution in orbit.

TABLE OF CONTENTS

I. INTRODUCTION

The primary goal of this investigation is to assess the feasibility of conducting gas-surface interaction (GSI) experiments in earth orbit. Another objective assumed by this contractor is the evaluation of the need for such a satellite program.

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 (Ref. 1).

Cursory examination of the many alternative GSI experiments possible reveals that one type of experiment is highly desirable from an engineering viewpoint, while a second type of experiment 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 (e.g., Ref. 2). 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 such as solar radiation, bombardment by high energy particles, etc. We feel it is both important and feasible to expose an array of different surface types to the true orbital environment, and monitor over an extended time period several properties of the surfaces which might be related to gas-surface interaction processes. This proposed experiment is described in more detail in Section III.

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 obtain exact conditions of 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 overall concept somewhat harder to justify in the face of increasing progress in ground-based techniques (cf., Ref. 3). However, this orbital experiment certainly deserves continued consideration, and may prove to be a very worthwhile project if satisfactory molecule velocity measurement techniques can be developed.

The following sections describe, in sequence, requirements for the experiments, design features of the experiments, mission profile considerations, and our conclusions and recommendations arising from this study.

II. EXPERIMENT REQUIREMENTS

There are several crucial points that must be emphasized when examining the requirements of a GSI experiment.

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 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 (the through-flow ionization gauge, see Fig. 1) appears capable of measuring the gas density field reflected from a surface. Another concept (the metastable molecule time-of-flight system) may prove capable of measuring velocities of reflected gas particles, but is useful only for certain species of the atmosphere mixture. There is currently no *a priori* relationship between the measured densities and velocities which would enable one to compute momentum exchanges or other quantities of engineering interest. 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,

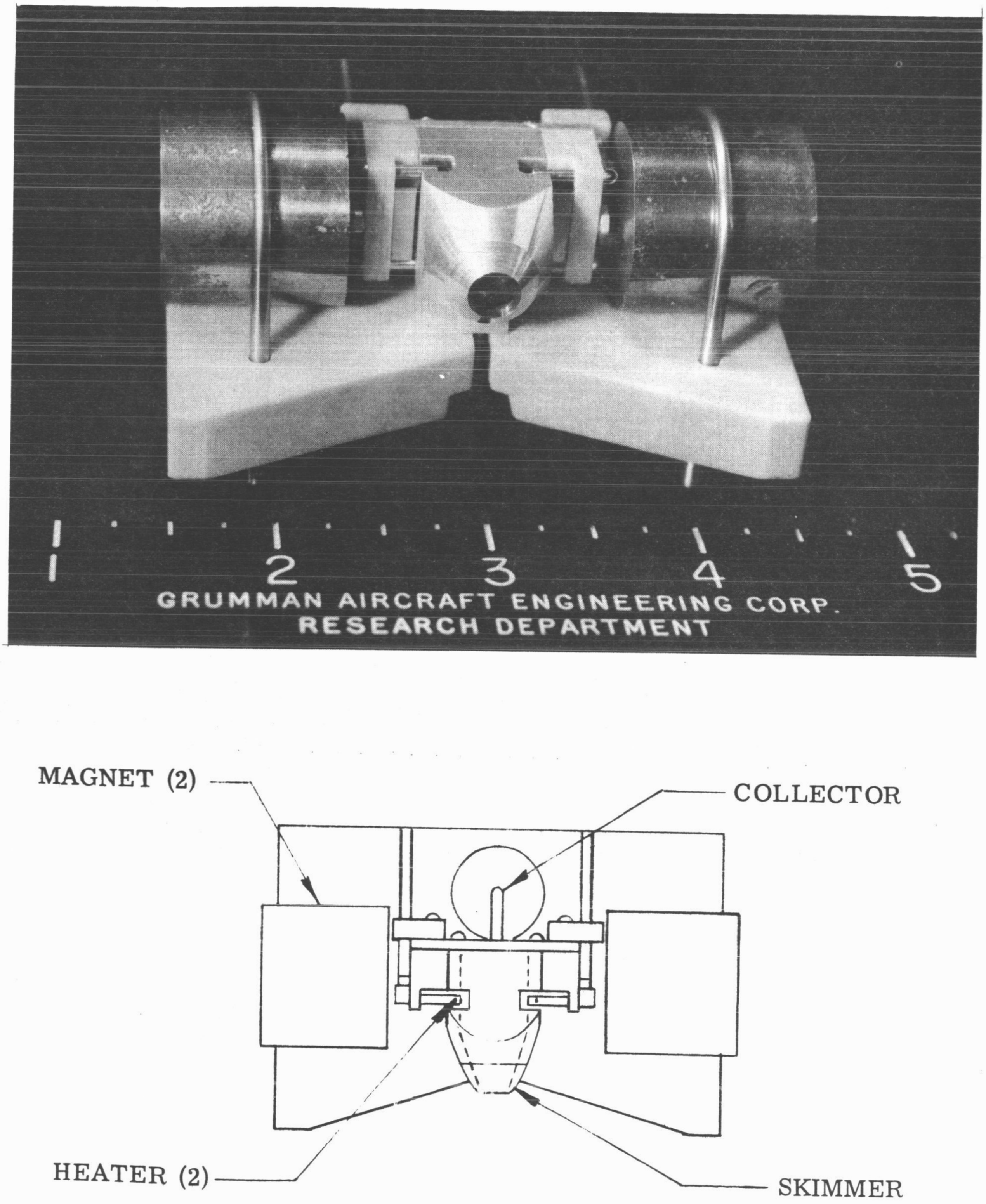

Fig. 1 Grumman Through-Flow Density
Measurement Gauge

and must possess the necessary sensitivity, signal/noise ratio, and reliability to be acceptable for the orbital mission.

The <u>third</u> major point to be emphasized is the requirement that the 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 emphasize 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 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 will 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 is a ready acceptance of excessive compromise which would yield information that is devoid of relatively wide-spread applicability.

III. EXPERIMENT DESIGN

A. Reflected Beam Experiment

The purpose of this experiment is to measure the spatial distributions of molecular density, flux, and velocity produced by the reflection of a relatively undisturbed incident flow from a well-characterized surface. The surfaces should be at several different angles of incidence, and several different surface types should be available in a single flight experiment. The impinging molecules (and/or atoms) must be composed primarily of particles which have not had a gas or solid phase collision in the vicinity of the vehicle so that they are fairly representative of the state of the incident flow on the external surfaces of a vehicle in free molecule flow.

