

A STUDY OF ENVIRONMENTAL
EFFECTS CAUSED BY CESIUM
FROM ION THRUSTERS

March 1971

Contract No. : NAS5-11826

Modification No. 4

Report No. : HIT-487

Prepared By
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N72-12342 GODDARD SPACE FLIGHT CENTER
(NASA-CR-122306) A STUDY OF ENVIRONMENTAL
EFFECTS CAUSED BY CESIUM FROM ION THRUSTERS
(Hittman Associates, Inc.) Mar. 1971 72 p
Unclas CSCL 04A
10091

G3/13

FACILITY F

(PAGES)

CR 122306

(NASA CR OR TMX OR AD NUMBER)

(CODE)

(CATEGORY)

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ABSTRACT

The ATS-F satellite will carry two cesium ion thrusters. Cesium is a material that is not present in the upper atmosphere, and there is concern that the introduction of this material may result in some unexpected behavior. A study has been conducted to assess the magnitude of the effects that are to be expected. No observable effects were found as a result of the study. Consideration was given to the origin and destination of the material and the various reactions that could occur. The origin was considered to be anywhere in space from altitudes of about 100 km upward. The probable short term destination is in the form of cesium ions trapped in the earth's magnetic field or as ions and atoms in the heterosphere. The maximum possible number of cesium atoms in the field of view of an earth based observer is of the order of $10^6/\text{cm}^2$, far too few to be observable by visible, near-visible, or radio-frequency means. Further, no phenomena could be found that would result in the occurrence of an observable event.

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1. INTRODUCTION

For many years man has been inserting material into the upper atmosphere. Recently, with the advent of rockets, the quantities inserted have grown drastically and the material has been injected directly into the atmosphere a hundred or more miles above the surface. In many instances, the material so inserted has not been of too great a concern because it already is there in far greater quantities in a natural form. (There appears to be some justification for the argument that this is not a sufficient reason for the insertion to be assumed safe. For example, water vapor is present in the atmosphere in large quantities, but the addition of water which forms high clouds has been of concern to a number of writers.) In other instances, and the insertion of cesium is one of these, the material is not in the atmosphere in the natural form in the concentration that would result from its artificial insertion, and its addition may introduce unexpected phenomena. This report presents the results of a study which covers cesium introduced to the upper environment of the earth by ion thrusters.

The easiest aspect of the study is the one pertaining to a potential health hazard. The quantities of cesium introduced via ion thrusters cannot cause a health hazard. They are too slight to be of concern. Aside from the technical backup for this conclusion (see Appendix III. 6), no further discussion will be devoted to this topic.

The behavior of cesium injected into the atmosphere will depend, in part, upon the injection point. The reasons for this pertain to the phenomena which exist several hundred or more miles above the earth's surface. (For the reader who is not familiar with this topic, Section 2 will be devoted to a short discussion of the behavior. Further information is presented in Appendix I from the aspect of the behavior of charged particles and in Appendix III with respect to other information.) The expected observable behavior, if any exists, will be of an optical or a radio wave interaction nature. These aspects are discussed in detail in the Appendices, and briefly in Section 2. The reader who is familiar with these topics may go directly to Section 3. None of the results of the study will be presented in Section 2.

2. BACKGROUND

2.1 REGIONS OF THE UPPER ATMOSPHERE. The earth's atmosphere is divided into a number of regions depending upon the topic under discussion and the phenomena that take place as a function of altitude. For example, if one is concerned with chemical reactions, then the chemosphere is referred to. This is simply the region up to about 120 km (75 mi) in which most of the chemical reactions take place. Above this, the density is slight, and the reaction rate is low (although important processes also may occur above 120 km).

If the area of concern is composition oriented, then the atmosphere may be divided basically into two regions, the homosphere and the heterosphere. The former extends to an altitude of about 60 mi and, as its name implies, is characterized by a region of uniform composition. The latter extends upward

from the homosphere and is characterized by little mixing between the constituents. In the heterosphere, the composition changes with altitude. The atoms and molecules basically are distributed according to their masses due to the effect of gravity. The heavier species tend to predominate at the lower altitudes. Atoms such as oxygen, helium, and hydrogen (in that order with increasing altitude) dominate in the higher regions. From an altitude of about 500 mi outward, the mean free path of a particle is greater than 100 mi, and an atom or molecule with the necessary velocity vector can escape the earth. Light atoms or molecules can escape the earth more readily than heavier ones because, if everything else is equal, the former have longer mean free paths. Therefore the lowest altitudes at which this escape mechanism is important is not well defined, but appears to be in the region of 300 to 600 mi. Note that this behavior is restricted to neutral particles. Those which carry a charge will behave in a much different manner because of the influence of the earth's magnetic field.

Material at low altitudes will exist principally as atomic or molecular species. As altitude is increased, the proportion of the molecular species will tend to lessen, and the proportional quantities of atomic and ionized species will become greater. At altitudes of several hundred miles, the relative quantity of the ionized species is high. The energy necessary for ionization normally will be present in the form of sunlight and there will be a low probability of recombination with an electron, in part because of the low density of ions and electrons and in part because of the energetics. An atom and an electron that does interact will have more than enough energy to fly apart again and some of this energy must be eliminated in order for the neutral atom to retain the electron.

2.2 BEHAVIOR OF MATERIAL AT HIGH ALTITUDES. Material released at altitudes greater than several hundred miles will behave drastically differently, depending upon whether it is ionized or neutral. Ionized material will be affected by the earth's magnetic field and may be trapped at high altitudes for years. On the other hand, neutral material will travel for many miles before undergoing an interaction with another particle (on the average) and, if it has sufficient velocity, may escape the earth's environment altogether. If it reaches a low enough altitude that it has a high probability of undergoing collisions, then it will become trapped in the earth's atmosphere and settle out at a rate that is in part dependent upon its mass.

The earth's magnetic field converges in the vicinity of the north and south poles. Basic physics will show that a charged particle in a magnetic field will travel a spiral path as it moves along a field line. If the field is converging, then the particle will execute a spiral of decreasing radius and, if the effect becomes strong enough, the net direction of the particle will reverse and it will begin to travel in the direction of diverging field strength. In the earth's magnetic field, this means that the charged particle can execute a movement from the vicinity of one pole to that of the other. The point of reversal is referred to as the "mirror point". Whether a particle becomes trapped or not depends upon its injection direction. For the most part, energetics do not enter into the picture because the particles do not possess enough energy to cross magnetic lines and they therefore must travel along them. If the injection angle is not favorable, then the mirror point will occur

at a point low enough in the atmosphere that there will be a high probability of an interaction with an environmental particle and the charged particle therefore will have a short life.

Of course, this is an idealized discussion. The actual magnetic field of the earth is not uniform with respect to position on the surface nor is it uniform with respect to the sun. There are changes with respect to the surface that are not predicted for a uniformly magnetized sphere for reasons that are not fully understood and which will not be of concern here. The effect of the solar wind also has a strong effect upon the magnetic field and will dominate at a distance of about ten earth radii in the direction of the sun. On the side away from the sun the magnetic field is swept out to distances of several hundred earth radii. These effects will change the behavior of charged particles located a long distance from the earth.

Neutral material released at high altitudes within the magnetic field of the earth will, as previously noted, not be affected by the field as long as it remains neutral. However, the sunlight intensity is great enough that many atoms will have a high probability of being ionized by interacting with a photon from the sun. When this occurs, there is a good chance that the atom will remain ionized because the probability of a collision with an electron that results in capture of the electron will be low. Therefore, the particle will behave just as though it were ionized in the first place provided its velocity and direction are comparable to the directly produced ions when the event occurs.

2.3 INTERACTION WITH PHOTONS. Ionization of material via interaction with photons from the sun was mentioned in the previous subsection. This event occurs when a photon of sufficient energy is absorbed by an atom. A portion of the energy is transferred to the outermost orbital electron and the electron energy becomes so high that it cannot be retained by the attractive forces which exist between the nucleus and the electron. The electron therefore escapes carrying a negative charge with it. The remaining portion of the atom will retain a positive charge. For each electron that is ejected from an atom by this process, a certain unique amount of energy is required. The energy that is available beyond the amount utilized in the ejection process can be given to the electron in the form of kinetic energy or can be retained within the atom (or both). In the latter instance the atom will remain in an excited state and normally will return to the ground state via the emission of a low energy photon or by interaction with another particle.

The behavior is very different if the incoming photon does not have enough energy to eject an electron from the atom. Orbital electrons may exist only in certain allowed energy levels within an atom. No levels are possible between these allowed states. Therefore, for an electron to move from one allowed state to another requires that the necessary precise quantity of energy be available; no more and no less. An incoming photon with just the right amount of energy for jumping an electron from one allowed level to another can interact and be absorbed in the process. If it possesses a different amount of energy, an interaction is not possible and the photon will behave just as though the atom were not there; the atom will be completely transparent. This implies that absorption is a line process, and indeed for practical purposes, this

is the case. However, the lines are of a finite width because of many effects, such as the velocity of the atom relative to the incoming photon and the relative energy seen by the atom because of this effect. (There are many other effects as well that will be mentioned in more detail in Appendix II.) In the situation where there is a large density of atoms (or molecules), the inter-atom collision rate will be high, and the effect will be to create broad absorption lines (a range of energies can react). If the density of the atoms is low, as is the case at altitudes of several hundred or more miles, then the collision rate will be small and the lines will be very narrow, but still of finite energy width.

The absorption of an photon will leave an atom in an excited state; it will possess more energy that it had before the absorption. This is an unstable position and the atom will tend to return to its lowest energy position, referred to as the ground state. There are a number of ways in which this can occur. If the density of atoms is high, then energy can be transferred by interactions with other atoms. If the atom is a part of a molecule, then energy can be transferred to other atoms within the molecule, or, if it is sufficient, bonds holding the molecule together can be broken, thus utilizing some of the energy. Finally, a common process is for the atom to reject some of the energy by emitting a photon with an energy corresponding to the amount required for an orbital electron to move from one level to another. This energy may or may not be of the same amount as the energy absorbed in the original excitation process. For example, if the original excitation resulted in raising an electron to the first permitted level, then decay to the ground state will result in the re-emission of a photon with the same energy as absorbed. (Note that the direction probably will be different since the re-emission process will be isotropic.) If the original event resulted in raising the electron to a level higher than the lowest permitted excited state, then the re-emitted photon may or may not be of the same energy (and wave length) as the one absorbed. Obviously, if the decay is directly to the ground state, then this will be the case. But, if the decay is to a state higher than the ground state, then the emitted photon will be of an energy lower than that of the absorbed photon. The atom in this situation will still be in an excited state and will still tend to decay to the ground state. Absorption of photons while in an excited state also is possible provided the energy is favorable. In this case, it is permissible for the excited atom to decay, in some instances, with the emission of a photon of more energy than the last one that was absorbed. Also possible is the triggering of excited state atoms wherein an incoming photon with the right wavelength (energy) can cause the excited state atom to decay at a rate more rapidly than would be the case without the stimulus.

2.4 INTERACTIONS WITH RADIO WAVES. Atoms and particles will interact with radio waves as well as with photon energy in the visible and near visible range. At low altitudes (less than 20 to 30 miles) the interaction will be with free molecules and suspended particles. Most of the effect will, in a non-condensed atmosphere, be due to an interaction of the radio wave with the electric moment of water molecules and with the magnetic moment of oxygen molecules. At higher altitudes, which will be of more concern for this study, the interaction is due to charged particle effects. For practical purposes, electrons will be the dominant species that interact. Ions also will have an effect, according to theory, but the effect is mass dependent and the effect of the ions will be negligible in comparison to the electron effect in a neutral atmosphere (one is which the density of electrons is the same as that of the ions).

The dominant feature of the earth's atmosphere insofar as interaction with radio waves is concerned is the behavior of the ionosphere. This layer (or layers if one wishes to consider it in detail) has a high charged particle density and is responsible for much of the reflection of radio waves back to the earth's surface that otherwise would be lost to space. The portion of the radio spectrum below about 10 MHz interacts strongly with the ionosphere and the ground investigator cannot use this range for astronomy purposes. The range from about 10 MHz to almost 10^5 MHz is available to him. Satellites located at altitudes above the ionosphere can utilize the range from 10 KHz to 10 MHz. Observations at frequency ranges below 10 KHz cannot be performed within the environment of the solar system. Such observations would have to be performed by utilizing spacecraft located far away from the solar system.

2.5 CHEMICAL REACTIONS. The upper atmosphere may be considered as an extremely rarefied "soup" consisting of a wide variety of species. For many purposes, it may be considered to be a vacuum. Despite the rarefied conditions, a number of phenomena are taking place. One of these is airglow, which is observed as a faint glow in the sky that becomes brighter as the field of view is moved toward the horizon. This results from solar energy stimulated chemical reactions which take place in the rarefied upper atmosphere. The precise mechanisms are not understood.

The population in the upper atmosphere consists of ions, atoms, and a few molecules of probably rather simple structure. Many of these would, under ordinary circumstances, be considered to be highly reactive (such as atomic oxygen, which exists at certain altitudes). However, the number of such species that are available to react is very small when ordinary volumes are considered, and the mean free path typically is of the order of a few miles or more. The observed phenomena ordinarily occur over very large volumes and it is the cumulative effect of thick layers that is seen. Nor are the reactions limited to the so-called upper atmosphere. This rarefied region also is reacting with the more dense regions closer to the earth as well as within the radiation belts. The behavior may not always be considered on a macroscopic basis. The presence of very small quantities may have a profound influence upon the behavior of the system. A reaction of considerable importance in the ionosphere is due to very small quantities of nitric oxide, which exists in a total column density of about 1.7×10^{14} molecules/cm². This is easily ionized and is responsible for much of E-region electron and ion concentration. Since the total quantity of material above 85 km is about 10^{20} molecules/cm² (or equivalent), nitric oxide is present in only about one part per million.

3. CESIUM EFFECTS

3.1 THE CESIUM SOURCE. The spacecraft for which this investigation is being conducted is the ATS-F which is to carry two cesium ion thrusters. Each will carry 3.4 kg of cesium propellant which will be adequate for 4400 hours of full time operation. This is anticipated to provide for 28 months of station keeping capability (Ref. 1). The planned orbital altitude is about 22,000 miles, which will result in an orbit period of 24 hours (Ref. 2). The present plan is not to operate the thrusters until the spacecraft orbit has been established. Therefore, the injection of cesium will not take place at low or intermediate

altitudes. For purposes of this study, this aspect of the injection will be ignored and the study will be expanded slightly so that the effects of injection may be determined at all altitudes. The thruster also will be oriented somewhat in the direction of the earth. Again, to keep the study general so that it may be used for other applications as well, the directionality will not be limited to the ATS, but all thrust directions will be considered. The same approach will be taken with respect to the energy and fraction of the cesium ionized. As will be seen, these generalities will not be a problem in applying the results to the ATS or, for that matter, to any other proposed satellite.

Typical thruster operating parameters are with a cathode at 500°C and a voltage differential of about 600 V. Thruster propellant utilization efficiency will range from about 80 percent to 95 percent (the percentage of the cesium that is ionized). The ionized portion will be traveling at a velocity of about 35,000 m/sec and the neutrals at a velocity somewhat greater than 3000 m/sec. (The precise velocity of the neutrals is open to question. The assumption usually is made that the neutral velocity may be taken as that corresponding to the temperature of the originating surface, but there is information that indicates that the actual velocity may be greater than this. The question will not be of concern here since it will make no difference for purposes of the study. (See references 1, 3, and 4 for more information.) The cesium injection rate based upon the storage capability for 4400 hours of operation is $(3.4)(10^3)/4400/3600 = 2 \times 10^{-4}$ gms/sec. This corresponds to a rate of $(2 \times 10^{-4})(6.02 \times 10^{23})/132 = 10^{18}$ atoms/sec or a total of 1.5×10^{25} atoms per thruster.

3.2 BACKGROUND. There is little previous experience with this type of contamination. A few spacecraft have flown with ion thrusters and, to our knowledge, there have been no observed effects. These were low altitude missions (Refs. 5 and 6); one with a mercury thruster and one with a cesium thruster. In addition, there have been a few studies which indicated that there would be no problems. These latter were performed with mercury. There have been no previous studies of which we are aware that were done with the injection of cesium from thrusters. In addition, considerable work has been done with the injection of large amounts of cesium at relatively low altitudes (in the vicinity of a hundred miles). This experience will be reviewed briefly in the following paragraphs.

The ATS-IV was launched into a low parking orbit on August 10, 1968 where it remained attached to the Centaur stage, which failed to achieve a second burn. The orbital altitude was a 218 km perigee and a 760 km apogee. This satellite carried two cesium ion thrusters. Five separate ion engine tests were performed, the final one on October 9, 1968. To our knowledge, no effects were observed in the atmosphere that could be attributed to the ion thruster operation. The SERT II was launched on February 3, 1970 and, with the exception of two periods of several hours each, a thruster was operated continuously for several months. Orbital altitude was about 1000 km in a near polar orbit. There were two thrusters on board, each of which carried 15.0 kg of mercury propellant. In general, for thruster one the performance was the same as determined in the ground tests. Within data accuracy, the accelerator current was the same as found in vacuum tests on earth at a pressure in the tank of 5×10^{-6} torr. This indicates a negligible interaction of the ion thruster beam with the environmental gas. (Interactions would produce charge exchange effects with resulting accelerator impingement

and a change in the accelerator current.) Thruster two also duplicated the ground data with the exception of the main discharge current. This was slightly higher in the flight tests than found in the ground tests. The reason for this is stated not to be understood.

The propellant supply furnished was adequate for about eight months of operation and, at the time of the report, about three operational months had passed. No information was given that would indicate an interaction problem with the thrusters. Note, however, that the author was concerned only with the behavior of the thruster. Again, we are aware of no observations of phenomena as a result of these operations.

A large number of tests have been conducted in which quantities of alkali metals, including cesium, were released at altitudes in the range up to about 100 mi. Some of these were releases of large quantities (up to 80 kg of cesium containing mixture are reported). The observable results were of a short term nature. (See Refs. 7 and 8 and Appendix III for further information.) This altitude range is below where one would expect to find an effect due to the earth's magnetic field, but is in the range where the material should remain in the atmosphere for an extended time. The observations were that it expanded rapidly and reached the pressure of the environment rather quickly. To obtain a feel for the applicability of the tests to the proposed application, consider that the material involved was of the order of 1000 kg (a guess, no attempt was made to obtain an actual total for all tests), and further assume that all of the material was cesium. The surface area of the earth is about $(4\pi)(4000)^2(5280)^2(2.54)^2(12)^2 = 5 \times 10^{18} \text{ cm}^2$. The number of atoms of cesium is $(1000)(6.02 \times 10^{23})(1000)/132 = 5 \times 10^{27}$. If all of this material were to be distributed uniformly over the earth's surface, there would result a density of $5 \times 10^{27}/5 \times 10^{18} = 10^9 \text{ atoms/cm}^2$. (This may be considered as the number of atoms that would be seen if an observer were to look upward through the atmosphere. It would make no difference at what altitude the atoms were actually located provided they were in a rarefied region so that the interaction rate with other material was small.) This is a very small density, and probably cannot be seen although this conclusion remains to be substantiated (which will be done later in this report. If the conclusion is correct, then a portion of the reason the material is not seen for an extended period of time is immediately evident; there is not enough of it once it has been spread out over a small portion of the atmosphere.

