A MECHANISM FOR THE LOCAL CONCENTRATION ENHANCEMENT OF THE SHUTTLE ATMOSPHERE

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Abstract. Preliminary calculations suggest that collisions between instreaming atmospheric constituents and secondary backscattered molecules can generate unexpectedly large enhancements in neutral gas concentrations in the vicinity of the shuttle. This effect is a result of a rapid decrease in the mean free path length of the scattered components following the initial expected concentration enhancement. A study will be outlined for the theoretical investigation of this mechanism. The shape dependence of associated glow halos on vehicle configuration will be discussed.

Introduction

Scattering of the unidirectional flux of ambient gas molecules incident on Low-Earth Orbit (LEO) spacecraft surfaces results in an increased gas density on the ram facing surfaces and filling in of the rarefied wake region. The thermal component of the ambient atmosphere impinges on surfaces oriented parallel to the velocity vector and also contributes to the wake region.

The gas scattering dynamics determine line-of-sight column densities and may influence optical glow processes and the spatial extent of glow halos. The multiple scattering may lead to new approaches in atomic oxygen beam and glow simulation testing. These considerations in turn may impact space shuttle experiments, free flying space platforms, Space Station, and Strategic Defense Initiative systems.

The gas density increase on ram surfaces has been previously investigated by various authors (Bird, 1962; Melfi et al., 1981; Bareiss et al., 1975; Rantanen, 1977). The techniques employed include rarefied gas dynamics, direct simulation by Monte Carlo and three dimensional contamination configuration models. One such configuration model, SPACE II (Bareiss et al., 1981), is intended to calculate contamination related parameters. In its current form it does not calculate the density increase around shuttle due to backscattered ambient species re-emitted from the Orbiter surfaces. In the Monte Carlo modeling analyses of the shuttle, environment backscattering components are included and the results vary significantly from SPACE II.

The goal of the present study is to model shuttle gas flowfield densities and optical glow phenomena in a form applicable to shuttle, Space Station, and other space systems. By using and modifying existing models, a cost-effective approach may be easily applied to optimization studies, attitude variations, configuration changes, and model verification. An approach using a multiple interaction density enhancement iteration algorithm to improve existing configuration models is presented here as is a glow halo shape simulation test procedure.

Considerations

From the shuttle frame of reference, the ambient gas molecules have velocities of about 8×10^5 cm/s $\pm 1 \times 10^5$ cm/s due to orbital motion superimposed on background thermal velocities. Gases impacting on the shuttle surfaces are thermally accommodated and are emitted at velocities near 5×10^4 cm/s for atomic oxygen and 4.0×10^4 cm/s for N_2, for surface temperatures near 298° K.

Figure 1 schematically illustrates the details of physical interaction mechanisms for surfaces oriented perpendicular to and parallel to the velocity vector. The gas density increase on a surface perpendicular to the direction of orbital motion is due to the ram flux and backscattering of the surface re-emitted ambient species. A surface parallel to the velocity vector, Figure 1, is impinged upon by the thermal component of the ambient. As the gases are re-emitted, they collide with the ambient and with each other. Some are scattered back to the surface. The result is that the greatest gas density is at the trailing edge on a surface parallel to the flow.

The gases in the wake region, Figure 1, are the result of the thermal component of the ambient and those gases scattered back from the edges of the surface. These molecules collide at different energies than those on the ram side.

The mean free path for the undisturbed ambient gases is given by

$$MFP_A = \frac{1}{N_A \sigma_A}$$

where N_A = ambient density and
σ_A = collision cross section of ambient species.

The mean thermal velocity of a molecule or atom emitted from a surface is low compared to the ambient impact velocities. If there was no gas density buildup on the ram side, the mean free path of an emitted gas would be

$$MFP_R = \frac{V_R}{N_A V_A \sigma_{AR}}$$

where V_R = re-emitted gas velocity,
N_A = ambient density,
V_A = ambient velocity, and
σ_{AR} = collision cross section between ambient and re-emitted species.