Although there are several alternative possibilities, we have chosen the preliminary design configuration shown in the frontispiece. We believe this design offers most of the desired features in an efficient package. Its principal disadvantage relative to a "nude surface" approach is an inherently large loss in the incident beam intensity because of the skimmer-shield arrangement. Conversely, there are several advantages to our proposed design such as: better angular resolution of the incident stream, better structural rigidity, thermal control, and micrometeorite protection, and enhanced reliability through the use of redundant components. However, the fundamental question of performing this kind of experiment depends not on the configuration employed, but rather on the ultimate capabilities of the diagnostic devices to be used. It should be possible to perform a perfectly satisfactory set of experiments using either a closed or nude design approach if an acceptable method of measuring gas velocity can be devised.

The over-all spacecraft control required by this experiment is limited to alignment of the gas beam axis with the flight velocity vector at perigee. The tolerance on this alignment is not rigid, but the intensity of the beam will fall off rapidly if the misalignment becomes much greater than ±2 degrees. The expected speed ratio, S, in the atmosphere is close to 10, and the fraction of the incident flow at a given misalignment angle, $\Delta\theta$, will decay as $e^{-S^2\Delta\theta^2}$. Because of this factor and the attenuation of the beam, it will be necessary to monitor the target intensity if more than just a relative flux measurement is required.

1. Measurement of Density Distribution

It should be possible, with slight modification to established techniques, to measure the density distribution reflected from a 1 cm^2 area target exposed to a beam formed from the oncoming atmosphere, for an ambient density of 10^9 molecules/cm^3. This would allow for attenuation of the incident beam of about 100:1 and a local scattered density 0.1 of that incident on the target.* We would employ the through-flow electron bombardment ionization gauges first proposed by Hagena and Henkes (Ref. 4) and now being used successfully in our shock tube driven molecular beam. We would match each of these gauges (see Fig. 1) to an electron multiplier stage for increased sensitivity. When used with a low frequency chopper, the basic gauge has a sensitivity of 5×10^{-18} amp-molecule^{-1} cm^{+3} at 1 ma of emission current in N_2. We should be able to achieve a gain factor of 10^6 with a semiconductor type of electron multiplier. This system would give a steady (i.e., dc) current

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*$I/I_0 \approx (Sd/x)^2$, where S is the incident speed ratio, d is the initial beam diameter, and x is the distance from the collimator to the target. For $x = 1$ meter, $d = 1$ cm, and $S \approx 10$, the target intensity is about 0.01 of the incident value. These are deliberately pessimistic values.

of about 10^{-3} amps at a background pressure of 10^{-7} torr (our best guess at the background for a noncryogenic internal molecular beam experiment). The audio range rms noise due to this background is about 5×10^{-10} amp on our gauge, without a multiplier stage. Low frequency chopping yields an unaugmented signal/noise ratio of unity with signal levels of 10^{8} molecules/cm^{3}. A loss factor of 10^{3} from ambient-to-scattered measurements creates a requirement for signal/noise enhancement factor of 100, at an ambient density of 10^{9} molecules/cm^{3}. The primary noise source is the fluctuation in the background signal and the multiplier dark current due to their stochastic variations, a very small contribution in the frequency range of the chopper. Signal/noise ratios of this level and below have been measured easily in our laboratory calibration apparatus. In summary, we are confident that it will be possible to make satisfactory measurements of reflected density distributions in orbit, although some proposed extensions of present measurement techniques will have to be verified in the laboratory before this becomes definitely established.

2. Measurement of Velocity Distribution

To our present knowledge, the only workable schemes for measuring translational velocities in the required range are time-of-flight techniques using either a mechanical chopper or a metastable source which can be modulated at high speed. Of the two, the only one which appears to have real promise is the metastable Time of Flight, ToF, experiment (proposed for this project by Dr. J. Zorn) (Ref. 5). Extensive research on this technique is still required, although results available at the time of this report from the University of Toronto Institute of Aerospace Studies and at the University of Michigan are encouraging. We have studied several approaches to the mechanically chopped ToF concept including phase-sensitive detection and signal enhancement techniques. It is concluded that there is no mechanical way to chop the beam rapidly enough to use this method at satellite velocities, although it is widely used in laboratory experiments at lower incident energies. Should the metastable technique prove usable, we would strongly advocate a molecular beam scattering experiment. Without the capability of measuring velocities of the reflected molecules, such an experiment does not appear to be worthwhile.

B. Long Term Exposure Experiment (Surface Contamination)

In view of the established importance of surface contamination, and the virtually complete ignorance of the state of surfaces after long-term exposure to an orbital environment, this experiment probably is the most important one to be considered. Theoretical methods are now becoming available which can predict interactions for well-characterized surfaces. Although these methods have not been thoroughly tested experimentally, they do give trends which conform to those found in the best laboratory experiments. A report is now in preparation at our laboratory which presents results of an extensive series of calculations on the interactions of noble gases with single-crystal silver surfaces. Our results for low energy incident molecules show the same trends as those shown in the experiments of Saltsburg and Smith (Ref. 6); the lobes of maximum intensity of reflected molecules become sharper and lie further from the normal to the surface as the energy of the incident beam increases. At higher energies (above 0.25 eV), where no experimental data are available, this trend reverses, showing that a new scattering mechanism becomes dominant.

1. Surface Types

We propose a system of several basic types of surfaces which would be exposed to the orbital environment and analyzed in accordance with a definite schedule to detect changes in their surface characteristics. Within the surface types to be tested are the following:

a) Refractory Metals

Tungsten and/or tantalum ultra pure single crystals.

b) Structural Class Metals

Nickel, aluminum, and possibly magnesium. Some single crystals, some engineering finishes.

c) Nonmetallic Surfaces

Replicas of solar cell surfaces, spacecraft thermal control coatings, anodized surfaces.

d) Noble Metals

Gold, possibly platinum. Probably plated on structural base metal.

We have not made final selection of test surfaces, as we feel this can be done better at a later stage of the project.

2. Surface Analysis

We anticipate three methods of surface properties analysis. The most direct would be to use a low energy (i.e., $\sim$ .03 eV) helium effusive beam with a small null-seeking detector to detect changes in the helium scattering pattern after exposure. This technique should detect many changes which are important to high energy GSI because at low energy, helium acts in much the same manner that a heavier, larger gas molecule would at higher energy. Since helium will not adsorb to any important extent, it should not affect the over-all experiment results significantly. This analysis should be quite simple to implement for a satellite package.

A second approach which is extremely simple is the measurement of surface potential levels. This can be done by allowing the test surface to be one plate of a vacuum-gap capacitor. Electrical dipoles are induced on surfaces in many types of adsorption, and these should, in principle, be measurable. Unfortunately, it is not too easy to determine precisely what is happening at a surface, even though one does observe that the surface potential is changing.