Knauer (Ref. 9) conducted a study of the behavior of mercury thrusters in which a very pessimistic discharge of ten tons annually was assumed. He compared this release of material to the amount injected into the lower atmosphere by natural processes and found that the natural amount was higher. He then concluded that the artificial injection of this amount would not be a problem for this reason. (We attempted to do the same thing for cesium, but were not able to find the data upon which to make the comparison.) The behavior in the upper atmosphere was found to be quite different. There is a very low population of mercury in the upper atmosphere, and the amount introduced by the assumed thrusters (20 to 50 with a discharge of about 200 kg each annually) was far in excess of the natural amount. He concluded that, with this amount, there might be some very small effects that could be observed. One was the generation of a belt of mercury ions in much the same manner

as was the case with the injections from the high altitude nuclear explosions (see Appendix II). The other was the generation of faint artificial auroras at the locations where the ion beams from low orbiting satellites enter the atmosphere. These conclusions will be commented upon in the next subsection.

Masica (Ref. 10) also conducted a brief study of the SERT behavior. As a basis, he took the actual SERT characteristics and found no observable results. This is a conclusion similar to that of Jahn (Ref. 11), who also limited his discussion to the SERT mission.

Finally, Kellogg (Ref. 12) looked at the problem in a more general approach in which he estimated the contribution that would double the natural quantity of material. Although he did not specifically look at cesium, he did investigate the behavior of some of the other alkali metals and found that only a small addition at the upper levels of the atmosphere would double the concentrations that resulted from natural means.

These studies, many of which have not been published, are presented in more detail in Appendix III. Those that have not been published are abstracted completely so that all of the information presented by the author is made available in this report.

3.3 ANALYSIS OF PREVIOUS WORK. As mentioned, Knauer took a release of ten tons annually as the basis for predicting the results. To make his work comparable with the other studies, which were based on the SERT behavior, we first will ratio his results downward by a factor of 300, which is about the amount of the mass difference with no account taken for the difference in the time span for the two studies (per year vs. 18 mo.). Knauer predicted a mercury belt population of 10^{27} ions. This was stated to result in a flux of about $10^5/\text{cm}^2 \text{ sec}$. (The natural belt fluxes are stated to be about 10^6 to 10^8 protons/ $\text{cm}^2 \text{ sec}$ in the energy range below 0.1 Mev.) This means the mercury ion flux must be ratioed downward to about $300/\text{cm}^2 \text{ sec}$. (If one works with actual numbers, the value will be a little higher than this, the difference being due to the round off in the estimates.) This is a small value and probably cannot be found. Masica estimated that the concentration of mercury ions would be of the order of one/cm^3 if they were spread out over the earth's atmosphere and the upper limit would be of the order of $1000/\text{cm}^3$ with conservative loss assumptions and consideration given to the generation behavior. Jahn simply assumed that all of the ions would be trapped within a belt of thickness corresponding to one gyro radius, and found a number density of about $30 \text{ ions}/\text{cm}^3$. Knauer estimated about 2×10^3 natural mercury atoms/ cm^3 at 80 km altitude. His estimate of the thruster contribution is about a factor of ten below this. The thruster contribution, on a comparable basis, is about $200/300 = 1 \text{ atom}/\text{cm}^3$. If the roughly 30 kg potential release of the SERT thrusters is considered, the total number of potential ions is about 10^{26} . If these are assumed spread over the earth's surface the density is about $10^{26}/5 \times 10^{18} = 2 \times 10^7 \text{ ions}/\text{cm}^2$. Knauer's estimated value with five percent ionization is about 10^7 (the 10^8 value mentioned is the natural mercury density) from 80 km upward, certainly in the same ball park when the values are ratioed to account for the differences. Note that the simple spreading approach provides a value higher than obtained when loss mechanisms are considered. Jahn reported about $10^7/\text{cm}^2$, about

what one would expect from the assumptions. As an approximation, we may conclude that all investigators are arriving at about the same number densities. Knauer was the only one that predicted a belt of ions that would reach observable proportions, and this is not the case when the values are ratioed to the SERT proportions.

Knauer also predicted a faint aurora at 200 R when the ion beam entered the atmosphere. This was based on the assumption that the ion beam from the thruster would be initiated at a low altitude (at first) and would travel along the magnetic field lines with undiminished energy until entering the atmosphere. The beam was assumed to be of ten amps with a particle energy of 2000 ev. It was assumed to be confined to a area of less than 10^{11} cm². The energy flux corresponding to this was about 2 ergs/cm² sec. The predicted radiation intensity then was about 200 R (Rayleighs), great enough to be seen as a faint glow. The SERT II thruster produces a 0.25 a, 3000 v mercury ion beam (Ref. 13). Using Knauer's value for the radiation, the corresponding glow is about 200 (0.25/10) (3000/2000) = 8 R. This may be compared to the lower levels in the nightglow which are about 10 R and the visual level which is at a minimum value of about 100 R. (The estimate of 200 R is based upon the conversion efficiency of protons, which is estimated to be 10^{-8} ergs/photon. Two ergs then provides 2×10^8 photons.) The assumptions upon which this value is based would appear to make it an upper limit, and the true value should be significantly below this. Therefore, one may conclude that the SERT II thruster will not cause an observable effect. The reader also should remember that the prediction is based upon a low altitude satellite with the proper injection direction. For station keeping applications, the altitude would be higher, and the injection direction also would not be ideal for aurora production.

In all other aspects, the investigators agree in their overall conclusions. There will be no effects that can be observed.

3.4 CESIUM ANALYSIS. As mentioned, the amount of cesium in the atmosphere was not found in the literature. Therefore, as a first step in the analysis for effects from the cesium thruster, we will estimate the density of cesium that one might find in the atmosphere. Kellogg (Ref. 12) listed the total quantity of sodium in the atmosphere as 20 to 170 kg for the zone above 105 km. This corresponds to a particle density of 10^8 to 8×10^8 /cm². He also mentioned that one of the possible sources for the alkali metals in the atmosphere was from seawater and that experimenters had found that the ratio of potassium to sodium in the upper atmosphere was the same as found in seawater. We will make the assumption that the ratio of sodium to cesium in the upper atmosphere is the same as in seawater. The concentration of cesium in seawater is 2×10^{-3} ppm (Ref. 15). The concentration of sodium in seawater is 10,561 ppm. The ratio is about 10^{-7} . Therefore, the total cesium in the upper atmosphere is about 10^{-5} kg. This is far less than the amounts that will be introduced as a result of ion thrusters. One may conclude that the natural background of cesium will be drastically affected by the ion thrusters. The next step, then, is to see if there are any effects as a result of the addition of the material.

In this study, we will not be concerned with the lower part of the earth's atmosphere. All of the phenomena that are to be investigated will occur in the heterosphere. The reason is straightforward. The quantity of material

in the lower atmosphere is so great that there will be no effects due to the small amount of cesium introduced into the earth's environment that will not be found by a study of the effects in the higher regions. As already mentioned there are no effects of a biological nature with which we must be concerned, and therefore we need study only the physical nature and how the existing phenomena may be changed.

First, we will postulate that a cesium ion thruster is located at a low orbital altitude and that it is thrusting in the direction parallel to the earth's surface. This means that the ion beam will have the greatest chance of causing effects as it enters the earth's atmosphere. The cesium injection rate is 10^{18} ions/sec at an energy of 600 ev. This corresponds to an energy of 10^9 ergs/sec. At a conversion rate of 10^{-8} ergs/photon, the photon production rate is 10^{17} photons/sec. We will not assume that these photons are produced over one gyro radius, as was the case with Knauer's work, because this radius is based upon the velocity component in a direction perpendicular to the field lines and we assumed that the injection was in a direction that was parallel to the field lines. This is shown in the following equation:

$$r = mv_{\perp} c / (eB)$$

where:

r	=	radius of gyration
m	=	particle mass
$v_{\perp}$	=	velocity component perpendicular to the field lines
c	=	velocity of light in a vacuum
e	=	charge (normally the electron charge)
B	=	magnetic field strength

Instead, we will compute the minimum distance an observer could be from the generation point of the photons and still be able to see them. The human eye will respond to a level of about 100 R, or 10^8 photons/cm² sec. Immediately, we find that if a person were located further away from the generation point than about a hundred meters, he would not be able to see the light. Conversely, if the beam spread were more than to an area of about 10^9 cm², an observer would be unable to see any effect. We may safely conclude that the ATS ion beam will not be observable as it re-enters the atmosphere under the best conditions for the generation of light. Further, a beam could be several decades stronger than the one from the ATS thrusters, and there still would be no effect.

Next, the behavior of the material released from thrusters at various altitudes will be considered. If the orbital altitude is low, and the thrust direction is directly toward the earth, then the amount of material that is trapped in the magnetic field will be at a maximum (See Equation I-1). As already seen, if the thrust direction is along the field, the trapped material

is at a minimum (as also seen from Equation I-1). At any direction in between, the amount of material obviously will be between the two end points. Only one effect is of interest for loss rate of the material from the atmosphere, and this has already been considered. All other effects that we will wish to consider may be studied by considering the amount of material that is retained in the atmosphere. Therefore, if we estimate the maximum amount of material that can be retained, and find that there is no problem with this, then the objective of the study will be satisfied. Hence, the approach will be to assume that all of the material is retained and none is lost to the lower atmosphere. For the low altitude satellite, this corresponds to the case of thrusting directly toward the earth. Now consider the behavior as the altitude is increased. The injection altitude obviously goes up, and the strength of the magnetic field will decrease. The gyration radius will go up as a result of this, and the density of material trapped in the fields will be less than for the case of low altitude releases. Further, at least a portion of the material ejected from the thruster will be at angles less favorable to high altitude mirror points, and hence the amount of material that can reach the lower atmosphere without being trapped in the magnetic field will tend to increase with increasing altitude for thrusters that are operated while thrusting toward the earth. Any other thrust direction will tend to increase the chances for loss of material to the lower atmosphere. Finally, for operation at extremely high altitudes, the magnetic field may be in a state of disturbance, and some of the material may not follow the direction of field lines toward the earth, but instead may move into outer space. The overall conclusion of this discussion is that there are no effects that will not be found by considering the maximum amount of material and assuming it to be located at a relatively low altitude insofar as finding the density is concerned.

The studies performed with mercury have indicated that the assumption that all ejected material is spread evenly over the earth's surface with no loss will provide a higher density than if the loss mechanisms are considered and then attempts are made to find out how the material is distributed. This assumption will be made in the evaluation of the cesium release. The total release from an ATS thruster is 1.5×10^{25} atoms. The density if this material is spread over the surface of the earth is $1.5 \times 10^{25} / 5 \times 10^{18} = 3 \times 10^6$ atoms/cm². The effects that this material could cause are considered in the following subsections.

3.4.1 LIGHT ABSORPTION. As a first approximation, the behavior of cesium atoms may be considered by looking at only the first lines in the spectrum. These are the strongest and will be the ones that absorb to the greatest extent. For these purposes, the effluent from the thruster will be assumed to be completely un-ionized. This, of course, is not true; only a small fraction meets this assumption. However, it is very conservative because the cesium ions absorb only in the extreme energy range of the solar spectrum and the lines will be much weaker than is the case for the atoms. One additional assumption will be made. The cesium will be assumed to be in an atomic state. No molecular species will be assumed. The validity of this assumption has not been established. The overall effect of these assumptions probably is one of overpredicting an interaction of cesium with photons in the visible or near visible range.

The maximum width of the absorption lines for cesium, as shown in Appendix II, is of the order of 10^{-12} cm. The fraction of light that can be absorbed by lines of this width is extremely small and there will be no effect upon the overall light level. Further, Cole (Ref. 14) and Appendix II show that the absorption from any concentration below 10^9 atoms/cm² is negligible. There will be no effects due to the absorption of light that can be observed.

3.4.2 LIGHT SCATTERING. This does not completely eliminate the possibility that a photon scattering effect might be seen. To check on the possibility of the cesium reflecting sunlight, consider the spectral distribution of the sun as presented in Figure 1. The intensity in the vicinity of the strongest absorption lines is about $10 \mu\text{w}/\text{cm}^2 \text{ \AA}$. Cole shows that the fraction of light absorbed at a concentration of 10^9 atoms/cm² is about 0.01 within the line width, which is shown in Appendix II to be 1.4×10^{-12} cm. The fraction at a concentration of 3×10^6 atoms/cm² will be about 3×10^{-5} . If all of the cesium is in the non-ionized state, then the amount of light from the sun that can interact with the cesium will correspond to about 2×10^5 photons/cm² sec. If this same rate is assumed to be emitted, and half of it is emitted in the direction of the normal to each side of a plane layer of cesium, then the photon rate due to interactions with the sun will be of the order of $10^5/\text{cm}^2 \text{ sec}$. This is about 0.1 R, too low to be seen. There is one other line of about the same intensity as the one considered here, and all of the rest are two orders of magnitude or more narrower. Therefore, the contribution of the remaining lines will not affect the conclusions.

3.4.3 ELECTRON INTERACTIONS. Ingraham (Ref. 17) gives the collision cross section for cesium with electrons as about 10^{-14} to 10^{-13} cm² for electron energies in the low ev range. Even if all of the maximum number of atoms is concentrated within a layer of one centimeter thickness, one only has a density of $3 \times 10^6/\text{cm}^3$. An electron traveling in this medium would have a mean free path of about 10^7 cm. Since the cesium will not be concentrated in this manner and the estimate of the amount of cesium that is present is very high in the first place, the rate at which electrons will interact with the cesium will be small and there will be no effects.

3.4.4 RADIO WAVE INTERFERENCE. In a low density medium composed of simple ions and electrons, the interaction of radio waves with particles will be a function of the charge concentration. Examination of the governing equations shows that the mass of the particle acts to diminish the interaction. Since the mass of the cesium ion is so much greater than that of the electron, the effect of the ions may be neglected in comparison to the effect of the electrons. Electron densities typically are in the range of 10^3 to $10^6/\text{cm}^3$. The contribution that can be made by cesium ions will be negligible in comparison to the contribution made by the naturally occurring electrons, particularly when one takes into the account the fact that the electrons extend for a number of miles in thickness and the number of cesium ions (and corresponding electrons) will be negligible in comparison.

3.4.5 CHEMICAL REACTIONS. Cesium is a very reactive material and the possibility that it will enter into chemical reactions is likely. Certainly, this has been the case when it was introduced into the middle layers of the atmosphere as a tracer. However, the quantities that were introduced in this manner

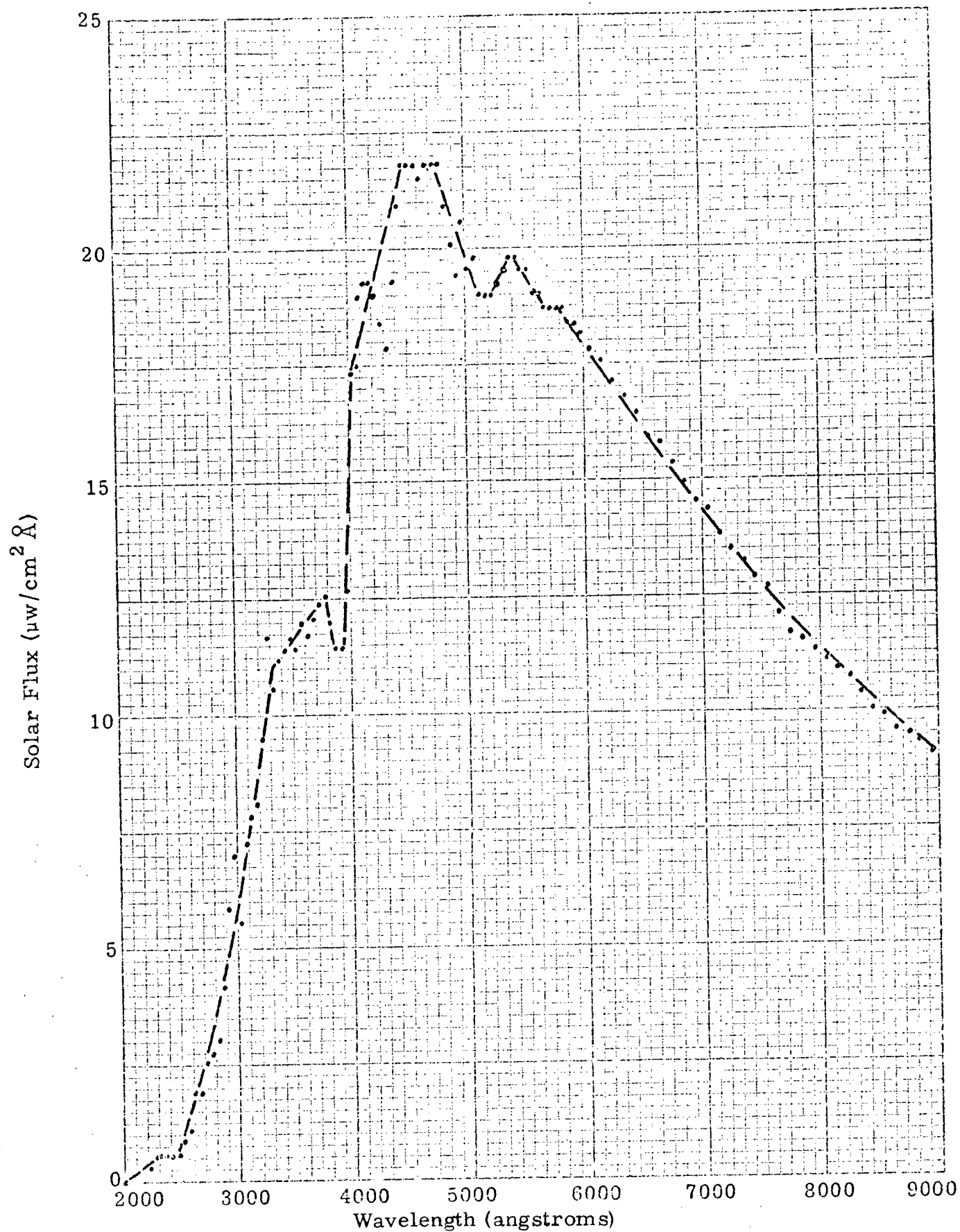


Figure 1. Solar Spectral Irradiance (Ref. 16)

were much greater within a small volume than will be the case for the thruster application. Even in these cases, the observable phenomena died out rapidly and no long term effects were found. Of course, these injections were made at a lower altitude than proposed here, and there is always the chance that something that was not anticipated will take place, but we could find nothing of this nature and feel that there will be no chemical effects that can be observed. A part of this conclusion is based on the observations to date and the other part is based upon the extremely low atom and ion densities that will be obtained. Unfortunately, a weakness of this study is that we have not undertaken a careful evaluation of the chemical reaction situation in order to present a good proof for these conclusions.

4. CONCLUSIONS

This study of the potential effects of the release of cesium in the form of ions and atoms from a thruster in the upper atmosphere has uncovered no phenomena of an observable nature. Most of the study has taken the form of a literature survey to determine the type of phenomena that may be expected. A few scoping types of calculations have been performed to allow the formation of semi-quantitative conclusions.

The cesium ions that are released from the thruster will become trapped within the earth's magnetic field. These will form a rarefied belt of charged particles, the density of which will be of negligible proportions when compared to the belts that are already there. The number that actually end up in the belt will depend in part upon the injection angles. The actual value was not predicted when it was found that no problems would result when all of the ejected material was assumed to be in the belt.