If the cross sections are the same then the mean free path of the re-emitted gases is less than the free stream ambient by the ratio of their respective velocities. However, in reality the flux of ambient gases impinging on the re-emitted gases is enhanced by the backscattered gases that were previously re-emitted, so that mean free path is further modified by these species. Calculations have been performed using a density iteration technique applied to the surfaces of circular disks moving in direct ram condition at an altitude typical of a shuttle orbit. If only the re-emitted gases are considered, the model calculations yield a density near the disk surface which is a factor of 32 greater than the free stream ambient. Because of backscattering, the model predicts densities near 50 to 60 times the free stream ambient.

Approach

The approach to modeling gas densities and resulting glow phenomena has four basic steps.

a. Update gas kinetics for shuttle with eventual applications to Space Station and other space systems using SPACE II and TRASYS II.
b. Utilize ground test simulation to aid in verifying, by visualization of gas density distribution profiles and variations with spacecraft size, configuration attitude and other factors.
c. Use results of Monte Carlo analyses by other investigators as a baseline standard for testing the modeling approach.
d. Correlate gas densities along viewing lines-of-sight with Imaging Spectrometric Observatory (ISO) data for glow model development and verification.

TRASYS II (Jensen et al., 1983) is used for developing the surface to surface or surface to a point density matrix around shuttle to allow more resolution for scattered and compressed gas algorithms than presently exists in SPACE II. A calculational technique is being developed which makes use of improved mass transport factors between surfaces and points and from points back to points so that backscattered gases can be added to the densities that exist as a result of gases emitted from the surface. The flux of gases at two points separated by a predetermined distance is calculated. The difference in flux between these two points then becomes the backscattered contribution from this region. A form factor is developed from this region back to the points between it and the surface.

Figure 2 shows preliminary results for the density, along the centerline axis of an 8-meter-radius disk and a disk of 1-meter-radius. The ratio of the calculated density to the free stream ambient density is plotted as a function of distance along the centerline upstream from the disks. The free stream ambient is 5×10^9 molecules or atoms/cm^3. The mean free path (MFP) for a re-emitted molecule or atom is 40 meters when considering only interactions of the re-emitted molecule and the incoming ambient.

The density at a point for no interactions with the ambient is equivalent to the calculations utilized in the current SPACE II model.

$$D_o = \frac{RFLR \times MTF}{V_R}$$

where RFLR = surface emission rate of re-emitted ambient,
MTF = mass transport function between the surface

and a point, and
V_R = re-emitted velocity.

The density at an off surface point is assumed to be reduced exponentially by the factor exp(-x/MFP). Then, after a primary reflection, the density, D_1, at an external point is

$$D_1 = \frac{RFLR \times MTF \times e^{-x/MFP}}{V_R}$$

where x = distance from surface to the point.

The first iteration of the process described in the present approach is shown as curve D in Figure 2. The enhanced density at a point p from the backscattered, re-emitted species is given by

$$D_{Bp} = \sum_{p+1}^{n} \left[(RFLR)(MTF_{n-1} e^{\frac{-x_{n-1}}{MFP}} - MTF_n e^{\frac{-x_n}{MFP}})(MTF_{p,n}) \right] / V_B$$

where
RFLR = surface emission rate,
MTF_n = mass transport function between the surface and the point,
x_n = distance from surface to a point,
x_{n-1} = distance from surface to n-1, point,
$MFT_{p,n}$ = mass transport function between point n and point p, and
V_B = backscattered velocity.

The backscatter calculation is added to the density D_1 at each point along Z. Basically, D_1 attenuates the density and D_B adds to the density.

After the densities have been altered, the mean free path can be adjusted according to the backscattered flux calculated during the first iteration.

The updated mean free path is given by

$$MFP = \frac{V_R}{N_A V_{A\sigma} + N_B V_{B\sigma}}$$

where
N_B = density addition due to backscattered gases, and
V_B = velocity of backscattered gases.