The third analytical method proposed would be selective desorption of adsorbed species. This would entail local destruction of the surfaces' history, so either duplicate surfaces or a very localized desorption technique would be needed. We would propose measuring the species concentrations of the effluent gas with a mass spectrometer and comparing these results with similar measurements previously conducted in the laboratory. Among the available desorption methods are flash heating by electron beam or electrical resistance, and bombardment by noble gas ions.

In support of this experiment, it is proposed that a laboratory program be undertaken to develop and calibrate the three proposed procedures. Such ground-based evaluation is especially necessary for the protracted exposure experiment and appears not difficult to perform.

3. Surface Control

Control of the surface condition should commence at the preparation stage and should progress through the preflight storage, orbital storage, and final deployment phases.

At least four special techniques are available to prepare the control test surfaces in the earth laboratory; baking, ion bombardment, vacuum deposition, and crystal cleaving. Not to be ignored are engineering type surfaces, such as might exist after normal manufacturing procedures, that have had no particular treatment or conditioning control prior to launch. The controlled test surfaces would have to be prepared under ultrahigh vacuum. Thereafter, they would be "canned" with up to one atmosphere pressure of ultra pure helium gas. Helium has favorable desorption properties and may reduce or prevent any surface contamination by more tenacious species. To assist in preventing the formation of a contamination gas layer on the test surface, gettering material (which selectively adsorbs undesired gases) could be provided in the canning envelope. The total gas volume and internal surface area of the capsule must be controlled so as to ensure much less than a monolayer of species that have strong adsorption bonds with the target. We believe this can be done, although it has yet to be demonstrated. Between the period of preparation in the laboratory and the exposure of the surface to the orbital environment, the hermetically sealed enclosure containing the helium gas buffer should preserve the surface in the freshly-prepared condition. To provide a reference for the various orbital measurements employed to characterize the surface, an identical plaque or portion of the original surface would remain in the laboratory for parallel measurements under controlled conditions. The removal of the sealed enclosure, in orbit, would signal the beginning of a schedule of periodic measurements by each analytical technique previously described for the satellite experiment package. In this manner, the orbit environment history and surface characterization measurements in orbit could be correlated with the controlled laboratory data. We believe this is a workable scheme that should provide adequate surface control.

A point might be made about the control of satellite outgassing which is a source of 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. During launch, very few active degassing measures can be exercised other than preventing new absorption by providing carefully designed venting for the enclosure of the satellite. In orbit, the satellite should be given every opportunity to outgas before conducting GSI experiments. Estimates of a day to a week have been associated with published discussion of the outgassing problem for various satellites. Grumman experience with OAO vehicles indicates a period of from 6 to 12 hours is reasonable to remove the majority of the "loose" gases. Periods of more than a day to create a negligible outgassing background are probably excessive for certain types of GSI experiments utilizing cryogenic liquids or for satellites having an expected lifetime of only three to four weeks. However, for longer lifetime satellites and many of the proposed GSI experiments described here, there is virtually no deterrent to the scheduling of a passive outgassing period of up to a month.

An additional note 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 being able to have 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 need for ultimate comparison with a uniquely designed unmanned satellite for GSI experimentation.

C. Experiment Package Concept

A consequence of the establishment of several GSI experiment requirements and the design features for two principal experiments, is the formulation of a conceptual experimental package for a satellite (see Fig. 2). Although, as previously discussed, certain elements of the experiments must still be developed, this package concept becomes a first step in providing direction to a future satellite system involving several complementary experiments.* It is assumed that eventual technological development, to provide certain currently unfilled measurement capability, will be accommodated within the geometric constraints of this package concept.

The reflected beam experiment of the package features a beam-forming skimmer, with auxiliary shield, that permits the upper atmospheric molecules, traveling at orbital speed, to enter through a 1.0 cm^2 area 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., $\sim$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.

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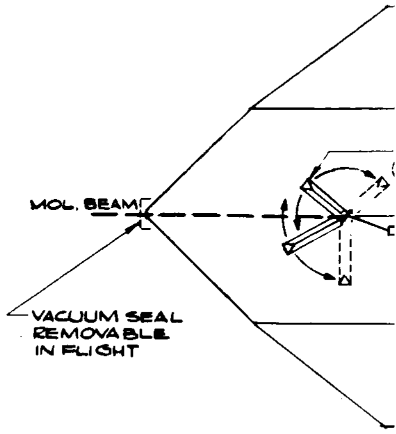
*Integration of these several experiments also is a future effort in establishing the total satellite system.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REMOVABLE
IN FLIGHT