Cesium atoms released from the thruster will, if they do not become ionized by electron impact or photon interactions, either escape to space or move rapidly toward the lower regions of the atmosphere. The assumption that all of the material from the thruster ends up in a layer in the atmosphere was made and then the possible reactions were considered. None were found that were of an observable nature.

Cesium atoms that become ionized before reaching the lower regions of the atmosphere will behave in the same general manner as the ions that were injected directly. Similarly, the ions that manage to capture an electron will behave as atoms, again with no basic differences.

5. REFERENCES

1. James, E., et al., "A One Millipound Cesium Ion Thruster System," AIAA Paper No. 70-1149, AIAA 8th Electric Propulsion Conference, Stanford, Cal., August 31 - September 2, 1970.
2. Gerwin, H. L., "Applications Technology Satellites F and G," Society of Automotive Engineers, National Aeronautic and Space Engineering and Manufacturing Meeting, Los Angeles, Calif., October 5 - 9, 1970 (Paper No. 700759).

3. Lyon, Warren C., "Thruster Exhaust Effects Upon Spacecraft," NASA X-460-70-401, GSFC, Hittman Associates, October 1970.
4. Lyon, Warren C., "Thruster Exhaust Effects Upon Spacecraft," AIAA Paper No. 70-1143, AIAA 8th Electric Propulsion Conference, Stanford, Calif., August 31 - September 2, 1970.
5. Hunter, Robert E., Robert O. Bartlett, Robert M. Worlock, and Edmund L. James, "Cesium Contact Ion Microthruster Experiment aboard Applications Technology Satellite (ATS)-IV," Journal of Spacecraft and Rockets, Vol. 6, No. 9, September 1969, p. 968-970.
6. Kerslake, W. R., et al., "Flight and Ground Performance of the SERT II Thruster," AIAA Paper No. 70-1125, AIAA 8th Electric Propulsion Conference, Stanford, Calif., August 31 - September 2, 1970.
7. Chemical Reactions in the Lower and Upper Atmosphere, Stanford Research Institute, Symposium Proceedings, April 18 - 20, 1961, Interscience Publishers, 1961.
8. Rosenberg, N. W. (Ed), "A Summary Report, Project Firefly 1962 - 1963," Cambridge Research Laboratory, Rept. AFCRL 64-364, May 1964.
9. Knauer, W., "A Prediction of Environmental Effects Caused by Mercury Ions from Ion Rockets," Hughes Research Laboratories, no number or date, transmitted by letter to Channing C. Conger, NASA Lewis, April 10, 1970.
10. Masica, William J., "Evaluation of SERT II Ion Emission," NASA Lewis Memo, no number, March 23, 1970.
11. Jahn, Robert G., Letter to Jerome P. Mullin, NASA Office of Advanced Research and Technology, Washington, from Princeton University, Dept. of Aerospace and Mechanical Sciences, March 26, 1970.
12. Kellogg, W. W., "Pollution of the Upper Atmosphere by Rockets," Space Science Reviews 3, 1964, p. 275-316.
13. Kerslake, W. R., et al., "Flight and Ground Performance of the SERT II Thruster," AIAA Paper No. 70-1125, AIAA 8th Electric Propulsion Conference, Stanford, Calif., August 31 - September 2, 1970.
14. Cole, Robert K., et al., "Ion Beam Neutral Component Determination by Resonance Radiation Absorption," AIAA Journal, Vol. 3, No. 2, February 1965, p. 263-269.

15. Weast, Robert C., and Samuel M. Selby, Handbook of Chemistry and Physics, 48th Ed., Chemical Rubber Co., 1967 - 1968.
16. Johnson, F. S., "The Solar Constant," Journal Meteorology 11 (6), December 1954, p. 431-439.
17. Ingraham, J. C., "Electron - Atom Collision Cross - Section Measurements In The Afterglow Of A Pulsed Cesium Plasma," contained in Perovic, B., and Tomic, D., Proceedings of the Seventh International Conference on Phenomena in Ionized Gases, Beograd, 22-27 August 1965; Gradevinska Knjiga Publishing House, 1966, p. 57-60.

APPENDIX I BEHAVIOR OF MATERIAL IN THE UPPER ATMOSPHERE

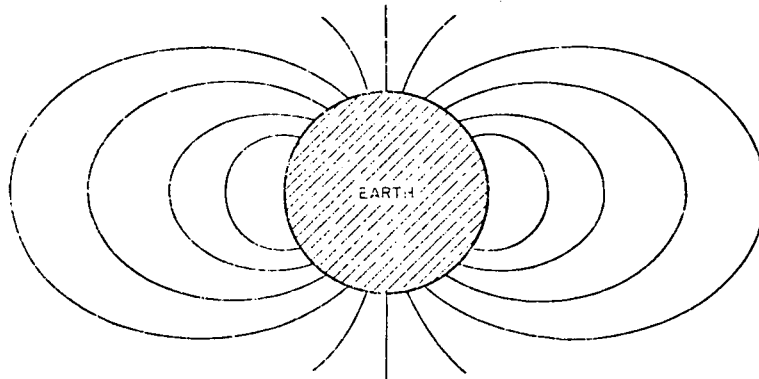
1. BACKGROUND

Cesium released at orbital altitudes will exist in principally two forms, neutral and ionized atoms. There will be few if any molecules and, for practical purposes, no particulate matter. Some aluminum can be expected which will originate from the thruster accelerator structure, but there will be few other contaminants. Cesium used in thrusters is relatively pure. The quantity of aluminum that appears will be small since, for it to be otherwise, thruster life would be short. This study will be limited to the cesium that is ejected since it will be the material present to the greatest degree and it is as active optically as any of the other substances likely to be present.

Several phenomena need to be considered in order to predict what happens to the released cesium. Foremost will be the effects upon charged material. Most of the exhaust will be ionized, and the atomic cesium that is released will have a high probability of becoming ionized under many of the conditions that may exist. Therefore, the behavior of charged particles that are released should be considered to see if any interesting events are taking place. This does not mean that the neutrals can be neglected. Interesting events may take place with these as well, even though their population probably will be smaller. The greatest effect upon the charged cesium probably will be due to the magnetic field of the earth until rather low altitudes are reached. The behavior will be similar to that of charged particles in the earth's radiation belts. Uncharged cesium will be affected by the earth's gravitational field as well as by the forces of sunlight. And, of course, the usual events of collision phenomena can be expected upon inter-particle collisions. Although these events probably will not occur too often, they will be briefly considered just in case something of interest is taking place.

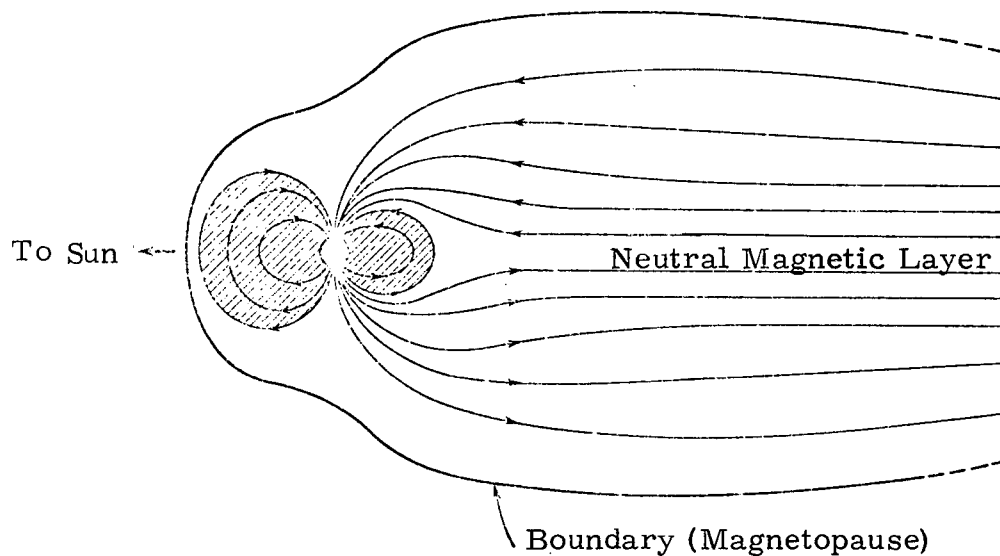
2. BEHAVIOR OF CHARGED PARTICLES IN THE EARTH'S UPPER ATMOSPHERE

Since a particle carrying a charge will be subjected to forces originated by the earth's magnetic field, we first review the shape of that field. As a rough approximation the field may be treated as shown in the following sketch:*



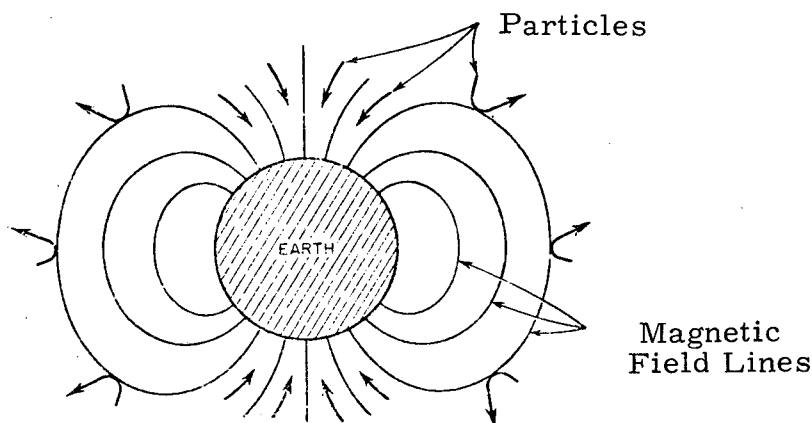
* These sketches are reproduced from Glasstone (Ref. I-1).

There are, of course, many variations within the indicated envelope. The north and south poles do not coincide with geographic poles and there are many local variations in the field. This concept of the magnetic field is only good for locations close to the surface of the earth. As we move further out, the effect of the solar wind must be taken into consideration. An indication of the distance the field extends in the direction of the sun may be obtained by considering energy densities. A comparison of the kinetic energy densities of the solar wind and of the magnetic field will show that the magnetic field cannot extend more than about 10 earth radii (about 40,000 miles) in the direction of the sun. On the back side of the earth (away from the sun) the situation is much different because of the shadowing effect of the earth and its magnetic field. The overall behavior is as indicated in the following sketch:



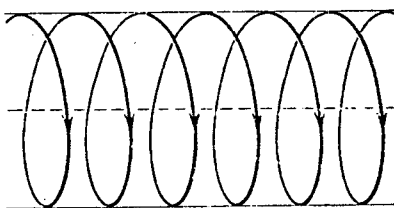
Beyond the magnetopause boundary (away from the earth) the magnetic field is reasonably stable. The same is roughly true of the field close to the earth. The region located just within the boundary is quite turbulent and subject to large variations in magnetic flux.

This boundary may be perturbed by action of the sun. In one effect, a quantity of plasma may be expelled from the sun's surface. This appears to become trapped in a sort of magnetic bottle that travels toward the earth. When the bottle hits the magnetopause boundary, a distortion takes place, and some of the charged particles become available to be trapped by the earth's magnetic field. Since these will not in general have sufficient energy to penetrate the magnetic field lines, they will be deflected along the lines and enter the earth's atmosphere near the poles:

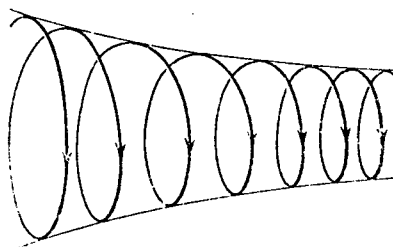


Most of these particles will be protons and they will possess energies in the Mev range, considerably above the energy of the cesium atoms with which we are concerned. Certainly, then, if the protons cannot penetrate the magnetic lines, the cesium will not be able to do so. The proton behavior and associated phenomena consequently will provide a guide for the cesium behavior.

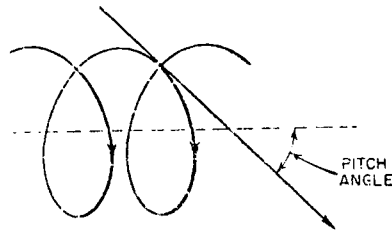
In general, any charged particle will be subjected to a force by a magnetic field. This force will act at right angles to the field direction and to the direction of particle motion. This means that a charged particle moving in a uniform magnetic field will follow a spiral path:



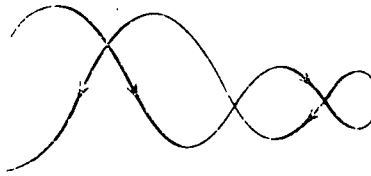
In a non-uniform field the behavior is similar, although not identical. Suppose, for example, the field is increasing in strength in moving from left to right. Then the spiral radius also will decrease when moving in the same direction:



If the particle direction were in the opposite direction, the radius would increase as the field strength decreased. Further, and this is important to the behavior, the helix that is formed in moving in the direction of increasing field strength becomes tighter; its pitch angle decreases:

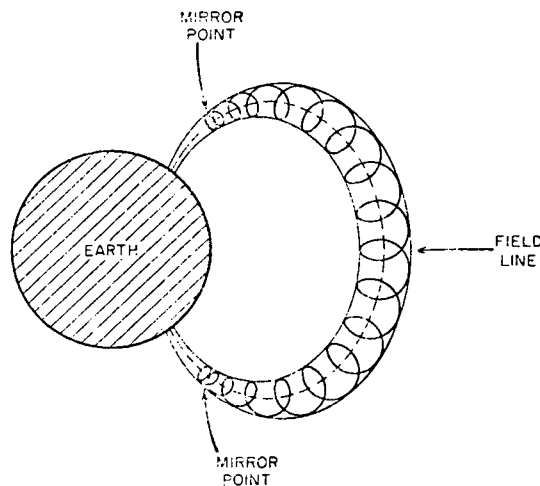


If the effect becomes strong enough, the pitch angle can reach 90° , and the net direction of motion of the particle can be reversed:



The particle now will spiral in the opposite direction. This reversal of direction is referred to as "reflection" in a "magnetic mirror". The point where the reversal occurs is referred to as the "mirror point".

This behavior now may be applied to the earth's field. In general, the strength is greatest near the surface and in the vicinity of the poles. Therefore the motion of a particle trapped by the earth's magnetic field will be about as shown in the following sketch:



Since the magnetic field rotates with the earth, and since the particles cannot move across the magnetic lines, the particles will tend to rotate with the earth as well as being reflected back and forth from pole to pole. If there were no other effects, a particle never would move around the earth. However, the decreasing strength of the magnetic field with altitude introduces a radial (east-west) force component upon the particles. (Positively charged particles are exposed to an east to west force; negatively charged ones to a west to east force.) This in turn introduces a small radial movement, causing a toroidal shaped belt of charged particles to be formed.

There are restrictions upon the trapping process; not all particles that are released within the magnetic field will become trapped with a reasonably long life. The reason for this behavior is the location of the mirror point. A minimum condition for reflection is:

$$v_{\perp} / v = \sqrt{B/B_m} \quad (I-1)$$

where:

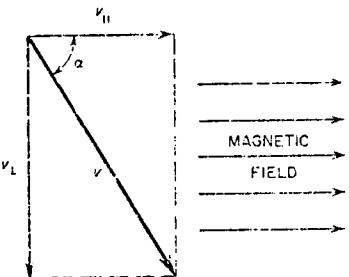
v = actual velocity

$v_{\perp}$ = perpendicular velocity vector with respect to the magnetic field

B = field strength in the region between mirrors where it is relatively uniform

B_m = field strength at the mirror point

Note that the actual value of the velocity is not important, provided it is low enough that the particle does not cross the magnetic lines. It is the ratio that is important. If the component perpendicular to the lines is too small, the mirror point may be located within the dense atmosphere (or even within the earth). When this is the case, of course, the particle will not be reflected but instead will be absorbed within the atmosphere and removed from the region of interest. Another way of looking at the problem is to consider the angle involved:

$$\sin \alpha = \sqrt{B/B_m} \quad (I-2)$$


This will be of more use for our purposes. If it shows that the reflection point occurs at an altitude of less than a few hundred miles, then the particles will not be reflected very many times prior to removal.

A uniformly magnetized sphere can be described by the following (Ref. I-2).

$$H = H_0(a/r)^3 \sin \theta \quad (I-3)$$

$$Z = 2H_0(a/r)^3 \cos \theta \quad (I-4)$$

$$B = (H^2 + Z^2)^{1/2} \quad (I-5)$$

$$V = (M/r^2) \cos \theta \quad (I-6)$$

$$M = H_0 a^3 \quad (I-7)$$

where:

H	=	horizontal magnetic field intensity vector component
H ₀	=	horizontal intensity at the equator (Z = 0) ≈ 0.31 gauss
a	=	sphere radius
r	=	distance from center of sphere
θ	=	polar angle
Z	=	vertical magnetic vector component
B	=	scalar field intensity
V	=	magnetic potential
M	=	magnetic dipole moment

For locations near to the earth, this is good to about 90 percent accuracy.

Selecting $\theta = 90^\circ$, and $r = r_m$, we find:

$$B_m = H_0 \left(\frac{a}{r_m} \right)^3 \quad (I-8)$$

At $\theta = 0$:

$$B = H_0 \left(\frac{a}{r} \right)^3 \quad (I-9)$$

and:

$$\sin \alpha = \left(\frac{r_m}{r} \right)^{3/2} \quad (I-10)$$

where r now represents the distance from the center of the earth where the particle is "injected" into the magnetic field.

3. REFERENCES

- I-1 Glasstone, Samuel, Sourcebook on the Space Sciences,
 Van Nostrand, 1965.
- I-2 Hess, Wilmot N., (Ed), Introduction to Space Science,
 Gordon and Breach, 1965.

APPENDIX II

CESIUM SPECTRAL CHARACTERISTICS AND ABSORPTION PHENOMENA

1. INTRODUCTION

In this appendix we will review the calculation of interaction photons in the visible and near-visible energy range. The review will be conducted only, for practical purposes, with respect to interactions that take place at very low particle densities. High densities, such as occur at atmospheric or near atmospheric conditions, will be of no interest.

2. TERMINOLOGY

Wavelengths commonly are given in microns (μ , 10^{-6}m or 10^{-4}cm) and angstroms ($\text{\AA}$, 10^{-8}cm). Many times, wave numbers are used:

$$\tilde{\nu} = \frac{1}{\lambda}$$

where:

$$\tilde{\nu} = \text{wave number (usually cm}^{-1}\text{)}$$

$$\lambda = \text{wavelength}$$

This should be interpreted as the number of waves per centimeter, or simply waves/cm. Frequencies are seldom used because of the size of the number (c/λ where c is the velocity of light). Wavelengths in air and vacua differ by about one part in 3000. We will neglect the difference. Wave numbers occasionally are given in Kaysers. This is simply cm^{-1} . Frequency, ν , is related to the wave number by:

$$\nu = c\tilde{\nu}$$

where ν typically has units of sec^{-1} (waves per second).

Energy is a common term. It may be related by:

$$E = h\nu$$

where:

$$\begin{aligned} h &= \text{Boltzmann constant} \\ &= 6.625 \times 10^{-27} \text{ erg sec} \end{aligned}$$

Inserting appropriate constants gives:

$$\tilde{\nu} = 8066 \text{ E cm}^{-1} (\text{E in ev})$$

$$\lambda = 12398/\text{E A} (\text{E in ev})$$

The Rydberg constant many times appears. This is $R = 109,700 \text{ cm}^{-1}$. (It varies in the fourth significant figure for different atoms. The difference is, for our purposes, negligible.) This corresponds to the first state of the hydrogen atom ($\tilde{\nu} = 109,678 \text{ cm}^{-1}$; $E = \text{energy} = 217.3 \times 10^{-13} \text{ ergs}$, = 13.58 ev).