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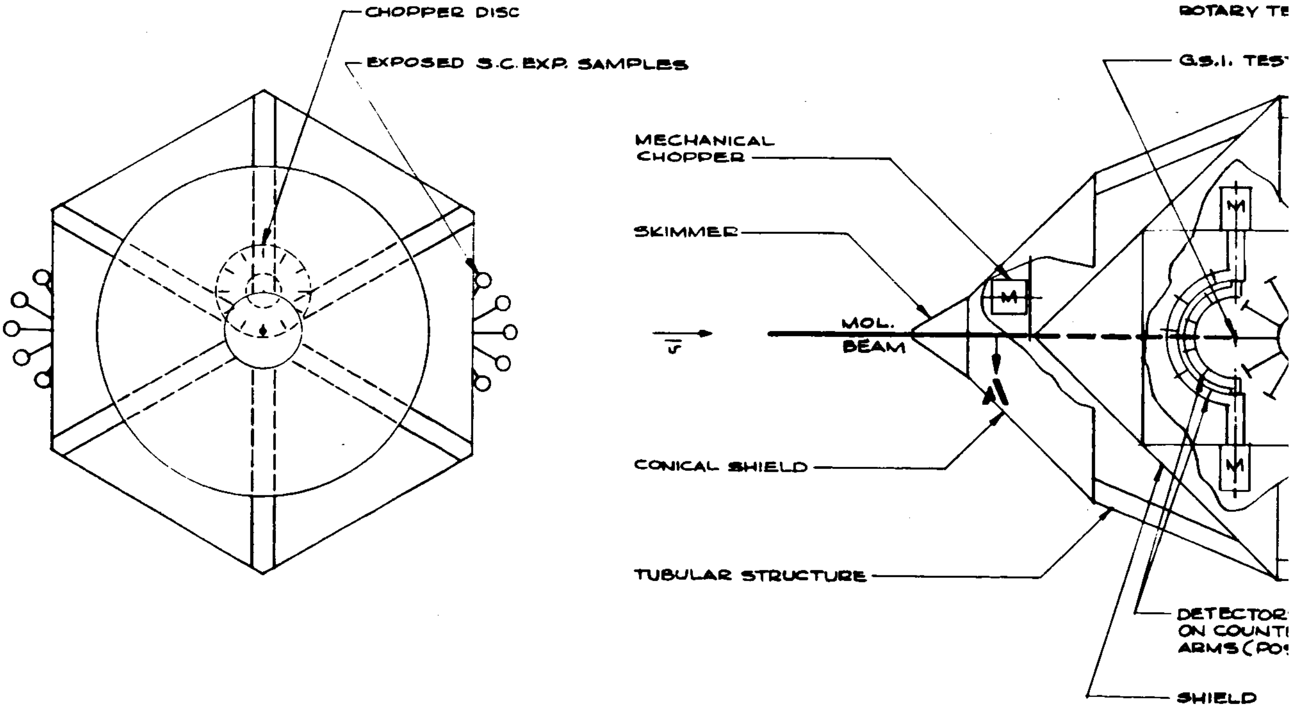
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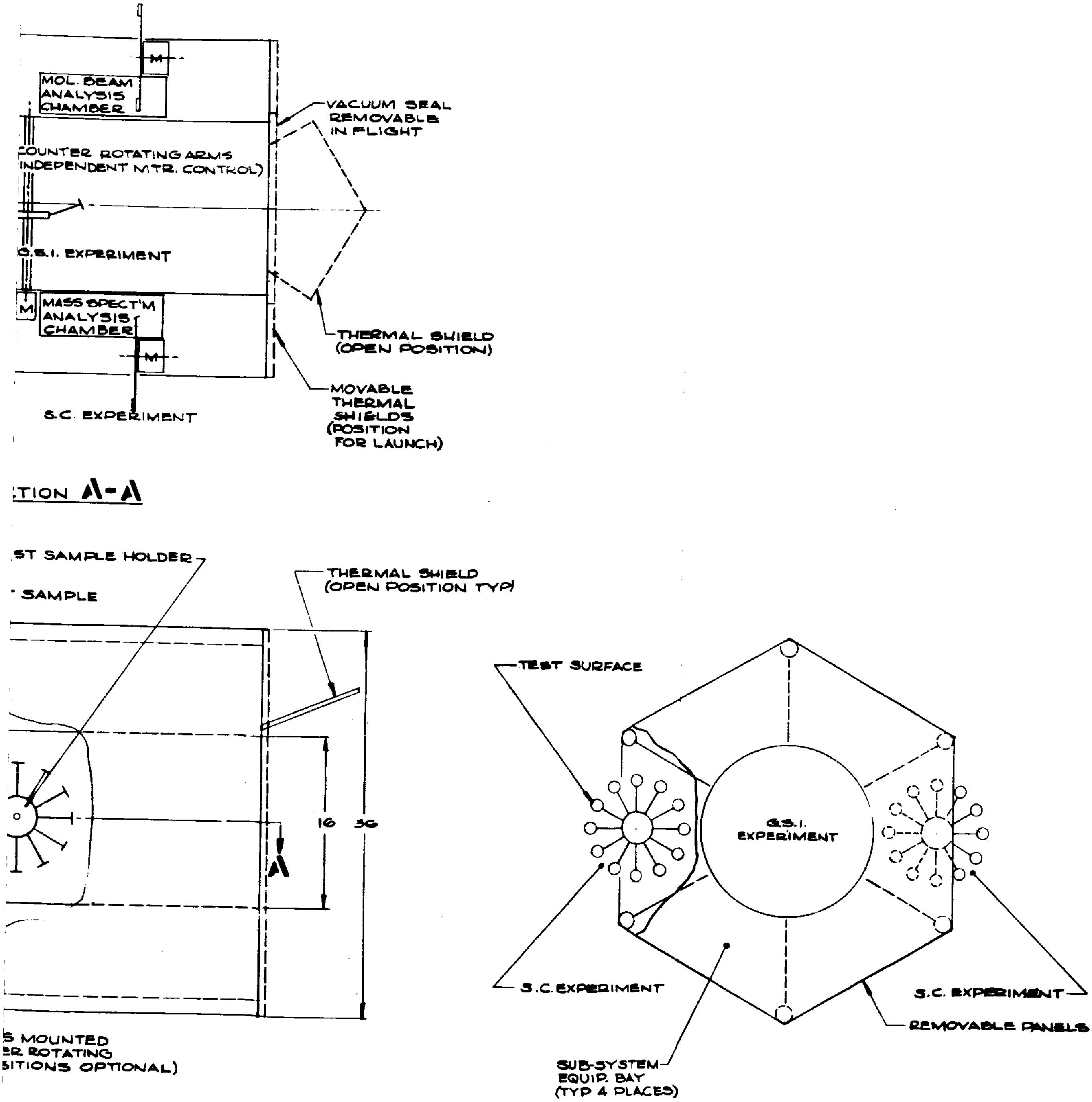

Fig. 2 Conceptual Satellite Design/ Spatial Flux Experiment

An interim decision to examine not more than 12 different test surfaces and three different incident angles for each test surface results in the need to expose up to 36 target surfaces to the incident beam. Concurrently, it has been decided that no more than 10 detectors should be employed to monitor the reflected beam. Locations of the detectors should include one normal to the surface, one in the specular direction, four or five in a near-specular array, and two for backscatter. A failure-mode analysis of fixed and movable configurations for the detectors and target surfaces shows that a near-optimum number of data points and best reliability should be obtained by the arrangement shown in Fig. 2. Here, the 36 targets, each having a surface area of 1 square centimeter, are installed on an indexing mechanism consisting of spokes radiating from a rotatable hub. 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 at least five angular positions for reflected beam measurements. At least three detectors of the through-flow density measurement type are mounted on each yoke. With these six detectors, about three times more data may be obtained than possible with a three dimensional fixed array of 10 detectors. If more than three detectors were to be used on each yoke, the data rate could increase proportionately. 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 will be used to shield the GSI experiment from solar rays when the rear of the satellite faces the sun. A rearward facing sun sensor activates movement of these panels to protect the internal equipment. 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 experiment of the conceptual package is a long term exposure, or surface contamination, experiment previously outlined in Section III-B. It consists of two arrays of specially prepared 1 cm^2 area 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 previously noted (see Section III-B-2). 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.

D. 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 data to be taken 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, three passive, two active, and three hybrid attitude control systems have been surveyed. A comparison of their relative features is given by Table 1. The active control moment gyro system and the passive gravity gradient with aerodynamic damping hybrid system both hold promise to perform as required. However, more analysis of acquisition or capture dynamics is needed before a final judgment based on performance is possible. In addition, a more detailed investigation beyond the scope of this study is necessary to define the cost, weight, and power requirements associated with the candidate systems.