3. PHOTON - ATOM INTERACTIONS

3.1 BACKGROUND. Photon - atom interactions normally involve the outermost electrons of the atom. Since a certain minimum energy is needed before an electron can be affected, those photons which do not possess the necessary energy cannot interact, and will pass an atom with no effect. The orbital electrons can only exist in an atom in certain allowed energy levels. Existence between these levels does not occur. Therefore, for a photon to interact, we also require that it have about the same energy as required by the electron to move from one level to another. If more photon energy is available than the electron can absorb without being ejected from the atom, then such ejection is possible, and the atom will become ionized since a negative charge has been removed. The excess energy above that required for ionization will appear as kinetic energy of the electron (or possibly as excitation energy of another electron). Interactions with ionized atoms also are possible, but normally this event will not occur as often, all other things being the same, because the energy required for the process is much higher than for reactions with neutral atoms.

3.2 PHOTON ABSORPTION AND EMISSION. If one applies classical theory, one finds that the frequencies emitted by an atom are identical to the atom's natural frequencies. One would assume that if photons of these frequencies are intercepted by the atom, the atom would be excited, and those photons could be absorbed. Stated differently, the absorption spectrum and emission spectrum would be the same. In some cases, this is observed experimentally. In other cases, it is not. Some atoms are completely transparent to photons which it emits in copious quantities when excited.

The explanation is straightforward. If we were exciting an atom by electron bombardment, the only requirement would be that the electron energy equal or exceed the energy required to displace an orbital electron to a different energy level. Excitation by absorption is different. It takes place only when the incoming photon energy is almost precisely the same as that required to move the electron from one level to another. Immediately, we conclude that the atom (or more properly, the gas composed of many atoms) will be completely transparent to photons whose energies do not coincide with the orbital electron transition differences.

Next, we must consider the original state of the atom. An excited atom will emit photons by movements of orbital electrons from one level to a lower level. Each jump will correspond to a particular wavelength. It is quite possible to excite an atom from the ground state to a higher level state, and then

have several photons emitted as the atom decays back to the ground stage by an orbital electron jumping from level to level. In the initial process of excitation, we might absorb one photon. In the decay process, where several photons might be emitted, we would see a different response or spectrum. To absorb a photon of an energy corresponding to a particular spectral line, we first require that the atom be at the level corresponding to the lower level of the quantum jump.

Various energy levels for atoms can be calculated. In theory, the calculation may be performed for about any atom. In practice the complexity of the calculation process allows computations only for very simple configurations. Of much more use for most investigations are tabulated data of spectral characteristics. These data normally are given to a great many significant figures. The implication is that the absorption process is one in which a photon, to be absorbed, must have an energy that is no further removed from the absorption line value than is given by the number of significant figures in the tables. This is not the case. In practice, a photon energy may be far removed from the tabulated line energy and still be absorbed. The reason is due to a phenomenon termed line broadening.

A number of things contribute to line broadening. Most line broadening is due to interaction of the excited atom with its surroundings during or following the decay process. Inherent in the emission process is the effect of the finite time the excited atom exists. The probability an atom lives in the excited state decreases exponentially with time. To measure the system energy with high precision, one must utilize a means of measurement which does not limit the time interval during which the measurement is obtained. If we measure characteristics for a short time, an indeterminacy is introduced. The shorter the time, the greater the uncertainty. An analytical analysis of the effect shows that the profile of a spectral line due to finite lifetime of the excited atom is a curve with the width inversely proportional to the decay time. This may be expressed by (Ref. II-1):

$$dI = I(E)dE = \frac{I_0 \Gamma h^{-1} dE}{\Gamma^2/4 + (E - E_0)^2/h^2} \quad (\text{II-1})$$

where:

- | | | |
|----------|---|---|
| I | = | intensity of light with quantum energy between E and $E + dE$ |
| Γ | = | reciprocal of mean life of the excited state |
| E_0 | = | average photon energy |
| I_0 | = | total rate of emission of energy in the transition |

$$\begin{aligned}
h &= \text{Planck's constant} \\
&= 6.5817 \times 10^{-16} \text{ ev sec} \\
&= 6.62 \times 10^{-27} \text{ erg sec}
\end{aligned}$$

Richtmyer (Ref. II-2) gives an approximation for transitions involving the ground state:

$$\Delta = \frac{\lambda^2}{2\pi c\tau} \quad (\text{II-2})$$

where:

$$\begin{aligned}
c &= \text{speed of light} \\
\tau &= \text{mean life of level}
\end{aligned}$$

or, if two excited levels are involved:

$$\Delta = \frac{\lambda^2}{2\pi c} \left(\frac{1}{\tau_1} + \frac{1}{\tau_2} \right) \quad (\text{II-3})$$

This type effect is, as we mentioned, inherent in the process and will occur regardless of the surroundings.

The observed spectral line frequency may be changed from that emitted relative to the atom due to the motion of the radiating atom. This is called the Doppler effect. The line apparent frequency increases if motion is toward the observer and decreases if motion is away from the observer. The actual frequency emitted corresponds to the observed frequency only when there is no velocity component in the direction of the observer. Normally, atoms in a gas will be moving with a Maxwellian type of velocity distribution. Consequently, the observed spectral line emitted by such a gas will be comprised of a range of frequencies. Since the velocity distribution broadens with increasing temperature, the observed range of frequencies also will broaden with temperature. This may be described by (Ref. II-2):

$$\Delta = 0.72 \times 10^{-6} \lambda \sqrt{\frac{T}{M}} \quad (\text{II-4})$$

where:

$$\begin{aligned}
\Delta &= \text{width of line, wavelength units} \\
\lambda &= \text{wavelength} \\
T &= \text{absolute temperature, } ^\circ\text{K} \\
M &= \text{atomic weight}
\end{aligned}$$

For this study under rarified conditions, this equation probably should not be applied. There are several reasons. First, the equation is based upon a continuous medium with only one component. Neither of these conditions is satisfied in the rarified atmosphere of orbital altitudes. Second, the velocity distribution is not necessarily Maxwellian due to the various processes involved. Finally, the interatomic collision rate will be so small that the effect probably is negligible insofar as collision phenomena are concerned. Instead, one would be interested in the velocity vectors which were existing due to other phenomena.

The spectrum also will be affected by external forces. These effects will be neglected. This is probably a good assumption for cases such as electrical and magnetic fields (The Stark and Zeeman effects, respectively). Such fields would have to be much stronger than exist here to cause a perturbation in the reported results.

Aller (Ref. II-3) has presented a relatively straightforward treatment of photon-atom interactions and his approach will be followed here. He introduces the Einstein coefficient of spontaneous emission, $A_{nn'}$, in the equation:

$$N_{\nu'} = N_n A_{nn'} \quad (\text{II-5})$$

where:

$N_{\nu'}$ = number of quanta of frequency $\nu(nn')$ emitted per unit volume per unit time

N_n = number of atoms per unit volume at level n

and the spontaneous decay is from n to n' . If radiation of frequency $\nu(nn')$ strikes atoms in level n , the atoms can be triggered into decaying with the emission of photons $\nu(nn')$. When this occurs, the total number of downward transitions becomes:

$$N_{\nu'} = N_n (A_{nn'} + B_{nn'} I_{\nu(nn')}) \quad (\text{II-6})$$

where:

$B_{nn'}$ = coefficient of induced emission or negative absorption

$I_{\nu(nn')}$ = photon intensity, ergs/cm^2

The interesting aspect of this behavior is the directionality. The induced photon emission is in the direction of the quantum responsible for the triggering.

Directly applicable to the absorption process is the effect predicted by B. If atoms of a lower level n' are exposed to photons of frequency $\nu(nn')$ at an intensity $I_{\nu(nn')}$, the number of upward transitions per unit volume per unit time is:

$$N_{\nu'} = N_{n'} I_{\nu(nn')} B_{n'n} \quad (\text{II-7})$$

Note that $B_{nn'} \neq B_{n'n}$, but they may be easily related. All substituted for $I_{\nu(nn')}$ the Planckian function for intensity*:

$$I_{\nu} = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} \quad (\text{II-8})$$

The following relationships may be shown to hold between them:

$$\tilde{\omega}_n B_{nn'} = \tilde{\omega}_{n'} B_{n'n} \quad (\text{II-9})$$

$$\frac{\tilde{\omega}_n}{\tilde{\omega}_{n'}} A_{nn'} = B_{n'n} \frac{2h\nu^3}{c^2} \quad (\text{II-10})$$

Here $\tilde{\omega}_n$ is the statistical weight of level n . If its inner quantum number is J ,

$$\tilde{\omega}_n = 2J + 1 \quad (\text{II-11})$$

The quantum-mechanical damping constant for pure radiation damping $\Gamma_{nn'}$ may be expressed in terms of the Einstein coefficients:

$$\Gamma_{nn'} = \Gamma_n + \Gamma_{n'} \quad (\text{II-12})$$

where:

$$\begin{aligned} \Gamma_n &= \sum_{n'} A_{nn'} (1 - e^{-h\nu/kT})^{-1} \\ &+ \sum_{n''} A_{n''n} \frac{\tilde{\omega}_{n''}}{\tilde{\omega}_n} (e^{h\nu/kT} - 1)^{-1} \end{aligned} \quad (\text{II-13})$$

The first summation is taken over all levels n' lower than n ; the second over all levels n'' above level n . If the intensity of the radiation is not large:

*This intensity is not the usual one with which the reader may be familiar. The units are:

$$I \equiv \frac{(\text{erg sec})(\text{sec})^{-3}}{(\text{cm/sec})^2} \equiv \text{erg/cm}^2$$

This is perhaps more properly termed an intensity distribution function. The true intensity over a frequency range $d\nu$ is $I d\nu$ erg/cm²-sec. The units of B immediately follow as cm²/erg-sec.

$$\Gamma_n = \sum_{n'} A_{nn'} \quad (\text{II-14})$$

One may show that the Einstein A value is related to the f value by:

$$A_{nn'} = \frac{8\pi^2 e^2 \nu^2}{mc^3} \frac{\tilde{\omega}_{n'}}{\tilde{\omega}_n} f_{nn'} \quad (\text{II-15})$$

In addition to f values and Einstein coefficients, it is useful to introduce the "line strength," a quantity which is symmetrical in the upper and lower levels:

$$f(\alpha'J'; \alpha J) = \frac{8\pi^2 mc}{3he^2} \frac{1}{\tilde{\omega}'_\lambda} S(\alpha'J'; \alpha J) \quad (\text{II-16})$$

where the primes denote the lower level. The expressions for the strengths do not explicitly involve the wavelengths or frequencies of the emitted radiation, whereas the Einstein coefficients and f's do. This means that if we are concerned with multiplets or configuration arrays in which the lines fall at different wavelengths, we may obtain the relative strengths quickly from appropriate tables or formulas (at least for atoms in good LS coupling) whereas the relative f or A values require that the wavelength of each line be included.

Like the f or A value, the strength of a line is an atomic constant. The intensity, however, depends on the physical excitation conditions. The relative, as well as the absolute, intensities of the lines in a given spectrum will vary in a more or less complicated fashion with change of excitation conditions. A knowledge of the relative intensities of the lines in a spectrum is of little help in obtaining empirical line strengths unless something is known about the mode of excitation.

In addition to the absorption oscillator strengths, an emission oscillator strength is defined as:

$$f_{nn',2} = \frac{\tilde{\omega}_{n'}}{\tilde{\omega}_n} f_{n'n} \quad (\text{II-17})$$

Although it is necessary to use the emission oscillator strengths in problems such as the application of sum rules, ordinarily it is better to employ conventional Ladenburg f values.

To compute effects, we rewrite Equation (II-10):

$$B_{n'n} = \frac{\tilde{\omega}_n}{\tilde{\omega}_{n'}} \frac{c^2}{2h\nu^3} A_{nn'} \quad (\text{II-18})$$

Next substitute Equation (II-15):

$$B_{n'n} = \frac{4\pi^2 e^2}{hmc\nu} f_{nn'} \quad (\text{II-19})$$

Substitution into Equation (II-7) gives:

$$N_{\nu'} = N_{n'} I_{\nu}(nn') \frac{4\pi^2 e^2}{hmc\nu} f_{nn'} \quad (\text{II-20})$$

which shows the photon absorption rate to be directly proportional to the number of atoms per unit volume.

Note that $\nu = c/\lambda$, so that Equation (II-20) can be rewritten:

$$N_{\nu'} = N_{n'} I_{\nu}(nn') \frac{4\pi^2 e^2 \lambda}{hmc^2} f_{nn'} \quad (\text{II-21})$$

This equation makes it possible to compute absorption effects.

As the ionization limit is approached, the lines become closer together and, as the limit is passed, a continuous phenomenon is found. The cross sections for these processes are low and the atom populations that can interact in this region probably also will be low. If the possible interaction rate can be shown to be no problem in regions of high reaction probability when all of the existing atoms are assumed to be in those regions, then other regions do not need to be considered. This is the approach we will follow in this investigation. The implication is that the predicted wavelengths will not be correct, but the order of magnitude of the predicted results will be higher than would occur in the actual situation.

Molecular absorption coefficients normally are higher than those of atoms or ionized atoms. This will be of no concern for the study being considered here because the probability of finding cesium molecules will be close to non-existent.

3.3 IONIZATION AND RECOMBINATION. The behavior for photoionization is treated in much the same manner as photon absorption without ionization. Following McDaniel (Ref. II-5), we recall:

$$I = I_0 e^{-\mu x} \quad (\text{II-22})$$

where:

- I = final intensity
- I_0 = initial intensity
- μ = absorption coefficient, cm^{-1}
- x = gas thickness, cm

Also:

$$\mu = q_p N \quad (\text{II-23})$$

where:

$$\begin{aligned} q_p &= \text{microscopic photoabsorption cross section} \\ N &= \text{number density of the gas} \end{aligned}$$

For the absorption equation to hold, we require that the radiation be nearly monochromatic so that there is no change in effective absorption with position and μ must be independent of gas temperature and pressure. The second condition is satisfied if changes in p and T do not significantly change the gas composition (for example, by molecular association or dissociation).

Photoionization cross sections may be related to the cross section for capture of an electron by:

$$\frac{q_c(v)}{q_p(\lambda)} = \frac{\Omega_i e}{2\Omega_f m c^2} \frac{V_p^2}{300 V_e} \quad (\text{II-24})$$

where:

$$\begin{aligned} q_c &= \text{radiative capture cross section (for electron capture)} \\ v &= \text{electron velocity} \\ \Omega_i &= \text{initial state statistical weight} \\ \Omega_f &= \text{final state statistical weight} \\ e &= \text{electronic charge} \\ m &= \text{electronic mass} \\ V_p &= \text{potential (volts) corresponding to the energy of the incident photon} \\ V_e &= \text{potential (volts) corresponding to the energy of the ejected electron} \end{aligned}$$

From quantum mechanics:

$$h\nu = \frac{hc}{\lambda} = \frac{e(V_i + V_e)}{300} = \frac{eV_p}{300} \quad (\text{II-25})$$

where:

$$\begin{aligned} \nu &= \text{incident radiation frequency} \\ \lambda &= \text{incident radiation wavelength} \\ V_i &= \text{ionization potential of the neutral structure} \end{aligned}$$

The photoabsorption cross sections for atomic systems are essentially equal to the cross sections for photoionization. (This is not true for molecular systems because a multiplicity of absorption mechanisms is available.) Interestingly, an appreciable amount of molecular absorption may occur in vapors that are predominantly monoatomic, such as the alkalis. The molecular absorption cross sections are high enough that the cross sections may not be ignored if a large number of collisions are taking place. Since, for this study, the probability of a cesium atom colliding with another cesium atom will be almost zero, the process may be neglected.

The alkali vapors can be ionized by ultraviolet photons. The relationship describing this behavior is:

$$h\nu_i = h\frac{c}{\lambda_i} = eV_i \quad (\text{II-26})$$

where:

$$\begin{aligned} \nu_i &= \text{threshold frequency} \\ \lambda_i &= \text{wavelength for ejection of the least tightly bound electron} \\ V_i &= \text{first ionization potential} \\ h &= \text{Planck's constant} \\ c &= \text{velocity of light in a vacuum} \end{aligned}$$

Further:

$$\lambda_i = \frac{12398}{V_i} \quad (\text{II-27})$$

where λ_i is given in angstroms and V_i is in volts. Ionization at wavelengths longer than the threshold value can occur in a two step process involving an atom that has already been excited. Wavelengths shorter than λ_i are required to eject electrons other than the one with the smallest binding energy in the atom.

For hydrogen-like structures, we may compute cross sections from the equation:

$$q_p(\nu, n) = \frac{g(32\pi^2 e^6 RZ^4)}{(3^{3/2} h^3 \nu^3 n^5)} \quad (\text{II-28})$$

where:

$$\begin{aligned} R &= \text{Rydberg constant} \\ N &= \text{principal quantum number of the initial state} \\ g &= \text{factor (see, Refs. II-6 and II-7)} \end{aligned}$$

Marmo (Ref. II-8) and Ditchburn (Ref. II-7) provide additional information. According to Marmo, the probability of photoionization of a cesium atom in the upper atmosphere is 6.5×10^{-4} per atom per second.*

Recombination is described by:

$$R = \alpha n^+ n^- \quad (\text{II-29})$$

where:

- R = number of recombination events per unit time and volume
- n = number density of each of the charge carriers
- α = recombination coefficient (cgs units of cm^3/sec)

The recombination coefficient can be related to the recombination cross section by:

$$\alpha = \int_0^\infty v_o q_r(v_o) f(v_o) dv_o \quad (\text{II-30})$$

where:

- $f(v_o) dv_o$ = fraction of encounters between positive and negative particles in which the relative velocity lies between v_o and $v_o + dv_o$

For most cases, α can be approximated by:

$$\bar{\alpha} = \bar{v}_o q_r(\bar{v}_o) \quad (\text{II-31})$$

where $\bar{v}_o$ is the mean value of v_o .

Radiative recombination behaves according to:



For thermal electrons ($\sim 300\text{K}$), radiative recombination coefficients are in the range of 10^{-11} to $10^{-12} \text{ cm}^3/\text{sec}$ for various positive ions.

Bates (Ref. II-9) has studied electron-ion recombination for optically thin plasmas. He wrote the equation:

$$Y = \alpha - SXn(1)/n(c) \quad (\text{II-33})$$

*Cross section times intensity

where:

γ	=	effective two body rate coefficient or collisional-radiative decay coefficient
α	=	collisional-radiative recombination coefficient
S	=	collisional-radiative ionization coefficient
X	=	$n(c) / n(N^+)$
$n(1)$	=	number density of atoms or ions in the first level
$n(c)$	=	number density of free electrons
$n(N^+)$	=	number density of singly charged ions

He neglects electronic transitions due to atom-atom, atom-ion, and ion-ion collisions. He further supposes all radiation escapes without absorption. Further:

$$\frac{\gamma}{X} = n(1) / n(c)^2 \quad (\text{II-34})$$

where:

$$n(1) = \text{rate of disappearance of free charges}$$

$$n_S(1) = \alpha n(c) / XS \quad (\text{II-35})$$

$$\dot{n}(1) = \gamma n(c) n(N^+) = -\dot{n}(N^+) \quad (\text{II-36})$$

Some of his tables provide data for a modified hydrogen atom which serves as a crude model of an alkali atom with excitation potential 1.9 eV and ionization potential 3.4 eV. (This is close to cesium.)