TABLE 1

COMPARISON OF SATELLITE ATTITUDE CONTROL SYSTEMS

PASSIVE SYSTEMS	DESCRIPTION	ALIGNMENT	TEST TIME	COMPLEXITY	COMMENTS
1. Gravity Gradient (i.e., G.E. M.A.G.S.)	Maintains dual axis alignment with earth gravity vector	Normally ±3° to 5° (flown ± 6°)	10-15 min/orb.	Req. extendable booms, and 3rd axis control	The use of this system is very questionable within the orbital envelope considered, due to large variations in aerodynamic drag. There is also the possibility of a dynamic instability problem.
2. Aero. Stabilized	Maintains 3 axis alignment with aerodynamic drag vector (velocity vector)	Not defined, designed-in system	10-15 min/orb.	Appears simple but not flown	General comments of #1 apply. Large vehicle drag due to stabilizing surfaces.
3. Spin Stabilized	Spacecraft axis fixed in inertial space. Sensors determine velocity vector.	< ½° but precesses ≈ ½°/day	1-1½ min/orb. 8 days max.	Simple system	Short test time also limited by precession rate. This rate will be a minimum for an equatorial orbit.
4. ACTIVE SYSTEMS	Spacecraft sensor measures direction of vel. vector and aligns with it automatically using: 1. Gas Jets, 2. Control Moment Gyros or Inertia Wheels	≪ ¼°	10-15 min/orb.	Very complex, high power, proven system 1. Gas Contamination 2. Questionable Bearing Life	Automatic alignment feature allows moving parts inside vehicle without affecting orbit. Ultra pure helium gas may have value for short lifetime applications.
HYBRIDS					
5. Gravity Gradient and Aero Stab. (i.e., G.E. Aero M.A.G.S.)	#1 with aero drag for 3rd axis control	Comparable to system #1	Same as #1	Greater than system #1	Both of these systems are simple combinations of the above but the comments of #1 apply.
6. Gravity Gradient and Magnetic Torquing	#1 with magnetic coil for 3rd axis control	Comparable to system #1	Same as #1	Greater than system #1	Due to the simplicity of these it appears that they warrant further detailed analysis.
7. Spin Stabilized and Magnetic Torquing	#3 with magnetic coils to correct for precession	< ½°	1-1½ min/orb. unlimited orbits	Well proven system	Limited only by short test time/orbit. Best for equatorial orbit. NOTE: System #1 req's initial tumble rate < 3 times orbital period to ensure capture by gravity gradient torque.

IV. 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

A. 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. Extensive discussion of these variations will not be included here because of the available abundant literature (e.g., Refs. 7, 8, 9, 10). 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 (e.g., see discussion in Section II). 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. Initial objectives of this study were directed toward a late 1968 to 1970 flight period. This schedule would have coincided with an expected peak sunspot activity of the 11-year cycle and would have provided a rare opportunity to conduct deliberate GSI orbital experiments together with long-term, in situ detailed aeronomy measurements during an extreme of atmospheric behavior. However, coordination with NASA technical monitors during the course of this study, has resulted in a redirection of the timing to the early 1970's when solar activity might be characterized better as moderate to low.

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 (Ref. 9). A comparison of these results with other typical reported values of density for 200 km altitude is given in Table 2. For relatively quiet-sun periods the day and night profiles of atmospheric density given by King-Hele (Ref. 9) have been applied without modification (see Table 3). For active-sun periods, the adopted King-Hele model atmosphere has been altered by the average ratio of active-to-quiet-sun density variation indicated by Harris-Priester (Ref. 11) and Johnson (Ref. 8) that are plotted in Fig. 3. For example, at 200 km altitude, the average ratio (ρ_{max}/ρ_{min}) from Fig. 3 is 4.7. Thus, the active-sun day density should be 4.7 times the quiet-sun night density, or $4.7 \times 1.5 \times 10^{-13} = 7.05 \times 10^{-13}$ gm/cm^3.

TABLE 2

COMPARISON OF REPORTED ATMOSPHERIC DENSITIES FOR 200 km ALTITUDE

Source, Date		Density, ρ, gm/cm^3		Years of Observations	Comparative Solar Activity
		Day	Night		
1. King-Hele & Quinn,[9] (Satellite Data)	1966	2.7×10^{-13} ± 10%	1.5×10^{-13} ± 10%	1962-65	Moderately Low to Low
2. King-Hele & Quinn,[10] (Satellite Data)	1964	2.7×10^{-13}	1.8×10^{-13}	1962-64	Moderately Low
		4.4×10^{-13}		1958	High
		4.2×10^{-13}	3.8×10^{-13}	1959	High
3. Hedin & Nier,[12] (Rocket Data)	1966		1.24×10^{-13} ± 20%	April 1965	Low
4. Johnson,[8]	1964	5.76×10^{-13}		Prior to 1964	Maximum
"	"	2.67×10^{-13}			Moderate
"	"		$.97 \times 10^{-14}$		Minimum
5. Kallman-Bijl,[7] (CIRA 1961)	1962	4.09×10^{-13}	3.83×10^{-13}	Prior to 1961	High

TABLE 3

AIR DENSITY AND SCALE HEIGHT VARIATION BETWEEN 160 and 300 km ALTITUDE FOR LOW SOLAR ACTIVITY YEARS (AFTER REF. 9)

Altitude, km	Air Density, ρ, gm/cm^3			Scale Height, H, km		
	Max. Day	Mean	Max. Night	Max. Day	Mean	Min. Night
160		1.4×10^{-12}			16	
170	9.4×10^{-13}	8.0×10^{-13}	6.8×10^{-13}	21	18	15
180	5.9×10^{-13}	4.8×10^{-13}	3.6×10^{-13}	23	21	19
190	4.0×10^{-13}		2.3×10^{-13}	25		23
200	2.7×10^{-13}		1.5×10^{-13}	28		25
220	1.4×10^{-13}		0.7×10^{-13}	31		28
240	7.5×10^{-14}		3.6×10^{-14}	33		31
260	4.2×10^{-14}		2.0×10^{-14}	35		34
280	2.4×10^{-14}		1.16×10^{-14}	36		36
300	1.4×10^{-14}		$.67 \times 10^{-14}$	37		37

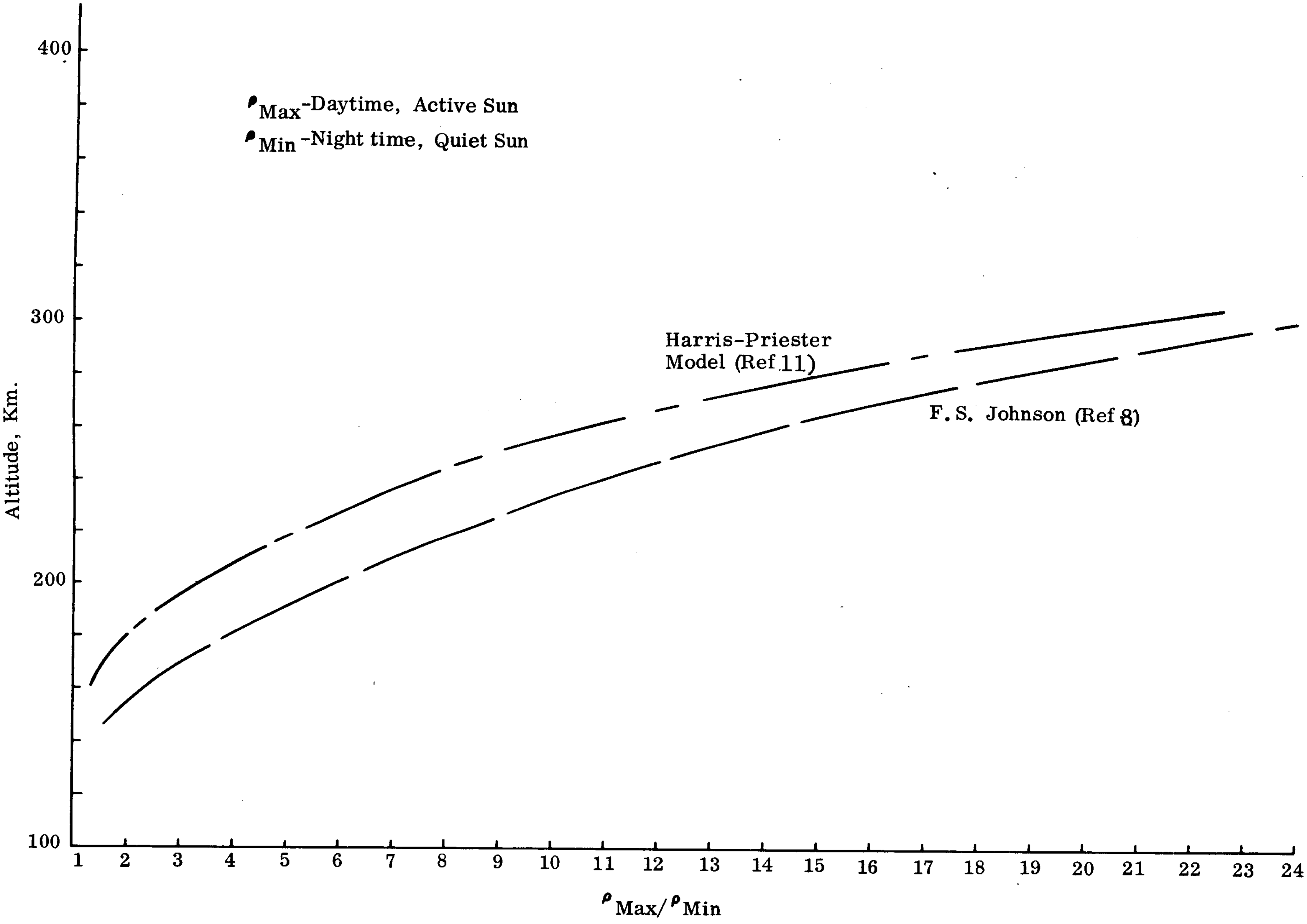

Fig. 3 Maximum Variations of Atmosphere Density Profile with Solar Activity

Another atmospheric parameter of importance for this study is the scale height, H. Figure 4 gives several models of altitude variation of H based on computations of Johnson (Ref. 8) and King-Hele and Quinn (Refs. 9, 10). It is evident that at a representative altitude of 200 km, the scale height may vary by as much as a factor of 2 between the period of low density atmosphere (i.e., quiet sun) and high density conditions (i.e., active sun). At higher altitudes, this atmospheric depth of pseudo-unchanging thermodynamic properties becomes somewhat larger, although the same relative magnitude of change with solar activity index is maintained as at lower altitudes. The changes in orbital atmospheric environment can, effectively, be considered small within this scale height dimension, at any particular time or satellite altitude.

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 observations (e.g., Refs. 12, 13, and 14) 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

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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.