Marmo (Ref. II-8) points out a serious discrepancy between theoretical and experimental determinations of electron-ion recombination rates and concludes other processes besides radiative recombination are taking place.

The collision frequency between electrons and neutrals in the gas phase is given by (Ref. II-10):

$$\nu = \left(\frac{8kT_e}{\pi m_e} \right)^{1/2} \sum n_i Q_i \quad (\text{II-37})$$

where:

$$\nu = \text{collision frequency, sec}^{-1}$$

$$k = \text{Boltzmann constant } 1.38 \times 10^{-16} \text{ erg/}^\circ\text{K}$$

$$\begin{aligned}
T_e &= \text{electron temperature, } ^\circ\text{K} \\
m_e &= \text{electron mass} \\
n_i &= \text{number of atoms of specie } i \text{ per cm}^3 \\
Q_i &= \text{collision cross section of specie } i, \text{ cm}^2
\end{aligned}$$

Elastic electron-atom collisions are important only in high pressure plasmas (Ref. II-11). Inelastic electron-atom collisions are important in both low and high pressure nonequilibrium plasmas.

Nygaard (Ref. II-12) presents cross section data for electron-impact ionization. First, we write the electron mean free path as:

$$\Lambda = (n\sigma)^{-1} \quad (\text{II-38})$$

where:

$$\begin{aligned}
n &= \text{cesium density, atoms/cm}^3 \\
\sigma &= \text{cross section, cm}^2
\end{aligned}$$

The slope of the 6s cross section curve is $2.7 \text{ A}^2/\text{eV}$ from $\sigma = 0$ to $\sim 7 \text{ A}^2$. It reaches a maximum of about 9.5 A^2 at $\sim 15 \text{ eV}$ and the total cross section curve never exceeds this value (to the reported limit of the study at 100 eV).

Another equation which can be used to compute the rate of ion production in a gas column due to electron impacts is:*

$$v_i = nn_a d K_I \exp\left(-\frac{V_I}{kT_e}\right) \quad (\text{II-39})$$

where:

$$\begin{aligned}
n &= \text{electron (gas) density} \\
n_a &= \text{atom density} \\
d &= \text{gas column depth} \\
K_I &= \text{factor which includes differential ionization cross section of the gas averaged over all excited states (and other quantities which are weakly dependent on } n, T_e, \text{ and } T_E \text{ if recombination is negligible)} \\
V_I &= \text{ionization potential of unexcited atom if all excited atoms and their resonance photons are rapidly lost from the plasma}
\end{aligned}$$

*Derived for emission of electrons from a hot surface.

(when excited atoms and their resonance radiation are preferentially trapped in the plasma, V_I becomes the excitation energy for the limiting step leading to ionization.)

k = Boltzmann constant
 T_e = electron (gas) temperature
 T_E = emitter temperature

The total effective emission current from the neutralizer (emitter) is:

$$J_s = J_S + J_i \quad (\text{II-40})$$

where:

J_s = total current
 J_S = Schottky enhanced emission current
 J_i = positive ion current from the ions

$$J_S = J_{S'} \exp(4.4E^{1/2}/T_E) \quad (\text{II-41})$$

where:

E = field strength, volts/cm
 T_E is in $^{\circ}\text{K}$
 $J_{S'}$ = zero field electron emission current density

The zero electrical field electron emission current density is:

$$J_{S'} = AT_E^2 \exp(-\phi_E/kT_E) \quad (\text{II-42})$$

where:

A = Richardson constant
 T_E = emitter temperature
 ϕ_E = emitter work function
 k = Boltzmann constant

which can be applied to predict these characteristics.

Additional information in these general areas can be obtained from Hansen (Ref. II-13) and Dayton (Ref. II-14).

Many of the referenced tables are reproduced by Lyon (Refs. II-15 and II-16), who also presents a more detailed discussion of some of the events which are taking place.

4. RADIO-FREQUENCY INTERFERENCE (RFI)

There are two basic means for interaction of radio waves with ionized particles. In the first, charged particles may attenuate a signal by energy removal. In the second, a wave can be changed in direction as it moves from a region carrying one charge density to one with a different density. In the first, if the charged particle density is sufficient high, the signal may be absorbed completely; in the second, waves may be completely reflected, as in the ionosphere.

The interaction mechanism is one of transfer of energy to the charged particle with a resulting oscillation of the particle. If there is no interaction of an atomic particle with a surrounding medium, it eventually will reradiate the energy at the same frequency as the one absorbed. If there is such an interaction, as will occur in an event with another particle, some of the energy may be transferred, and as a result the radio energy is permanently lost. In the atmosphere at low altitudes (about 40 or 50 miles), collisions will occur at a rapid rate, and if there is a large charged particle density, the wave will be attenuated very rapidly. At orbital altitudes, the ambient densities are much less, and there is a high probability that the absorbed energy will be re-radiated.

The phase change velocity of radio-frequency waves traveling through a medium may be calculated from (Ref. II-17):

$$u = \frac{c}{\sqrt{1 - \frac{ne^2}{\pi mf^2}}} \quad (\text{II-43})$$

where:

u	=	phase velocity
c	=	velocity of light in a vacuum
n	=	particle density
e	=	particle charge
m	=	particle mass
f	=	electromagnetic wave frequency

The phase refractive index of the ionized particles is given by (Ref. II-17)

$$r = \frac{c}{u} = \sqrt{1 - \frac{me^2}{\pi mf^2}} \quad (\text{II-44})$$

5. CESIUM CHARACTERISTICS

We have mentioned that the optical structure of an atom is due to the various energy levels of the electrons. With an insensitive spectrometer, some lines will appear broader than others. If these same lines are examined more closely with an instrument that possesses greater resolution, the lines will be seen to be composed of a number of fine lines. These are termed "fine structure" lines or "multiplets." The splitting is due to interactions between the electron spin and associated magnetic moment effects. Analysis of these effects for the alkali metals shows that doublets and triplets are to be expected. These normally are compiled in the existing data for spectra, as shown in Table II-1 for cesium. Note the closeness of the first two lines of the principal series, one at a wavelength of 8943 Å and the other at 8521 Å. This is a doublet. The next two lines occur at 4593 Å and 4555 Å, another doublet. Also note that four series are tabulated for cesium. The terms came about from the history of the study of the lines. The sharp series was so termed because the lines were observed to be sharp, as opposed to the broad fuzzy appearance of the diffuse series. The principal series was so named because these lines normally are the strongest ones of the spectrum. In general, transitions do not occur between the different lines of the same series. Further, they do not take place between all of the different series, but instead are subject to selection rules which we will not go into here. We will separate the various members of each series by simply stating that each may be described by the quantum number ℓ . The sharp series is described by $\ell=0$, the principal by $\ell=1$, the diffuse by $\ell=2$, and the fundamental by $\ell=3$. The principal series involves transitions which end at the ground state. The sharp and diffuse series for cesium both end on the doublet line at the first level above the ground state.

Many lines possess a structure that can be broken down even further than this. Lines which exhibit a structure finer than the "fine structure" are termed to have a "hyperfine structure". This is determined by the properties of the atomic state and by the nucleus. Although filters can be used to absorb all but one of the lines in a fine structure group, none have been developed which will allow one to examine the hyperfine structure of which a fine structure line is composed. Therefore, one must examine the behavior analytically. Cole (Ref. II-19) has studied a portion of the hyperfine structure of cesium. He found the 8521 Å line to be composed of four lines, while the 8943 Å line actually was composed of six lines. The smallest separation of the lines is of the same order as the Doppler broadening. Therefore, the lines can be seen in a rarefied atmosphere and, for a careful analysis, one would want to consider them for some applications.

TABLE II-1. CESIUM SPECTRA (REF. II-18)

<u>Principal Series</u>		<u>Sharp Series</u>	
<u>$\lambda(\text{\AA})$</u>	<u>ew from Ground State</u>	<u>$\lambda(\text{\AA})$</u>	<u>ev from Ground State</u>
8943.46	1.386	14694.8	2.299
8521.12	1.455	13588.1	
4593.16	2.699	7944.11	3.016
4555.26	2.721	7609.13	
3888.65	3.188	6586.94	3.337
3876.39	3.198	6354.98	
3617.41	3.427	6034.6	3.509
3611.52	3.433	5839.11	
3480.13	3.562	5085	3.893
3476.88	3.566	4945	
3184.2	3.893		
<u>Diffuse Series</u>		<u>Fundamental Series</u>	
<u>$\lambda(\text{\AA})$</u>	<u>ev from Ground State</u>	<u>$\lambda(\text{\AA})$</u>	<u>ev from Ground State</u>
36127	1.798	10124.7	3.034
34892	1.810	10120.0	
30100		10025.1	
9208.4	2.801	8079.02	3.344
9172.23		8078.92	
8761.35	2.807	8015.71	
6983.37	3.230	7279.95	3.513
6973.17	3.233	7279.89	
6723.18		7228.53	
6217.27	3.449	5952	3.893
6212.87	3.450	5917	3.893
6010.33			
5085	3.893		
4945	3.893		

5.1 LINE WIDTH AND MEAN LIFE. Equation II-2 gives the line width as a function of the mean life. This has not been obtained in our search of the literature, but it can be computed readily from some of the other data. To perform the calculation, first note that:

$$\nu = c/\lambda$$

This and Equations II-11 and II-15 can be combined to yield:

$$A_{nn'} = \frac{8\pi^2 e^2}{mc\lambda^2} \frac{2j' + 1}{2j + 1} f_{nn'} \quad (\text{II-45})$$

which allows computation of the decay coefficient from λ and f .

Mean life is imply $1/A_{nn'}$. Therefore Equation (II-2) is:

$$\Delta = \frac{4\pi e^2}{mc^2} \frac{2j' + 1}{2j + 1} f_{nn'} \quad (\text{II-46})$$

The following values (cgs) are applicable:

$$\begin{aligned} e &= 4.80 \times 10^{-10} \text{ esu (statcoulomb)}^* \\ m &= 9.11 \times 10^{-28} \text{ gm} \\ c &= 2.99 \times 10^{10} \text{ cm/sec} \end{aligned}$$

Therefore:

$$\frac{4\pi e^2}{mc^2} = 3.55 \times 10^{-12} \text{ cm}$$

and:

$$\Delta = 3.55 \times 10^{-12} \frac{2j' + 1}{2j + 1} f_{nn'} \quad (\text{II-47})$$

For the $P_{1/2}$ and $P_{3/2}$ initial states, respectively:

$$\frac{2j' + 1}{2j + 1} = 1 \qquad \frac{2j' + 1}{2j + 1} = 1/2$$

*The units of e (or ϵ , depending upon the reference) can introduce an understanding problem. Electrostatic force is described by $F = kq_1q_2/r^2$ where k = constant, q = charge, r = distance. In the cgs system, $k = 1$. If $q_1 = q_2 = e$ we find $e^2 = Fr^2 \equiv \text{dyne cm}^2 \equiv \text{esu}^2$.

The oscillator strengths are given by References II-20, II-21, and II-22. Taking values for the first two states of 0.394 and 0.814, the line widths are 1.4×10^{-12} for each of the first two lines. The decay constant is given by:

$$A_{nn'} = \frac{0.667}{\lambda^2} \frac{2j' + 1}{2j + 1} f_{nn'} \quad (\text{II-48})$$

and these are $3.29 \times 10^7 \text{ sec}^{-1}$ for the first line (8943 Å) and $3.74 \times 10^7 \text{ sec}^{-1}$ for the second line (8521 Å). Line widths for the next two lines are smaller by about a factor of 100. (See References II-15 or II-16 for additional detail.) These line widths are very narrow.

5.2 ENERGY ABSORPTION. Since the visible spectrum is many angstroms wide, and the line widths are very narrow in comparison, the fraction of energy that can be absorbed from the visible spectrum is completely negligible, as one would expect from introducing a material that absorbs only a finite number of narrow lines. Now the question becomes one of whether the lines can be seen at all. This aspect of the problem has already been studied, in effect, by Cole (Ref. II-19). He investigated the 8521 Å line in detail and found the absorption to be negligible for atom concentrations less than about 10^9 atoms/cm^2 and found it to be very small for concentrations of less than about $10^{10} \text{ atoms/cm}^2$. Therefore, the theoretical aspects of the absorption will not be pursued further because the concentration of cesium is considerably below this level.

6. REFERENCES

- II-1 Leighton, Robert B., Principles of Modern Physics, McGraw-Hill, 1959.
- II-2 Richtmyer, F. K., E. H. Kennard, and T. Lauritsen, Introduction to Modern Physics, McGraw-Hill, 1955.
- II-3 Aller, Lawrence, "Atomic Line Strengths" Chapter 3, Part 7, Reference II-4, pp. 7-54 - 7-65.
- II-4 Condon, E. V., and Hugh Odishaw (Editors), Handbook of Physics, Second Edition, McGraw-Hill, 1967.
- II-5 McDaniel, Earl W., Collision Phenomena in Ionized Gases, Wiley, 1964.
- II-6 Ditchburn, R. W., P. J. Jutsum, and G. V. Mars, "The Continuous Absorption of Light in Alkali-Metal Vapours," Royal Society of London, Proceedings, Series A, 219, 1953, pp. 89-101.
- II-7 Ditchburn, R. W., and U. Opik, "Photoionization Processes," Atomic and Molecular Processes, (Edited by D. R. Bates), Academic Press, 1962.

- II-8 Marmo, F. F., J. Pressman, and L. M. Aschenbrand, "Artificial Electron Clouds - II," Planetary and Space Science, Vol. 1, 1959, pp. 291-305.
- II-9 Bates, D. R., et al., "Recombination Between Electrons and Atomic Ions, I - Optically Thin Plasmas," Proc. Roy. Soc. (London) Series A., Vol. 267, No. 1330, May 22, 1962, pp. 297-312.
- II-10 Smoot, L. Douglas, and Donald L. Underwood, "Prediction of Microwave Attenuation Characteristics of Rocket Exhausts," Journal of Spacecraft and Rockets, Vol. 3, No. 3, March 1966, pp. 302-309.
- II-11 Dugan, John V., "VIII - Plasma Chemistry and Ion-Molecule Interactions," contained in Plasmas and Magnetic Fields in Propulsion and Power Research, NASA SP-226, Proceedings of NASA-Lewis Research Center Conference, October 16, 1969.
- II-12 Hygaard, Kaare J., "Electron-Impact Ionization Cross Section in Cesium," Journal of Chemical Physics, Vol. 49, September 1, 1968, pp. 1995-2002.
- II-13 Hansen, L. K., "Cross Section of the Electron-Induced 6s-6p Transition in Cesium," Communications, 1963 (?), pp. 254-255.
- II-14 Dayton, James A., "Survey of Electron-Cesium Collision Probabilities: Momentum Transfer Collisions," NASA-TM-X-1897, October 1969.
- II-15 Lyon, Warren C., "A Study of the Effects of a Cesium Ion Thruster Upon a Polaris Star Tracker for ATS-F and -G," HIT-454, Hittman Associates, May 1970.
- II-16 Lyon Warren C., "Thruster Exhaust Effects Upon Spacecraft," NASA-X-460-70-401, Hittman Associates, October 1970.
- II-17 Glasstone, Samuel, Sourcebook on the Space Sciences, Van Nostrand 1965.
- II-18 Nottingham, Wayne B., Proceedings of the IEEE, December 1963, pp. 1771-1772.
- II-19 Cole, Robert K., et al., "Ion Beam Neutral Component Determination by Resonance Radiation Absorption," AIAA Journal, Vol. 3, No. 2, February 1965, pp. 263-269.
- II-20 Corliss, Charles H., and William R. Bozman, "Experimental Transition Probabilities for Spectral Lines of Seventy Elements," NBS Monograph 53, July 20, 1962.
- II-21 Stone, Philip M., "Cesium Oscillator Strengths," Physical Review, Vol. 127, No. 4, August 15, 1962, pp. 1151-1156.
- II-22 Physical Review, Vol. 135, No. 7AB, September 28, 1964, p. 2.

APPENDIX III LITERATURE BACKGROUND

1. INTRODUCTION

Little work has been published concerning the behavior of material released at orbital altitudes that will be of use to this study. Considerable effort has been devoted to the release of material that already is present to some degree, such as water and particulate matter. Here, however, most of the interest was in the area of observations from spacecraft and how the released material would affect the observations. None of this will be of use for the proposed cesium release. To our knowledge, only three brief studies have been performed that are applicable, and these were done for mercury thrusters. None of these have been published, but they contain interesting information. Therefore, they will be presented in some detail in the first part of this appendix. Then the information will be compared and evaluated with respect to the effects upon cesium thruster behavior. Finally, some other information that may be of interest to predicting cesium effects will be discussed.

2. MERCURY THRUSTER INVESTIGATIONS

2.1 HUGHES RESEARCH LABORATORY STUDY. Knauer (Ref. III-1) has investigated the effect of mercury ion thrusters upon the upper atmosphere. He based his study on an assumption of a five to ten year lifetime for satellites with about 20 to 50 orbit raising maneuvers annually. He estimated about 200 kg of mercury to raise a medium sized satellite to synchronous orbit by ion thruster, with a total discharge of about 10 tons annually. He compared the amounts released in this manner to the quantities released by natural means, such as volcanoes, and concluded that there was no problem with respect to a potential health hazard. He also eliminated problems of a physical nature from within the lower atmosphere on the same basis. It is already there in quantities far in excess of the amount that could be added from ion engine sources. He found that situation to be far different in the outer atmosphere. Here, there is a low heavy metal population, and the population introduced by the ion thrusters far outweighs the natural population. Upon investigation, he found that two phenomena probably would reach observable levels. One was the generation of an artificial belt of mercury ions around the earth much in the manner of ions from the Starfish nuclear explosion, but with a much lower flux and energy density. The other was the generation of faint artificial auroras at the locations where ion beams from low orbiting satellites enter the atmosphere. He could not provide high quality numbers for the expected phenomena because of the unavailability of basic data, but did conclude that nothing would occur that would interfere with natural processes or with observation of faint natural phenomena. Interestingly, he felt the effects should be looked on as benefits since they would provide additional items that could be studied to learn something of our environment.

Knauer first considered the release of mercury at low altitude because the mercury thruster was considered as being applied in an orbit raising maneuver from a low altitude orbit. The original charged material therefore

remained at low altitude because it would follow the magnetic force lines back and forth between the earth's poles. At this altitude there is a strong likelihood of collisions which slow the ions. Some of these collisions will also result in a loss of charge. Other ions will remain charged after being slowed down, and will behave in a manner similar to the material released in the high altitude release experiments with barium. With mercury, resonant charge exchange mechanisms are ruled out because the ionization energy of mercury is stated to be too low. The lifetime that would result from radiative recombination is stated to be of the order of months, and therefore this is excluded as a removal mechanism. This leaves three-body collisions and dissociative recombination. Three body collisions will represent an effective means only if there is a relatively high density since the collision rate otherwise will be low. Dissociative recombination is stated to be an effective removal mechanism at altitudes as high as the ionosphere. One mechanism is the reaction with hydrogen to form Hg H with a binding energy of 2.3 ev. Then the molecule, which is still charged, can dissociate in the presence of electrons to form excited mercury and hydrogen atoms. The rate coefficient for this process is not known, but is believed to be somewhere in the vicinity of 10^{-8} cm³/sec. The corresponding lifetime is of the order of hours. Once the ions have been discharged, they no longer are constrained to follow the magnetic field lines, and can become distributed more or less evenly over the earth's surface (while still in the atmosphere). Then the atoms become attached to dust particles and water droplets and are removed by rain. An atom remains in the atmosphere, on the average, for about one year.

A possible atmospheric effect is a contribution to airglow, which is a summary of many contributions. Typical is twilight glow, caused in part by scattering of solar photons by sodium atoms (5893 A). This scattering takes place at about 80 to 110 km, where the density of natural sodium is about the same as that of natural mercury. But, earth based observations have provided no evidence of a mercury spectrum. The resonance transitions for mercury occur at 1850 A and 2537 A. The solar spectrum is relatively weak at this energy, but still strong enough that a significant reaction rate is possible. Resonance scattering of radiation by neutral atoms may be estimated from:

$$\alpha = \frac{\pi e^2}{mc^2} f \lambda^2 F$$

where:

- α = excitations/atom sec
- f = oscillator strength
- λ = wavelength
- F = effective photon flux per unit wavelength interval

With $f(1850) = 1.3$, $f(2536) = 0.03$, $F(1850) = 5.6 \times 10^{11}/\text{A sec}$ and $F(2537) = 4.25 \times 10^{12}/\text{A sec}$ the excitation rates become $\alpha(1850) = 2.5 \times 10^{-2}/\text{sec}$ and $\alpha(2537) = 2.25 \times 10^{-3}/\text{sec}$. The unit optical depth for radiation of 1850 A is reached near 60 km altitude, that of 2537 A near 40 km. The number of

natural mercury atoms in a vertical column above 60 km amounts to about $2 \times 10^{11}/\text{cm}^2$, that above 40 km is $2 \times 10^{12}/\text{cm}^2$. This leads to total resonance scattering rates of $5 \times 10^9/\text{cm}^2 \text{ sec} = 5000 \text{ Rayleighs (R)}$ at 1850 Å and $4.5 \times 10^9/\text{cm}^2 \text{ sec} = 4500 \text{ R}$ at 2537 Å. The detection limit is about 10 R. Consequently, this radiation probably could be seen by an observer located above the atmosphere. On the earth's surface, it is not seen because the atmosphere absorbs the short wavelength radiation. In any event, the estimated contribution of the mercury from ion thrusters is below the detection limit, even above the atmosphere.

Another contribution to airglow is nightglow. This is partly due to a recombination of ions and electrons which are generated by solar radiation during the day. For ionization, mercury requires radiation of wavelength shorter than 1180 Å. The altitude of unit optical depth for this wavelength is 80 km. At least a part of the natural mercury should be ionized from this altitude on up. In theory, one could calculate the concentrations that would exist if the physical data were available. However, the required photon ionization and recombinations are stated not to be well known. Nevertheless, they can be estimated by taking Hinteregger's photon fluxes (Ref. III-2) for wavelengths shorter than 1180 Å (the ionization limit). The total flux is roughly $5 \times 10^{10} \text{ photons}/\text{cm}^2 \text{ sec}$. Next assume the photoionization cross section is about $10^{-17}/\text{cm}^2$. At 80 km altitude the atmospheric density is $10^{14} \text{ particles}/\text{cm}^3$. Natural mercury should contribute a fraction of 2×10^{-11} to the total density; therefore, it should have a density of $2 \times 10^3/\text{cm}^3$. Accordingly, the photoionization rate should be about $(10^{-17}) (5) (10^{10}) (2) (10^3) = 10^{-3} \text{ cm}^3 \text{ sec}$.

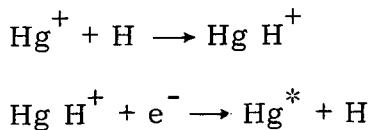
The recombination rate of ions with electrons can be determined from:

$$\frac{dN_i}{dt} = -\delta N_i N_e$$

where:

$$\begin{aligned} N_i &= \text{ion density} \\ \delta &= \text{recombination coefficient} \\ N_e &= \text{electron density.} \end{aligned}$$

If recombination occurs via the reaction:



then the recombination process is dissociate in nature and the recombination coefficient should be on the order of $10^{-8} \text{ cm}^3/\text{sec}$. At 80 km altitude the electron density is $10^3/\text{cm}^3$. Accordingly, the recombination rate is $10^{-5}/\text{cm}^3 \text{ sec}$. In equilibrium, ionization and recombination rates must be equal. By equating the rates the ion density is $10^2/\text{cm}^3$ at 80 km altitude, which corresponds to five percent of the atom density.

The rate of photon emission resulting from recombination is estimated simply by assuming that each newly formed atom is highly excited and, even though emitting several photons, will generally yield one photon of a kind. Assuming five percent ionization, the total number of ions in a column extending from 80 km upwards is $10^8/\text{cm}^2$. Thus, the total number of photons (of one kind) emitted by this column is $(10^{-3})(10^8/10^2) = 10^3 \text{ photons/cm}^2 \text{ sec} = 10^{-3} \text{ R}$ which is too small to be observable.

The ion thruster caused mercury contribution to the radiation will be about a decade lower than this, 10^{-4} R .

Release from a high satellite in an equatorial orbit will cause an entry into the geomagnetic field at a high pitch angle. Therefore, the mirror points will occur at low latitudes (high altitudes), and trapping within the magnetic field will be quite effective. Fluctuations of the geomagnetic field are stated to be small at low altitudes, and this possible mechanism for the transfer of ions across magnetic lines will not be an effective removal mechanism. (Note that this appears to be in disagreement with the discussion in Appendix I, Section B.) The removal mechanism therefore is stated to be due to something else. The most likely process is charge exchange with atomic hydrogen. It will have to be a non-resonant charge exchange process because the ionization energy of mercury is below that of hydrogen. Therefore, the cross section for the process has to be small. The charge exchange lifetime is given by:

$$\tau = 1/N\sigma v$$

where:

- N = neutral hydrogen density
- σ = charge exchange cross section
- v = ion velocity

With an assumed cross section of 10^{-16} cm^2 , $N = 1000/\text{km}^3$ at an altitude of 6000 km, and $v = 4 \times 10^6 \text{ cm/sec}$ (2000 eV), the lifetime is about one month. Therefore, if one third of the assumed annual release of ten tons is trapped at latitudes sufficiently low for long life trapping in the magnetic field, the trapped belt population can be found to be about 10^{27} ions. The energetic electron population from the Starfish explosion was estimated to have been an initial 10^{26} . Of course, the starfish electrons were of a much higher energy than the mercury ions, and the potential energy available on a per particle basis therefore was greater. Still, there are more mercury ions and one would expect to be able to see an effect. If the assumption is made that the mercury is spread over a volume of 10^{28} cm^3 , the flux density will be about $10^5/\text{cm}^2 \text{ sec}$. Fluxes in the natural belts are about 10^6 to 10^8 protons/ $\text{cm}^2 \text{ sec}$ with energies below about 0.1 MeV. Separation of mercury ions from protons at these levels should be possible with charged particle detectors, which means that they can be found if they exist at the predicted population density. They cannot be seen visually, however, because the estimated photon density due to resonance scattering at 1650 and 1942 Å is much too low to be detected.

Knauer states that if ions are ejected at a relatively short distance from the atmosphere, they will not be trapped by the geomagnetic field, but instead will reach the atmosphere directly along the magnetic lines. His sketches appear to indicate that the assumed directionality of the ion beam is perpendicular to the earth's surface. Hence, the ion beam, when first released, is perpendicular to the field lines and does not have the required parallel component for a mirror point to occur at high altitude. Therefore, the postulated behavior is that the ion beam reaches the atmosphere along field lines with roughly its entire original kinetic energy. This energy will be decreased by elastic and inelastic collisions with the environmental atoms. The resulting excited atoms may generate a great enough photon density that the location of reentry of the ion beam can be seen. The behavior would be very similar to the natural generation of aurora. Protons are in part responsible for the natural effect, with an estimated energy generation of 10^{-8} erg/photon. One problem with trying to estimate the effect for mercury is that the photon conversion efficiency is not known. (The excitation rates for hydrogen, helium, oxygen, and nitrogen upon mercury ion impact are unknown entities.) To estimate the effect, Knauer assumes the ion beam will cover less than the area enclosed by one ion cyclotron diameter, which would be about 10^{11} cm². With an ion beam of ten amps, and an energy of 2000 eV, the energy flux is two ergs/cm² sec. This leads to a radiation intensity of 200 R. This is a faint effect, but should be visible.

Knauer's conclusions are summarized in Table III-1.

TABLE III-1. ENVIRONMENTAL EFFECTS OF
MERCURY FROM ION ROCKETS

<u>Effect</u>	<u>Approx. Intensity</u>	<u>Comments</u>
Health Hazard	2×10^{-6} $\mu\text{g}/\text{m}^3$	Concentration in air is well below health limit of 1 $\mu\text{g}/\text{m}^3$
Airglow Twilight glow	0.5 R	Radiation intensity is below detection limit, natural mercury with 5000 R could be visible above atmosphere.
Night glow	10^{-6} R	Well below detection limit.
Artificial Auroa	200 R	Should be faintly visible.
Artificial Ion Belt	10^5 particles/cm ² sec	Particle flux should be observable with charged particle detectors

2.2 NASA LEWIS STUDY. Other work has predicted that there will be no effect of any observable nature. Masica (Ref. III-3) has performed a limited study based upon the SERT II. He used a sun-synchronous circular orbit with a radius from the center of the earth of 7300 km, and with a polar inclination angle of 99° . Orbital period assumed was 105 minutes and the average spacecraft velocity was 7.3 km/sec. The assumed ion engine location is such that the ion emission is directed along the radius vector of the orbit. Emission rate is 10^{18} singly ionized mercury atoms per second. Since the ion beam is neutral, the same number of electrons will be emitted. The accelerator operated at 3 kev, with a resulting ion velocity of 53 km/sec. With an assumed flight time of 18 months, the quantity of ionized mercury released is 24 kg. Orbital altitude changes by about 100 km during the flight.

Variation of the earth's magnetic field is from about 0.4 gauss at the geomagnetic pole to about 0.2 gauss at the equator at an altitude of 10^3 km. The radius of gyration for a nonrelativistic charged particle in motion within the field is given by:

$$r_g = m v \sin \alpha / q B \quad (\text{III-1})$$

where:

q	=	particle charge
m	=	particle mass
v	=	particle velocity
α	=	pitch angle as given in Appendix I
B	=	magnetic field strength

This radius approaches zero at the poles. At the equator, it is about 5.2 km, sufficiently small that Alfven's guiding center approximation for the motion of the charged mercury may be used. A dipole magnetic field also is assumed.

The first invariant of the motion is given by Equation I-2. The author then adds that if the mirror point occurs at altitudes of less than about 100 km the particles will be removed from the magnetic field very rapidly. He next stated that he set $B_m = 0.5$ gauss, the approximate value at 100 km, and substituted a range of angles for the orbital flight path. There resulted the conclusion that the only mercury that would be trapped by the earth's magnetic field would be that emitted in a shell extending across the equator from 35° S to 35° N. This is consistent with the behavior of trapped protons in the earth's natural charged particle field. This then lead to the conclusion that a maximum of 9.6 kg of mercury would be trapped above the F layers in the ionosphere.

The second invariant of the motion, which relates the longitudinal oscillations of the ions between the mirror points, is given by:

$$J = (v t_b \cos \alpha) / 2 = 2 r_o (1.30 - 0.56 \sin \alpha) \quad (\text{III-2})$$

so that:

$$\frac{J}{\pi r_o} \approx \frac{2}{\pi} (1.30 - 0.56 \sin \alpha) > 0.5 \quad (\text{III-3})$$

where:

$$\begin{aligned} J &= \text{north to south oscillation path length} \\ t_b &= \text{bounce time} \\ r_o &= \text{radius of spacecraft orbit} \end{aligned}$$

which means that the particles spread over a wide latitude range.

Next, a third invariant of the motion is introduced that is associated with a longitudinal drift in the particle motion. For positively charged particles, the motion is from east to west. The period of this drift around the earth is:

$$t_d = \frac{(1 + E) m_e r_e}{E(2 + E) m_{Hg} + r_o} (1.2 \times 10^4) \approx 10^6 \text{ sec} \quad (\text{III-4})$$

where:

$$\begin{aligned} t_d &= \text{drift time} \\ E &= \text{kinetic energy to rest energy ratio} \\ m_e &= \text{electron mass} \\ r_e &= \text{earth radius} \\ m_{Hg} &= \text{mercury ion mass} \end{aligned}$$

Now the density of mercury ions that are deposited by the ion beam can be calculated. The smallest radius of gyration for trapped particles is:

$$r_{g \min} = r_{g/\phi} = 35^\circ = r_{g/\phi} = 0 \quad \frac{\sin \alpha_{\max}}{2} \approx 2 \text{ km}$$

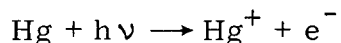
where the factor of 1/2 is used to account for the maximum increase in B at $\phi = 35^\circ$ with $\alpha_{\max} = 45^\circ$ and $\phi = \text{latitude}$. The number of ions deposited in a unit volume in one second per orbital pass is:

$$n(Hg^+) = \frac{\text{emission rate}}{\text{spacecraft velocity} \times \pi r_g^2} = \frac{10^{18}}{(7.3)(\pi)(2)^2} \approx 10 \text{ Hg}^+/\text{cm}^3$$

Next the possibility of trapped mercury ions combining to form neutral atoms is considered. The expected recombination rate is small, but nevertheless may be significant over the assumed 18 month orbital life. Typical

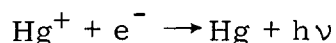
properties taken at 10^3 km are 10^6 air "molecules"/ cm^3 , 10^4 e^-/cm^3 , and a mean free path of 10^5 to 10^6 km for a particle with about a 10^{-8} cm radius. The author concludes that if a neutral atom is formed, it probably will be lost if it retains a significant amount of its original kinetic energy because of the large mean free path at that altitude.

Next, the probability of photoionization is considered. This is given by:



A comparison using known electron ionization cross sections for lithium gives an estimated value for mercury of 10^{-17} cm^2 . With a solar flux intensity of about 10^{13} quanta/ cm^2 sec at the transition point of 1200 Å, the probability of a photoionization is about 10^{-4} /sec.

One loss mechanism is an electron-ion reaction which results in radiative recombination. The process initiates with the reaction:



The emitted wavelength is stated to be about 1200 Å, which means that all of the energy has been assumed to be contained within one photon and that there has been no allowance for the kinetic energy effects which might have resulted in some other behavior. As a first guess, this certainly is a good approach. If this type of behavior takes place, it will not be seen from the ground because the emitted wavelength is well below the atmospheric cut-off. The number of recombinations per unit volume per unit time is given by:

$$R = \beta n(\text{Hg}^+) n(e^-)$$

where the recombination coefficient is given by:

$$\beta \approx \nu \sigma \text{ cm}^3/\text{sec}$$

The listed properties at 10^3 km lead to the approximation that the cross section for mercury ions is about 10^{-17} cm^2 . Therefore the recombination coefficient is about 10^{-11} cm^3/sec . This is about the same size as the value for most atmospheric ions. Taking the number density of the mercury ions to be $10/\text{cm}^3$, the author found $R \approx 10^{-6}/\text{cm}^3\text{sec}$. Therefore, the radiative recombination rate is very small. For equilibrium to be maintained with an influx of 10 $\text{Hg}^+/\text{cm}^3\text{sec}$ would require $n(\text{Hg}^+) = \rho(\text{Hg}^+) \approx 10^7$ Hg^+/cm^3 . The author further states that this number would be an upper limit on the ion density concentration.

Other loss mechanisms also are mentioned. These include ionic reactions, such as charge transfer processes and ion-atom interchanges with O_2 . Reaction rates for these processes may be scoped by considering that the photoionization cross section for mercury ions is about a factor of ten lower than for mercury atoms. Further, the solar flux at the absorption wavelengths is about a factor of 100 lower. Therefore, this type of loss process will be negligible. The effect of nuclear collisions, cosmic ray and solar wind interactions, and similar phenomena also are felt to be entirely negligible. Therefore these other loss mechanisms were neglected.

The analysis to this point has shown that the emitted density flux per orbital pass is about 10 mercury ions per cubic centimeter, and that the maximum local concentration that is possible is about $10^7 \text{ Hg}^+/\text{cm}^3$. Next the accumulation of ions over the flight duration must be considered to find the maximum number density.

There are four factors which will tend to distribute mercury ions over the earth's surface. These will tend to retard the accumulation of ions in one location, and therefore must be considered. They are:

- (a) The east-west drift associated with the third invariant of the ion motion.
- (b) The east-west rotation of the magnetic field caused by the earth's rotation.
- (c) The dispersion caused by the precession of the spacecraft orbit.
- (d) The local inhomogeneity, violation of the invariants, and long term temporal variations in the earth's magnetic field.

These four factors lead one in the direction of assuming that the ions are spread in a homogeneous manner over the spherical 100 km thick atmosphere that covers the earth. With no loss mechanisms, the uniform density would be of the order of one ion/ cm^3 . The author felt that this approach should not be followed until it was investigated, and therefore went into the distribution of material. He first decided to ignore the precession of the spacecraft orbit and assumed a constant orbital altitude. He next considered a fixed elemental volume located at the equator, where the number density should be the greatest. Next, a constant recombination rate of 10^{-6} was selected. Now, at time zero, the spacecraft is assumed to pass through the elemental volume and deposits a density of $10 \text{ Hg}^+/\text{cm}^3$. The drift and rotation of the magnetic field causes the ions to move out of the reference elemental volume prior to the next pass of the satellite (6300 sec). The next insertion of ions into the elemental volume therefore takes place about a factor of 100 later than would otherwise have been the case. The accumulation is described by:

$$\frac{\rho(\text{Hg}^+)}{10 \text{ Hg}^+/\text{cm}^3} = 1 + x + x^2 + \dots + x^{n_0-1}$$

where $x = 0.99$ at $R = 10^{-6}$, $t \approx 10^5$ sec, and n_0 = number of orbits. Therefore:

$$\frac{\rho}{10} + x^{n_0} = 1 + x + x^2 + \dots + x^{n_0} \quad \xrightarrow{n_0 \rightarrow \infty} \quad = \frac{1 - x^{n_0}}{1 - x}$$

and:

$$\rho(\text{Hg}^+) \approx 10^3 \text{ Hg}^+/\text{cm}^3$$

for the 18 month duration of the flight. The estimate is very conservative because of the loss assumptions that have been made. This is the maximum number of ions that will accumulate during the orbit of the SERT II.