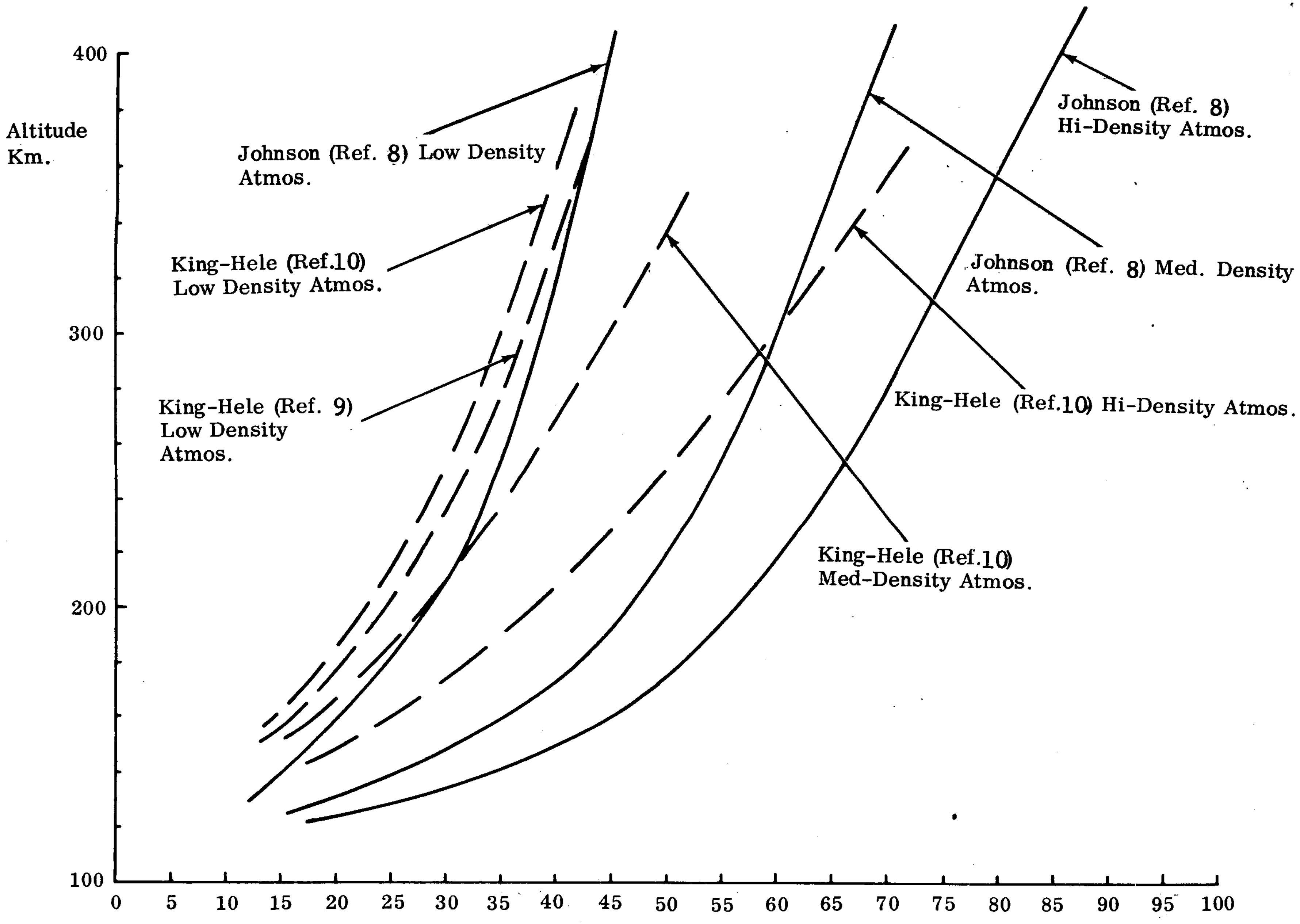

Fig. 4 Different Models of Scale Height Variation with Altitude

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. Our current theoretical calculations of oxygen atom recombinations at the surface may also help to clarify all of these questions.

The apparent diurnal variation of atomic oxygen to molecular nitrogen concentration ratio (Refs. 11, 13) 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, see Ref. 11) at the lowest altitude for which the mission could be conducted, and the lowest density atmosphere model (i.e., 400 hours, quiet sun, see Ref. 11) at the highest likely altitude of testing. Based upon the representative comparison of density models given by Table 2, Johnson's maximum and minimum density atmospheres (Ref. 8) have been employed (see Table 4). 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.

It is interesting to note that in the altitude band of 140 to 350 km, for a maximum dynamic range of mass or number density of 100:1, the corresponding maximum dynamic measurement ranges for the major atmospheric constituents are the following ratios:

TABLE 4

ASSUMED ATMOSPHERIC CHARACTERISTICS FOR GSI INSTRUMENTATION PERFORMANCE REQUIREMENTS (AFTER REF. 8)

	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^{-13}	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	$< 10^{-4}$

for (N_2) — 300:1
for (O) — 20:1
for (O_2) — 1000:1 .

Thus, monitoring of atomic oxygen is, perhaps, the least sensitive measurement parameter for a given dynamic range of a common measuring technique, e.g., a mass spectrometer. Molecular nitrogen concentration measurement is more nearly of the same order of magnitude as the possible full range of density variation. Molecular oxygen, on the other hand, is 10 times more sensitive a variable, over a potential range of test altitudes, than the atmosphere density. If comparable degrees of sensitivity of specie detection were desired, then different dynamic ranges of measurement would have to be provided for each constituent. This provision introduces undesirable complexity into an experimental program.

Two subsidiary points of possible difficulty have been examined relative to the mission environment. The first involves the accumulation of charge on the satellite which could interfere with on-board instrumentation that cannot be suitably shielded. A recent report (Ref. 15) for a near-polar orbit satellite between about 200 and 500 km altitude indicates that the potential of a representative vehicle is likely to vary between zero and less than -20 volts; such levels of change of effective satellite ground potential are not expected to affect the types of diagnostic devices planned for GSI experiments. The second point concerns the rotational speed of the upper atmosphere relative to the rotating earth. A west-to-east wind of approximately 1.3 times the earth's rotation is inferred by King-Hele and Allan (Ref. 16) on the basis of principally satellite and some high altitude vapor-trail data, between 200 and 300 km altitude. If so, the drag force acting on a satellite would not be in the plane of orbital motion and the net effect would be to act to decrease the orbital inclination as well as to alter the satellite orientation relative to the true velocity vector. However, since the satellite orbital velocity is approximately 8 km/sec and the earth's rotational velocity is about 0.45 km/sec relative to its center, it is clear that the relative wind represents less than 1.5 percent variation in the magnitude of the velocity vector, and is not likely to be discernible in the context of the accuracy of atmospheric density and GSI experiment instrumentation.

B. 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. Allowing for the approximate size of a satellite and the variations of atmospheric properties, this establishes an altitude of about 160 km as the lower limit for any GSI experiment. At this altitude, there is almost certainly a high enough atmospheric density to permit measurements to be made at nearly all times with state of the art instrumentation. 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 because of relatively high atmospheric drag forces. This characteristic would severely limit the amount of data that could be obtained. Therefore, an initial perigee of 160 km with a low eccentricity orbit would yield 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 Aircraft Engineering Corporation Molecular Beam Test Facility is capable (with modification) of measuring scattered distributions formed from a source of about 10^9 particles/cc minimum number density. This corresponds to an altitude slightly in excess of 230 km for a minimum density atmosphere at night (see Table 4 and Ref. 8). The day-to-night density ratio is approximately 1.5 for quiet sun (Ref. 9) so that an initial operational altitude of 240 km may be associated, during daylight, with a minimum density atmosphere. We conclude, therefore, that an initial perigee of 240 km is just compatible with existing density measurement technology for incident mass flow, under minimum, quiet-sun atmospheric conditions. For more dense atmospheres, either a higher perigee of an additional 20 to 40 km can be accommodated, or the output signal amplitude of the GSI measurement devices can be increased to their midrange values. Development of more sensitive instrumentation than current state of the art similarly would permit higher perigee or an increased signal level to be employed. The calculated lifetime of a satellite with ballistic coefficient, M/C_DA, of 1.0 slug/ft^2 is about 18.5 days for a 240 km circular orbit, using the atmospheric density model of Table 3. The circular orbital lifetime is linearly proportional to the ballistic coefficient so that longer desired lifetimes would require larger ballistic coefficients. For example, lifetimes of 30 or 300 days would necessitate coefficients of 1.63 slugs/ft^2 and 16.3 slugs/ft^2, respectively. The orbital period would be approximately 90 minutes.