Next, one needs to consider the intensities of the radiative transitions that can take place. There are two classes for concern. One is the radiation from radiative recombinations of the mercury ions, and the second is the radiation from decay of excited mercury ions which result from electron collision transitions. The total intensity of the radiative recombinations is given by:

$$4\pi I = NPh\nu$$

where:

N = fraction of sites undergoing the transition

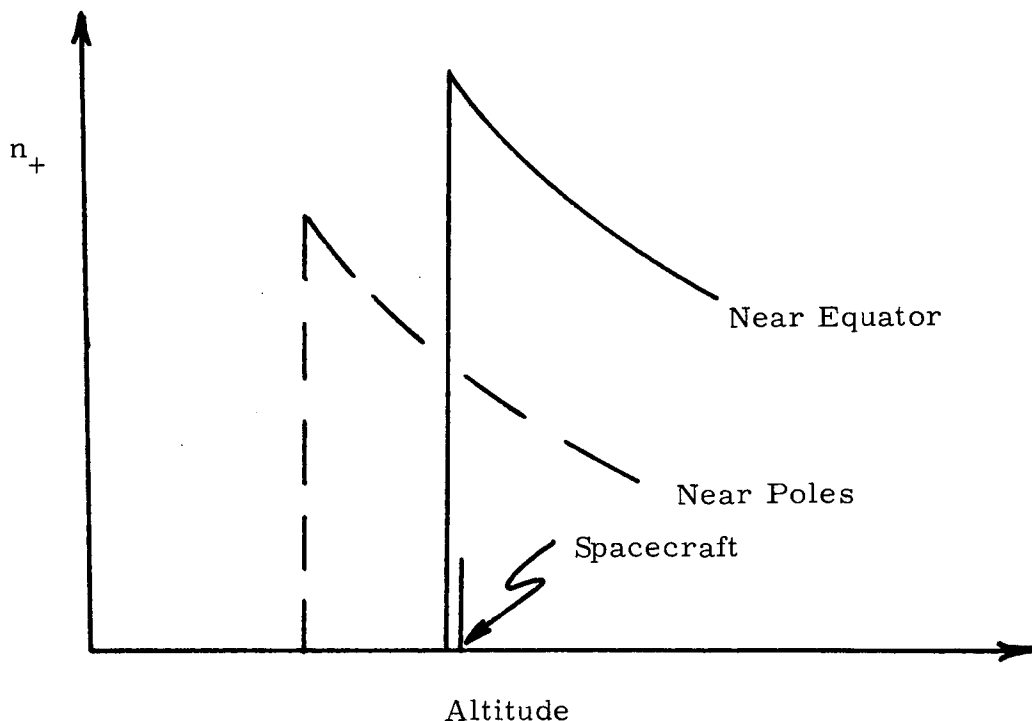
P = transition probability

For the radiation recombinations with $R = 10^{-6}$, NP is a maximum of the order of 10^{-3} , and the intensity is about 10^{-3} quanta/cm² sec ster. These radiative transitions are stated to be absorbed by the earth's atmosphere and therefore are of no concern. The second class of transitions are those with wavelengths between 3600 and 6000 Å. There are about a dozen lines in this range. Taking the transition probability of these as 10^{-3} that of the principal lines, one finds an intensity of 10^{-6} quanta/cm² sec ster.

There are other effects which are neglected. These include radiative excitations, stimulated radiation, and Raman scattering. The last two are stated to be insignificant. The first is stated to be negligible because it will produce no net change on the earth's surface. This is incorrect. The argument that is presented is the radiative excitation transition will be immediately followed by a radiative decay at the same wavelength, and hence there will be no change in the solar spectrum that reaches the surface of the earth. The reason this may not be true is twofold. First, the re-radiation process is an isotropic one in which the probability of photon emission is equal in all directions. Hence, the photon flux reaching the earth's surface could be decreased by the interactions. Second, the decay process does not always result in the same wavelength photons being generated as were absorbed. The assumption is good if one is interested in the total quantity of energy involved (and indeed we have used the assumption in some of our work), but may introduce an error if one is interested in a careful evaluation of the spectral characteristics.

Finally, a column height of 100 km is considered, which results in an intensity of 10 quanta/cm² sec for the entire column. This is the same as about 10^{-5} R, a value too low to be seen. (Less than 10^2 is sub-visual.) The intensity of the principal sodium line in the night glow spectrum is of the order of 10^2 R. The lower levels in the night glow are about 10 R. Thus the intensity of radiation at the maximum estimated number density of mercury ions is of the order of 10^{-6} that of anything that is seen in the night glow spectrum.

2.3 PRINCETON UNIVERSITY COMMENTS. Jahn (Ref. III-4) has come up with some very preliminary conclusions based upon discussions and a simplified model in regard to the SERT II thruster. The analysis is based upon a spacecraft altitude of 540 n. m. At this altitude, the magnetic field of the earth is stated to vary from about 2.0×10^{-5} weber/m² at the equator to about 3.8×10^{-5} weber/m² at the poles. A mercury ion emitted with a velocity of 4×10^4 m/sec in a direction of 9.5° to the vertical while the spacecraft is near the equator has a gyro radius of about four kilometers. If the spacecraft is considered as progressing toward the poles, the magnetic field increases and the thrust angle with respect to the local magnetic field decreases, which both decrease the gyro radius. He concludes that the ions therefore will be trapped within the magnetic field, and that the thickness of the shell that is thus formed will be equal to the local gyro radius. Other conclusions also are similar to those of the previously discussed work, namely that the ions will be reflected back and forth between the mirror points and that they will drift in the westward direction due to the radial gradient in the magnetic field intensity. This behavior leads to the conclusion that the ion density in the azimuthal and polar directions will be roughly uniform. The behavior in the radial direction is felt to be more difficult to estimate. This statement is based on the statement that the spacecraft will spend more time over the equatorial flux shells than over the polar ones. The postulated distribution is felt to be roughly as shown in the following sketch:



As a first step in the analysis the author assumes the radial profile of the mercury ion density has a perfect spherical uniformity. Therefore, the areal density of ions seen by an observer on the earth's surface who is looking outward to infinity will be about $10^7/\text{cm}^2$. If all of these ions were contained in a shell of one gyro radius thickness, the density would only be about $30/\text{cm}^3$. The density of the natural species at this altitude is given as $\text{O}_1 = 10^6$; $\text{He} = 10^5$; H_1 , N_1 , and $\text{N}_2 = 5 \times 10^4$; and $\text{O}_2 = 10^3$. The density of natural mercury in the solar environment is stated not to be well known, but that in interstellar space is stated to be about 10^{-11} that of H_1 , which is about $1/\text{cm}^3$. If we look toward the edge of our galaxy in its plane, an areal density of natural hydrogen of about $10^{21}/\text{cm}^2$ will be seen. This means the density of natural mercury will be about $10^{10}/\text{cm}^2$ when looking in the same direction. This is 10^3 larger than the contribution from the artificial mercury introduced into the earth's environment by SERT II. The author adds that the best telescopes require about 10^{12} before recording spectra in either the emission or the absorption modes.

He concludes that the bulk of the mercury will be trapped near the orbital sphere of the spacecraft and that virtually none of it will be trapped near the Van Allen belts. The resulting volumetric and line of sight densities will be far too low to be seen in any manner associated with astronomical spectra. Then he adds that, because of these conclusions, he did not go into the time of decay of the mercury after it was released. He added, however, that if the release of considerably more mercury than for the SERT II was to be considered, then such a calculation would be in order. The expected principle loss mechanism would probably be loss of material in the vicinity of the mirror points.

3. OTHER RELEASES AT HIGH ALTITUDES

A number of other studies have been performed that contribute some understanding to the potential problems that are of concern here. One of the most applicable is that of Kellogg (Ref. III-5), who investigated the amount of material that would have to be introduced into the upper atmosphere on a continuous basis in order to double the natural worldwide concentrations. He considered the natural atmospheric abundances, the residence times in various atmospheric regions, and the chemical and photochemical stability.

The natural composition of the heterosphere (the region above 105 km) is shown in Table III-2. The quantities of sodium, potassium, calcium, lithium, etc., and their oxides and ions are stated to be difficult to assess quantitatively. Observation and theory indicate that the free sodium atoms have a maximum concentration at about 90 km altitude. (The sodium can be detected by resonant scattering or absorption of sunlight.) Concentrations at altitudes below this decrease rapidly due to oxidation at the higher pressures. Above 90 km, the free atoms predominate. Above 105 km, free sodium is in diffusive equilibrium with the rest of the atmosphere. The alkali metals K and Li also have been observed in the twilight sky.

Observation and theory indicate that only a small portion of these metallic atoms are ionized below 100 km. However, recombination rates in the heterosphere are much slower, and a larger fraction will be ionized above 100 km.

TABLE III-2. NATURAL QUANTITIES OF STABLE
CONSTITUENTS IN THE HETEROSPHERE (REF. III-5).

<u>Constituent</u>	<u>Total Mass above 105 km</u>	<u>Particles/cm² above 105 km</u>
N ₂	6.1 x 10 ⁸ tons	2.6 x 10 ¹⁸
O ₂	5.3 x 10 ⁷ tons	1.9 x 10 ¹⁷
O	1.1 x 10 ⁸ tons	7.7 x 10 ¹⁷
H	20 to 90 tons	2 x 10 ¹² to 10 ¹³
Na	20 to 170 kg	10 ⁸ to 8 x 10 ⁸
Li	30 to 300 g	5 x 10 ⁵ to 5 x 10 ⁶
H ₂ O	4 x 10 ³ tons	4 x 10 ¹³
CO ₂	2 x 10 ⁵ tons	6 x 10 ¹⁴
NO	1.3 x 10 ⁴ tons	5 x 10 ¹³

One of the postulated origins of the alkali metals is from meteors and micrometeors. Each source introduces about 8 x 10⁴ kg of sodium (~10⁵ kg/yr total). The residence time for atoms and molecules above 60 to 80 km is stated to be about 10 years. This means there is about 2000 times more sodium introduced than is found via airglow and absorption measurements (which give only free sodium). Presumably, the remainder is tied up as oxides or some other form. If the major source is assumed to be chondritic meteorites, then the relative compositions will be as shown in Table III-3.

TABLE III-3. RELATIVE ABUNDANCE OF
METALS IN METEORITES (REF. III-5).

<u>Element</u>	<u>Abundance Relative To Sodium</u>
Li	2 x 10 ⁻³
Na	1
Mg	1.9
Al	1.5
Si	20.0
K	0.12
Ca	1.1

Another possible source is from the oceans. An argument for this source is the observed relative abundances, $K/Na = 0.01$ to 0.02 in the upper atmosphere and in sea water. In any event, the situation has not been resolved.

One result of the study is based upon a rocket that is defined to introduce 10 kg of a trace element into the atmosphere above 105 km. About 100 to 800 of these rockets would have to be launched each year to double the natural concentration of sodium, BUT only 0.2 to 2 would double the lithium concentration. (These quantities are based upon a residence time in the heterosphere of about one week as opposed to ten years for the total region above 60 to 80 km.) The same numbers for the turbulent region between 60 to 105 km are 200 to 1700 rockets/year for sodium and 0.01 to 0.1 per year for lithium.

The study concluded that injection of most materials would be no problem, but that lithium and potassium might be significant. (The cesium concentration in the E region of the ionosphere was stated to be unknown. This was the only mention of cesium in the report.) The addition of modest amounts of these materials could modify the natural background. This modification was stated to be detectable by sensitive spectroscopic measurements but no other effects were found. This introduced the possibility of using clouds of lithium as tracers for studying atmospheric circulation. However, repeated use of the same tracer could result in interference with previous tracers and a reference to this occurring was mentioned.

Low (Ref. III-6) has published a bibliography of contaminant release experiments. A few of his references are summarized here. However, most of the references were concerned with other aspects. One of Low's references, Pergament (Ref. III-7) set up a model of chemical release in the upper atmosphere and listed a number of references for further work in the area. This would be a good starting place if one were interested in a model which would require the application of digital computers.

Föppl (Ref. III-8) studied the effects of a release at very high altitude. He mentioned a release of sodium at 156,000 km geocentric distance from a Soviet rocket, but no details were given. As a result of his study, he found that they would need about 5×10^6 photons/cm² sec and a time of one minute to observe a cloud. (A high sensitivity film requires about 10^9 photons/cm² to obtain an appreciable density.) A release at 200,000 km would require about the following masses to be observable:

Element	Minimum Mass (kg)	
	Photographic	Photoelectric Image-Converter Tube
Ca	33	16.5
Sr	38	19
Ba	4.8	2.4
Eu	4	2

Possible effects upon the environment were not considered.

A number of releases of cesium have been made into the ionosphere to study the effects of electron clouds, mass transport, and the decay of the density of electrons in the presence of sunlight (Ref. III-9). Nine of these were conducted in sunlight within altitudes from 74 to 115 km. In five of the releases 20 kg of a cesium containing mixture were released. In the others greater amounts were involved, with the maximum in the range of 80 kg. Much of the movement of material that was observed was due to high altitude winds, temperature differentials, and other phenomena which will not be useful in understanding the behavior of releases at altitudes of the type associated with a satellite. Optical effects could be determined for periods of 5 to 20 minutes, whereas radio frequency (rf) data could be obtained for as long as one to two hours. In general, the rf reflectivity was found to be high and varied strongly with the altitude. General conclusions are that a high electron density can be achieved over a localized area for purposes of rf reflection for several thousand seconds. The outer wave of small particulate matter moves with a velocity of about seven km/sec to a distance of several kilometers, and rapid ionization of the cesium occurs as a result of the sunlight. Actual photoionization data are not presented, but laboratory data are referenced that show a photoionization time constant for solar radiation of the order of 2000 sec. Therefore, the experiments expected to achieve one percent photoionization in about 20 sec. Oxidation of the cesium at the lower release altitudes was relatively rapid (below about 100 km).

Five releases were made at night at altitudes ranging from 90 to 140 km. All used 20 kg of a cesium containing mixture. The releases produced a 3500°K plasma of 10 kg of finely divided alumina, 300 moles of inert gases including carbon monoxide and hydrogen, 30 moles of cesium and sodium vapors, and a small amount of cesium ions and electrons. Expansion velocities in the range of 4 km/sec were found. The persistent liminous cloud produced no adequate spectral data because of the low intensity, which was estimated to be about 10^{-9} w/cm². The continuous emission over 500 seconds produced an estimated luminous energy of about 2×10^{13} ergs. Since the entire payload contained only 10×10^{13} ergs, and the efficiency of the conversion process is only in the range of one percent, there was felt to be a substantial contribution from the environmental material, possibly oxygen atom recombination.

The rf observations showed an initial radial growth of the electron front that matched the optical observations. The electron density decayed more rapidly at the high altitudes than at low ones. In general, the electron yields were sufficient in the absence of sunlight that the rf reflections could be followed for about 1000 sec. The visible luminescence from the surface of the reacting gas mass was visible for minutes and the gas reached the ambient pressure in one to two seconds.

Some experimental evidence for the behavior of charged particles which are released in the upper atmosphere has been obtained as a result of high altitude nuclear explosions. A nuclear explosion releases a large number of radioactive nuclei, most of which decay by the emission of high energy electrons (beta particles). The average energy of these is in the million volt range. The "electron" release rate is very high at first, and then decays rapidly in an exponential manner. Neutron decay also contributes to the electron source. These, however, are used up in the first hour or two following the explosion

because they have a half-life of a few minutes. Hence, the behavior of a step input of electrons may be investigated, followed by a study of the behavior with a rapidly decreasing source of electrons.

Two bombs were exploded at relatively low altitudes (for purposes of this discussion) during August, 1958. One was set off at an altitude of 50 mi and the other at 27 mi. A bright aurora formed almost instantly in the vicinity of the explosion residue and a similar phenomenon was observed about a minute later at 14° S latitude, about 2000 mi away from the explosion point. These probably were due to electrons trapped in the earth's magnetic field as they spiraled back and forth between their mirror points. Most of these were trapped in the magnetic field at low altitudes, and had a high probability of undergoing collisions with atmospheric atoms. As a result, after a few days, most had suffered collisions which scattered them out of the magnetic field and they were absorbed in the atmosphere.

Three small bombs were set off on August 27, August 30, and September 6, 1958, at about a 300 mi altitude. The explosions took place over the south Atlantic Ocean (Project Argus). The resulting electron movement back and forth between the minor points plus the west to east drift around the earth produced a well defined radiation belt about 60 mi thick from about 1.7 to 2.2 earth radii. These belts persisted for several weeks before the electrons leaked out of the magnetic field. The distance of the belt from the earth did not change significantly during its life.

The Starfish explosion of July 9, 1962 was of much greater magnitude. Immediate auroras occurred at the 250 mi burst point and 3000 mi away in the Southern Hemisphere. A radiation belt with a lifetime of years was produced and several satellites were put out of commission because of damage to their solar cells. Considerable geomagnetic field disturbance occurred, and the increased ionization in the ionosphere caused trouble with radio communications over a wide area for days. The residue from the explosion rose rapidly with the result that a number of the electrons were introduced into the upper atmosphere at much higher altitudes than that of the explosion. Many of these were released in the lower levels of the earth's inner (natural) radiation belt, with the result that the natural proton flux was disturbed for several months. The longer life electrons were injected into a belt that extended out to about four earth radii. The flux of electrons with energies in excess of 0.25 MeV rose rapidly with increasing distance from the earth to about 800 mi, then decreased slowly out to about 2800 mi, and then decreased even more slowly out to a distance corresponding to the outer part of the Van Allen belt. The initial electron flux in the vicinity of the maximum was as high as 10^9 e⁻/cm² sec. On the average, the higher energy electrons were found at distances from the earth relatively close to the explosion altitude, and the lower energy electrons were found at greater distances. The lifetime of the belt was found to be very short for electrons with mirror points in the lower atmosphere, as one would expect. Decay of the belt from 1.2 to 1.7 earth radii was very slow (lifetimes of several years), but for distances greater than this, the decay rate increased with increasing distance. At a distance of about 2.5 radii, the belt practically disappeared after a couple of months. The reasons for this have not been, to our knowledge (and we did not undertake a good literature search on this point) defined, although several reasons pertaining to magnetic

field variations have been postulated. In any event, reactions with the atmospheric atoms are not effective as a removal mechanism out beyond about 1.7 earth radii.

Three nuclear explosions were set off by the USSR on October 22, October 28, and November 1, 1962. These produced belts at higher altitudes than the previous shots, and most of the effect was observed in the region between the inner and outer Van Allen belts. The lifetime of the artificial belts so produced was a few weeks. One of the reasons for the short life probably was the position of injection into the magnetosphere, at a latitude of about 70 or 75°N, and particles injected at this position should not have a long life. Another reason may have been disturbance of the geomagnetic field.

According to Cladis (Ref. III-10) the Starfish burst (July 9, 1962) caused a significant increase in the 55 Mev proton flux. At 275 km, the flux increased by a factor of ten. Examination of possible sources of the protons eliminates the bomb as a source because it is not capable of emitting such high energy sources. Phenomena associated with the burst also are considered to be unlikely sources. The increase probably is due to a slight redistribution of the high energy protons trapped in the inner radiation belt. A change of about 3° in the equatorial pitch angle has been estimated to be sufficient to give the observed results.

The Starfish detonation produced a wide variety of phenomena, such as a magnetic bubble, collision-free shock waves, hydromagnetic waves, micro-pulsations, whistlers, plasma jets and instabilities, injection of trapped particles, and redistribution and loss of previously trapped particles. Very few of the phenomena are well understood theoretically and few relevant experimental data are available.

Additional information may be obtained by referring to Rosenberg (Ref. III-11) or to the lists of references contained in the bibliographies in the reports which have already been discussed.

4. RADIO WAVE PROPAGATION

Considerable work has been done with the propagation of radio waves with respect to communications and as a tool for the investigation of various phenomena. None of the work is directly applicable to this study, but some of it lends an insight to the problems and phenomena involved. According to Millman (Ref. III-12) tropospheric (to about 30 km altitude) absorption of radio waves is due to interaction with free molecules and suspended particles (principally water droplets). In a non-condensed atmosphere, absorption principally is due to interaction of the radio wave with the electric moment of the water molecule and with the magnetic moment of the oxygen molecule. Attenuation in the ionosphere (between about 70 and 1000 km) is due to electron collision processes.

According to Stone (Ref. III-13), the portion of the radio spectrum below 10 MHz cannot be investigated reliably or at all through the terrestrial ionosphere because of reflection, refraction, scattering, or absorption of radio

signals from celestial sources before they reach the ground. The ground based observer can use the five decades from 10 MHz to almost 10^5 MHz. The three decades from 10 KHz to 10 MHz can be utilized by satellites located above the troublesome regions of the earth's environment. Observation at frequencies below 10 KHz would require sending instruments beyond the solar system.

Pawlik (Ref. III-14) mentions electrical interference in his discussion of solar electrical propulsion. The problems he referred to were principally ones which originated within the thruster, and not from the exhaust. They appeared to be a potential integration problem, but are of no assistance in the evaluation of the effects of the exhaust.

An interference signal that originated with the electrical converter system was reported with the Alouette I spacecraft (Ref. III-15). The problem, which occurred with the very low frequency (vlf) receiver (400 Hz - 10 KHz) only appeared under special conditions during the day. Osborne (Ref. III-15) studied this effect and found that interaction of the spaceplasma could explain the behavior. His proposed mechanism involved a coupling of a DC-DC converter signal to the solar cells where the distribution of electron collection over the satellite and its antennas is modified. The degree of coupling is controlled by the $V \times B$ effect resulting from the satellites motion in the earth's magnetic field. The effect appears only in daylight because of a diode which serves to prevent discharge of the batteries when the cells are not exposed to the sunlight. This diode disconnects the cells at night. A limited laboratory study was conducted to verify the proposed mechanism and the Alouette II was modified to avoid the problem.

Similar results are reported by Hayakawa (Ref. III-16) who conducted a laboratory study with a DC-DC converter-spacecraft simulation arrangement. He found that effects did not occur when there was no plasma, but did occur in the presence of a plasma.

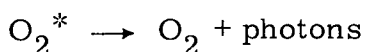
Poehler (Ref. III-17) has pointed out some of the difficulties in an attempt to determine the behavior of rf in the vicinity of an exhaust plume. In general, he concludes that the usual simplified approaches are not applicable when the behavior within the plume varies drastically over a distance corresponding to the wavelength of the radio waves being considered. Analytic solutions for the propagation through the inhomogeneous plasma are not available except in the case of special circumstances and these did not apply to the cases he was attempting to study. For his purposes, it was necessary to resort to rather sophisticated computer programs. If this behavior is extrapolated to our circumstances, it means that rf predictions cannot be made easily for close-in behavior. Behavior further out should be predictable and order of magnitude effects probably can be scoped for the close-in behavior. Any hand calculations must be considered in this light.

5. CHEMICAL REACTIONS IN THE ATMOSPHERE

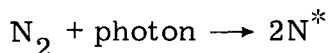
In this section the chemical reactions that take place in the atmosphere will be discussed. There will be no attempt to present a complete discussion;

many reports and several books have been devoted to this subject. Instead, a few postulated reactions will be presented to give an idea of the type of behavior that takes place. Most of this material has been taken from references III-18 and III-19.

In the heterosphere, where there are large differences in composition with altitude, the effect of the solar radiation is significant. For example, there are large amounts of atomic oxygen which result from photodissociation of molecular oxygen. This atomic oxygen is an important atmospheric constituent for a depth of several hundred miles. One reaction that has been observed is a yellowish glow when nitric oxide gas is introduced. The reaction is believed to take place according to the reaction:



The base of the heterosphere is composed principally of molecular nitrogen and oxygen. The proportion of atomic oxygen increases with altitude until, above about 140 mi there is little molecular oxygen. The number of nitrogen molecules continues to decrease with altitude, but apparently remains as a constituent of reasonable concentration up to high altitudes. There is a photodissociation of the molecule that proceeds according to:



but the probability of this taking place is small. Nevertheless, atomic nitrogen is a constituent, and its proportion increases with altitude. Apparently, it always remains as only a minor constituent. Photoionization of nitrogen and oxygen also occurs. The relative concentration of nitrogen ions increases to an altitude of about 450 mi, where the maximum ratio of $\text{N}^+/\text{O}^+ = 0.07$ is reached.

At even higher altitudes, above 600 mi, the quantities of helium and atomic hydrogen begin to predominate. At the lower altitudes, these were only minor constituents. The helium layer is sufficiently high that some of the atoms can escape from the earth's influence. It apparently is replenished by helium resulting from alpha decay of radioactive elements within the earth.

The highest layer that may be considered an atmospheric constituent is that of atomic hydrogen which lies above the helium. The source of this probably is photochemical decomposition by solar ultraviolet radiation of water vapor, methane, and hydrogen from the homosphere. Many of the atomic hydrogen atoms also are ionized to form hydrogen ions and, of course, electrons which always result from an ionization process. These hydrogen ions normally are referred to as protons, and the region containing them is called the protonosphere. This extends far into space with the density decreasing with distance, and the proportion of ionized hydrogen increasing. The density at about 4000 mi altitude is roughly 4000 atoms/cm³ with about half of the

material in an ionized form. At about 40,000 mi the density is about 30 to 60 atoms/cm³, of which almost all is ionized. The density in interplanetary space is about one to five hydrogen nuclei per cubic centimeter.

The density of the atmosphere at high altitudes is a strong function of the sun activity, and it is not possible to represent it as having any particular constant value with altitude. Nevertheless, it is informative to consider typical values with altitude to get an idea of the type of behavior to be expected. Such a density plot is shown in Figure III-1. This is for a period of maximum sunspot activity. The density will be lower when the sunspot activity is less. For our purposes, the differences will be unimportant. The densities are perhaps not as meaningful in the presented terms as they might be. Note that at

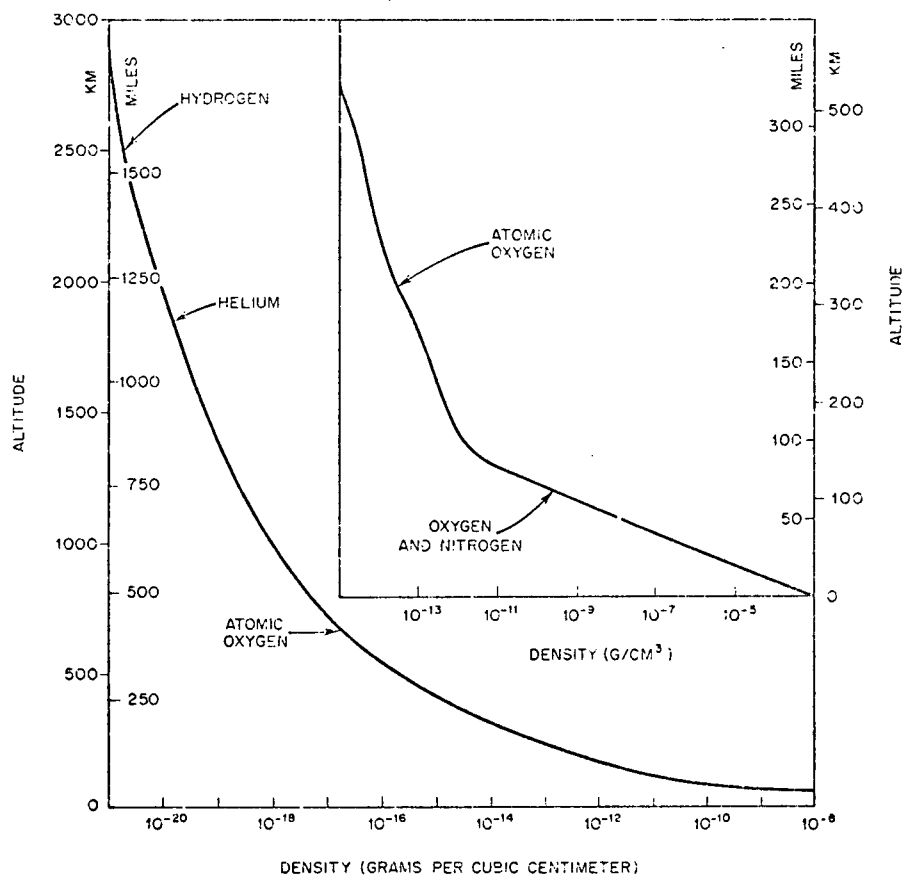


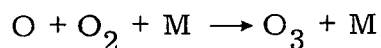
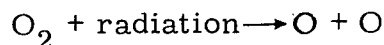
Figure III-1. Mass Density of the Atmosphere (Ref. III-18)

an altitude of 500 mi, the density is equivalent to only about 4×10^5 O atoms/cm³. At 1250 mi, it is about 1500 He atoms/cm³.

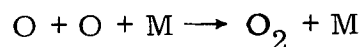
In addition to breaking the atmospheric regions down by composition, many times it is considered with respect to the regions where chemical reactions are taking place. In this case, it is referred to as the "chemosphere". This region extends, for the most part, to an altitude of about 120 miles, although there really is not any upper limit to the height. The behavior in this

region, which by definition is the one in which reactions are taking place, is one in which the minor constituents are very important.

One minor constituent of the region that is of tremendous importance is ozone. It exists only in the proportion of about one molecule per hundred thousand air molecules. Yet, it is of vital interest to life on earth since it strongly absorbs wavelengths greater than about 2100 Å to roughly the visible region (3800 Å). This characteristic prevents harmful amounts of ultraviolet radiation from reaching the earth's surface. Ozone is produced in the reaction:

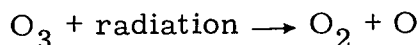


where M is some other atom or molecule. Another reaction that takes place is:

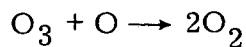


In the last two equations the presence of the third body is necessary to carry off the excess energy from the reaction. Without the third body, the chances would be excellent that the molecule on the right hand side would break up as a result of the total energy that is contained. At altitudes of over about 60 mi, the concentration of molecules is low, and the probability of three body collisions also is low. Therefore, the formation rate of O_3 is small. This in effect defines the upper level of the ozone layer.

The absorption of photons by ozone causes the reaction:

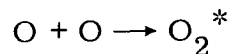


Then the following reaction may occur:

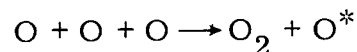


or two oxygen atoms may combine to form O_2 .

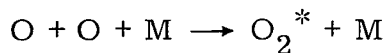
Other chemical reactions are responsible for nightglow. One of the observed sources appears to be due to oxygen reactions. In effect, an excited state atom or molecule, O^* or O_2^* is formed which then decays to the ground state with the emission of one or more photons. The process to form the excited state occurs during the day when the sun is available as a source of energy. One of the reactions which may take place is:



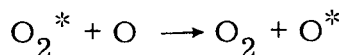
Another, which can only occur in regions of relatively high density, is:



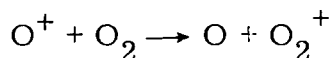
The oxygen molecule that is formed can carry off some of the energy as kinetic energy, and the emitted wavelength therefore is less energetic than the maximum possible emission from the previous formation technique. Another reaction which may take place is of the form:



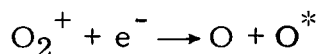
where the third body removes some of the reaction energy. Then:



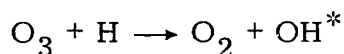
also can take place. Another reaction that will explain some of the observations is:



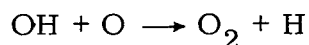
followed by:



Another wavelength band can be explained by:

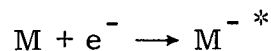
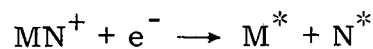
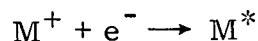


and hydrogen atoms are regenerated by:

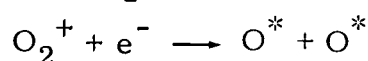
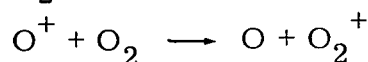
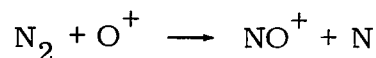
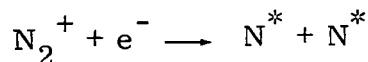


A number of other constituents have been determined to exist in the upper atmosphere by observation, in part, of the nightglow. Sodium, potassium, lithium, calcium, and magnesium all have been reported on the basis of the nightglow spectrum. Sodium is by far the most abundant. Calcium is on the threshold of detectability, and magnesium has been seen only, to our knowledge, by mass spectrographs at high altitudes. One of the postulated sources of these elements is from the ocean. Another is from meteoroids. A third was from the high altitude nuclear explosions, but these introduced only temporary effects. The other two may be used to explain different behavior that has been observed on both a seasonal and a random basis.

Several reactions also take place in the ionosphere. Aside from the ionization and dissociation processes which can take place and require only the right kind of energy, the types of chemical reactions which occur are:



where M and N are any species which may be present. Other reactions which involve oxygen and nitrogen are:



One may conclude that the necessary energy is available for most reactions to take place, but that the tendency probably is one of tending to break the species down to rather simple configurations. There will be few molecules of a complex nature.

A simple theory of the decay of the daytime ionization levels in the E-region of the ionosphere will show that the level drops below about $10^2 \text{ e}^-/\text{cm}^3$ immediately after sunset. Actual levels are higher than this (Ref. III-20). At a level of 105 km, where a peak in electron density usually appears at night, the level never falls below 10^3 . A valley in the density between 130 and 200 km is another characteristic of the nighttime behavior. Observed behavior is a rapid decrease in the electron density immediately following local nightfall, followed by a period in which the density drops slowly until midnight is reached. It then slowly rises again until the ionosphere again becomes sunlit. Calculations based upon assuming the geocornal Ly- β irradiation with an irradiance of 10 to 30 R show good agreement with the observations. The recombinations are thought to take place through a network of sixteen elementary chemical processes, which will not be presented here.

6. BIOLOGICAL CONSIDERATIONS

According to Sax (Ref. III-21), Cesium compounds have a toxicity that probably is similar to that of the parent metal unless they contain a more toxic radical. Cesium is stated to be quite similar to potassium in its elemental state, but has been shown to have a pronounced physiological action in experiments with animals. Replacement of the potassium with cesium in the diet of rats caused death in about 10 days. Overall analysis is that there is only a slight hazard due to ingestion for acute systemic and chronic systemic effects. The acute and chronic effects are listed as unknown. (No information on humans that is considered valid by the authors.)

The quantities added to the human environment are significantly lower than already exist. For example, the reported concentration of cesium in seawater is 5×10^{-4} ppm (Ref. III-22). If the seawater coverage of the earth is assumed to be 70 percent (an "out of the air" number), the weight of the uppermost one centimeter layer is:

$$(4) (\pi) (4000)^2 (5280)^2 (929) (1) (1) = 5.19 \times 10^{18} \text{ gms.}$$

The quantity of cesium in this layer would be $(5.19 \times 10^{18}) (5) (10^{-4}) (10^{-6}) \approx 25 \times 10^8 \text{ gms}$, far more than released by proposed ion thrusters.

We may conclude that the quantities of cesium that will be of interest for this investigation will not be a hazard problem to human life.

7. REFERENCES

- III-1 Knauer, W., "A Prediction of Environmental Effects Caused by Mercury Ions from Ion Rockets," Hughes Research Laboratories, no number or date, transmitted by letter to Channing C. Conger, NASA Lewis, April 10, 1970.
- III-2 Hinteregger, H. E., L. A. Hall, and G. Schmidke, Space Research V, 282, Wiley, 1965.
- III-3 Masica, William J., "Evaluation of SERT II Ion Emission," NASA Lewis Memo, no number, March 23, 1970.
- III-4 Jahn, Robert G., Letter to Jerome P. Mullin, NASA Office of Advanced Research and Technology, Washington, from Princeton University, Dept. of Aerospace and Mechanical Sciences, March 26, 1970.
- III-5 Kellogg, W. W., "Pollution of the Upper Atmosphere by Rockets," Space Science Reviews, 3, 1964, p. 275-316.
- III-6 Low, C. H., "Upper Atmosphere Research, Bibliography of Contaminant Release Experiments," Technical Memorandum HSA 176, Dept. of Supply, Australian Defense Scientific Service, Weapons Research Establishment, October 1968, (N69-19109).
- III-7 Pergament, Harold S., and Arthur Fontijn, "A Model of Chemical Releases Leading to Upper-Atmospheric Chemi-Ion Formation," AIAA Journal, Vol. 6, No. 1, January 1968, p. 94-98.
- III-8 Föppl, H. et al., "Preliminary Experiments For The Study Of The Interplanetary Medium By The Release Of Metal Vapor In The Upper Atmosphere," Planetary and Space Science, Vol. 13, 1965, p. 95-114.
- III-9 Chemical Reactions in the Lower and Upper Atmosphere, Stanford Research Institute, Symposium Proceedings, April 18-20, 1961, Interscience Publishers, 1961.
- III-10 Cladis, J. B., et al., "Redistribution of Trapped 55-MEV Protons By Starfish Nuclear Explosion, J. of Geophy. Res., 75, January 1, 1970, p. 57-68.
- III-11 Rosenberg, N. W. (Ed) "A Summary Report, Project Firefly 1962-1963," Cambridge Research Laboratory, Rept. No. AFCRL 64-364, May, 1964.
- III-12 Millman, George H., "A Survey of Tropospheric, Ionospheric, and Extra-Terrestrial Effects on Radio Propagation between the Earth and Space Vehicles," in Blackband, W. T. (Ed), Propagation Factors in Space Communications, AGARD Conf. Proceedings No. 3, Meeting in Rome, 1965, pp. 3-55.

- III-13 Stone, R. G., "Radioastronomy from Space," Science Journal, 6, March 1970, p. 68-74.
- III-14 Pawlik, E. V., et al., "Solar Electric Propulsion System Evaluation," Journal of Spacecraft and Rockets, Vol. 7, No. 8, August 1970, pp. 968-976.
- III-15 Osborne, F. J. F., et al., "Plasma-Induced Interference in Satellite v.l.f. Receivers," Canadian Journal of Physics, Vol. 45, No. 1, January 1967, p. 47-56.
- III-16 Hayakawa, Masaski, and Iwai, Akira, "Plasma-Induced Radio Frequency Interferences from Space Vehicle," Research Institute of Atmospherics, Proceedings, Vol. 17, January 1970, p. 99-106. (A70-35400)
- III-17 Poehler, Horst A., "Attenuation Predictions from Exhaust Plume Models," Journal of Spacecraft and Rockets, Vol. 6, No. 9, September 1969, p. 1057-1059.
- III-18 Glasstone, Samuel, Sourcebook on the Space Sciences, Van Nostrand, 1965.
- III-19 Hess, Wilmot N., (Ed), Introduce to Space Science, Gordon and Breach, 1965.
- III-20 Tohmatsu, Takao, and Noboru Wakai, "An Investigation of Night-time Ionizing Sources in Low- and Mid-Latitudes," Ann. Geophys., t.26, fasc. 1, 1970, p. 209-211.
- III-21 Sax, N. Irving, et al., Dangerous Properties of Industrial Materials, Reinhold, 1965.
- III-22 Ng, Yook C., and Stanley E. Thompson, "Prediction of the Maximum Dosage to Man from the Fallout of Nuclear Devices, II. Estimation of the Maximum Dose from Internal Emitters," UCRL-50163 Part II, Lawrence Radiation Laboratory, December 14, 1966, (Rev. October 22, 1968), p. 104.