Some gain in lifetime also is achieved by establishing low eccentricity orbits to reduce the decay effect of atmospheric drag forces near perigee. Although the period of small eccentricity orbits is slightly longer than a circular orbit of the same initial perigee altitude, 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 where the atmospheric density is such that a monolayer of atmospheric species would take about 1000 seconds to form on a clean surface. Quite obviously, this rule links the apogee 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 5 shows some typical orbit characteristics and requirements resulting from the three apogee possibilities discussed above, and an initial perigee of 240 km.

Selection of an orbital inclination is guided principally by recommended launch capabilities of the rocket booster; a maximum orbital inclination of 30 degrees is to be considered (Ref. 17).

TABLE 5

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

It is assumed that the launch site will be at Cape Kennedy (28.5° north latitude) so that barring a complex series of orbital corrections by on-board auxiliary propulsion rockets, the bulk of the experimental data will be obtained for equatorial atmospheric conditions.

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.

V. CONCLUSIONS AND RECOMMENDATIONS

The feasibility of a satellite-borne gas surface interaction experiment has been examined relative to the question of determining angular distributions of reflected molecular density, momentum and energy for surfaces of practical importance under orbital conditions.

The following conclusions appear evident from our study:

1. The condition of the surface is a vital factor in the interaction process. It is important and feasible to conduct experiments in orbit to examine the changes of surface characteristics brought about by exposure to the orbit environment. However, to prepare for a satellite experiment, additional development is needed to demonstrate the ability to store and protect clean test surfaces in orbit. Also, laboratory effort is needed to establish standard techniques for the characterization of surfaces in orbit relative to their gas interaction properties.

2. A molecular beam scattering experiment in orbit is highly desirable but currently not 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. However, laboratory demonstration of a proposed innovation to extend the sensitivity of an existing density measurement technique is required.

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*Although development work is in progress.

3. Preliminary examination of satellite attitude control requirements for GSI experiments shows a need for approximately 2° alignment of the molecular beam forming optics with the flight velocity vector during measurement intervals. The almost certain exclusion of reaction gas jets as an acceptable satellite attitude control technique (because of surface contamination problems) makes it necessary to employ either a passive gravity gradient or an active angular momentum wheel technique. Additional investigation is needed to evaluate the attitude holding performance of these methods, as well as weight, power, and cost data, to permit a decision on the preferable method.

4. 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.

5. A nominal initial perigee of 240 km and orbit initial eccentricity of between 1.5 and 3.5 percent is indicated for 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 the current pace of technological developments in instrumentation will soon change this status. There is little likelihood, however, that the conceptual experiments package configuration will have to undergo radical change because of a velocity measurement breakthrough.

The following minimum program description is recommended as the next step to be taken. It consists of three laboratory investigations and one analytical task. This program should resolve several crucial questions arising from this preliminary feasibility study, and thus enable expeditious exploitation of any advances in the technology to measure time-of-flight velocity of reflected gas molecules in a satellite-borne experiment.

Task I: Evaluation of Bendix Type Electron Multipliers for Orbital Instrumentation

The atmospheric density range likely to be encountered in a satellite experiment is many orders of magnitude less than the density experienced in the Grumman Aircraft Engineering Corporation molecular beam laboratory facilities. A much more sensitive output stage will, therefore, be needed for the type of density gauges that have proven satisfactory in our current laboratory research. Electron multipliers, available from Bendix, offer a means of obtaining this sensitivity with available flight qualified components, if sufficient compatibility to other factors can be demonstrated.

For proper evaluation, at least three electron multipliers with the necessary accessories should be procured. They should be incorporated as the final output stage of a modification of the present Grumman through-flow detector (TFD) instrumentation, which would also require an intermediate acceleration stage. The test objectives would be to obtain sensitivity, stability, frequency response, and reliability of the electron multiplier stage for measurement of the instantaneous, local gas density in a simulated satellite experiment. Of comparable importance would be the successful demonstration of suitability under these simulated environmental conditions of the modified TFD in a completely integrated configuration.

Task II: Storage and Protection of Clean Test Surfaces in Orbit

The objective of this task would be to design and evaluate practical means of encapsulating and deploying specially prepared test surfaces for satellite-borne, gas-surface interaction experiments. (The importance of surface condition to the GSI process has been stressed in Section II.) While adequate procedures are available to prepare candidate surfaces in the laboratory, we have concluded that the inclusion of such provisions in an unmanned satellite would be extremely difficult and unreliable. Therefore, we feel it is necessary to explore the practicality of preserving a laboratory-prepared surface for periods up to one year. Design and test effort is anticipated for this task. Various encapsulation methods would be formulated, and the necessary equipment would be designed and fabricated for typical test samples. After various storage time intervals, the mechanism protecting a small number of the test pieces would be removed in a controlled environment. The test surface would then be compared with its original GSI characteristics. A sufficient number of these tests would be conducted to assure a high degree of reproducibility.

Task III: Characterization of Solid Surface Contamination

It is reasonable to anticipate that exposure of the prepared test surfaces to the orbital environment will result in a time-dependent GSI process. At present, however, there is no single standard method of determining the relative interaction properties of an exposed test surface while in orbit. At least three suggested approaches warrant further consideration. One method is to monitor the spatial distribution of reflected, thermal energy, helium molecules that are supplied from a calibrated source. Theoretical predictions of these distributions have been computed for clean surfaces, and this method has been used to some extent as a laboratory standard. The proposed laboratory experiments under this task would seek to confirm these methods and disclose variations that accompany a contaminated surface. A second method, also proposed for examination, is the determination of the contact potential of clean solid surfaces and the variation of this quantity with exposure (i.e., contamination) to a controlled gaseous environment.

As a third technique, it would be desirable to study the use of flash desorption in conjunction with a mass spectrometer monitor, although it is preferable to use a technique that would not so completely destroy the history of the local surface area.

Task IV: Attitude Control Performance for GSI Orbital Experiment

Conceptual designs of orbital GSI experiments impose a need for alignment of the gas beam-forming optics with the flight velocity vector, especially near perigee. However, reaction gas jets for satellite attitude control create an unnatural gas envelope that might frustrate the purpose of the experiment. A preliminary survey of other applicable attitude control systems is presented in Table 1; more detailed analysis appears warranted, at this time, to judge the many potential options by providing relative performance information. Under this item, a limited analysis would be developed of the holding performance of a satellite by:

a) a passive gravity gradient method under the influence of aerodynamic torque, and

b) an active control technique using angular momentum wheels and an attitude referencing device (e.g., three directional ionization gauges).

Both analyses would stress the nominal attitude control system performance with limited emphasis on capture dynamics, for the passive technique, or acquisition dynamics, for the active control method.

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