For a point near the surface where the backscattered gas density is highest, the mean free path is 15 meters as opposed to 40 before the adjustment was made. The adjusted mean free path, as a function of distance from the 8-meter-disk for the surface re-emitted gases, is shown in Figure 3.

The incoming ambient mean free path near the surface is between 13 to 26 meters depending on its velocity which has been reduced via collisions.

The next iteration would utilize the adjusted mean free path and the same calculational technique. Until the results of the first iteration processes are verified, via Monte Carlo modeling, the second iteration will not be performed.

The 1-meter-radius disk shows significantly less buildup upstream as compared to the 8-meter-radius disk. Sensitivity studies are underway to determine the influence of surface size, surface shape, velocity vector orientation, combinations of surfaces, and the parameters used in the calculations.

A technique for calculating the densities in the wake region via collisions at the outer edge of a surface is under development.

The modeling approaches will be incorporated into SPACE II when completed and the predicted results will be compared to Monte Carlo modeling of the shuttle orbiter. The gas densities along ISO experiment lines-of-sight will be calculated. Excitation mechanisms and corresponding cross sections will be applied to the different gas species. The resulting spectra will be compared to the ISO data and updated as required.

A simple but informative simulation technique has been developed to simulate the glow shape as a function of altitude, attitude, and spacecraft geometry to aid in visualization of the gas density distribution and to assist in modeling. Small particles are accelerated, via gravity, from the top of a silo onto targets at ground level and the density profile is photographed. Geometrical shapes, such as cylinderss cones, spheres, flats, and models of shuttle and the Space Station, have been used as targets. The target surfaces are textured to produce diffuse scattering. The re-emitted particles have a decreased velocity relative to the incoming particles which is determined by the particle surface material selection. Figure 4 shows the relative "glow shapes" observed thus far. Improved particle sizes and diffusers are planned for future tests.

Implications/Recommendations

The multiple collisions experienced by the incoming ambient gases and the resulting density profiles have an impact on glow mechanisms, predictions, and simulation testing.

The glow investigations to date have concentrated on surface-related excitations to explain the near surface visible glow. It is proposed that collision excitation mechanisms may occur at distances comparable to space vehicle dimensions. Some of the possible excitation processes may cause intense optical emissions at specific wavelengths.

The relatively high densities on the ram facing surfaces allows sufficient numbers of collisions between incoming ambient and the re-emitted ambient component to reduce the translational energies of the incoming molecules below orbital impact energies. This would seem to imply that simulation testing of materials may be successfully carried out with impact energies significantly lower than the 5 eV AO beam which is presently unobtainable at sufficient fluxes.

Besides the AO at appropriate energies and fluxes, other gases such as N_2 should be part of a simulated ambient atmosphere.

Simulation of the glow phenomenon in laboratory testing is impacted because of the multiple gases and complex collision process. Other excitation mechanisms should be available simultaneously such as solar radiation and electrons. Impact excitation should be simultaneously simulated in an appropriate test configuration.

Models of the shuttle, Space Station, and other space system environments should be updated to include major aspects of the gas densities and glow emissions. The enhanced gas density profile affects the transport of contaminants to surfaces and to optical lines-of-sight.

The first time a systematic contamination evaluation and model was created was for Skylab. It did not, however, model the return flux phenomenon because of altitude (435 km) and a low ambient gas period.

On shuttle, the same modeling methodology derived from Skylab was adopted with the inclusion of return flux of contaminants scattered by ambient collisions.

The next evolutionary step in modeling gaseous space environments is the glow halo phenomenon. An adequate knowledge of contaminants exists and mathematical models are available to assess and minimize the problem. The erosion of materials by AO is understood well enough that hardened materials or coatings will result. Spacecraft glow remains as the phenomenon that is least understood. A comprehensive program of modeling, testing, and experiment is required to fill the understanding of glow phenomenon. This should include combinations of surfaces, gases, vehicle attitudes, day/night orbit conditions, sensors, and background levels and should be performed by shuttle, rockets, tethered systems free flying payloads or sources, and ground-based telescopes or combinations of these.

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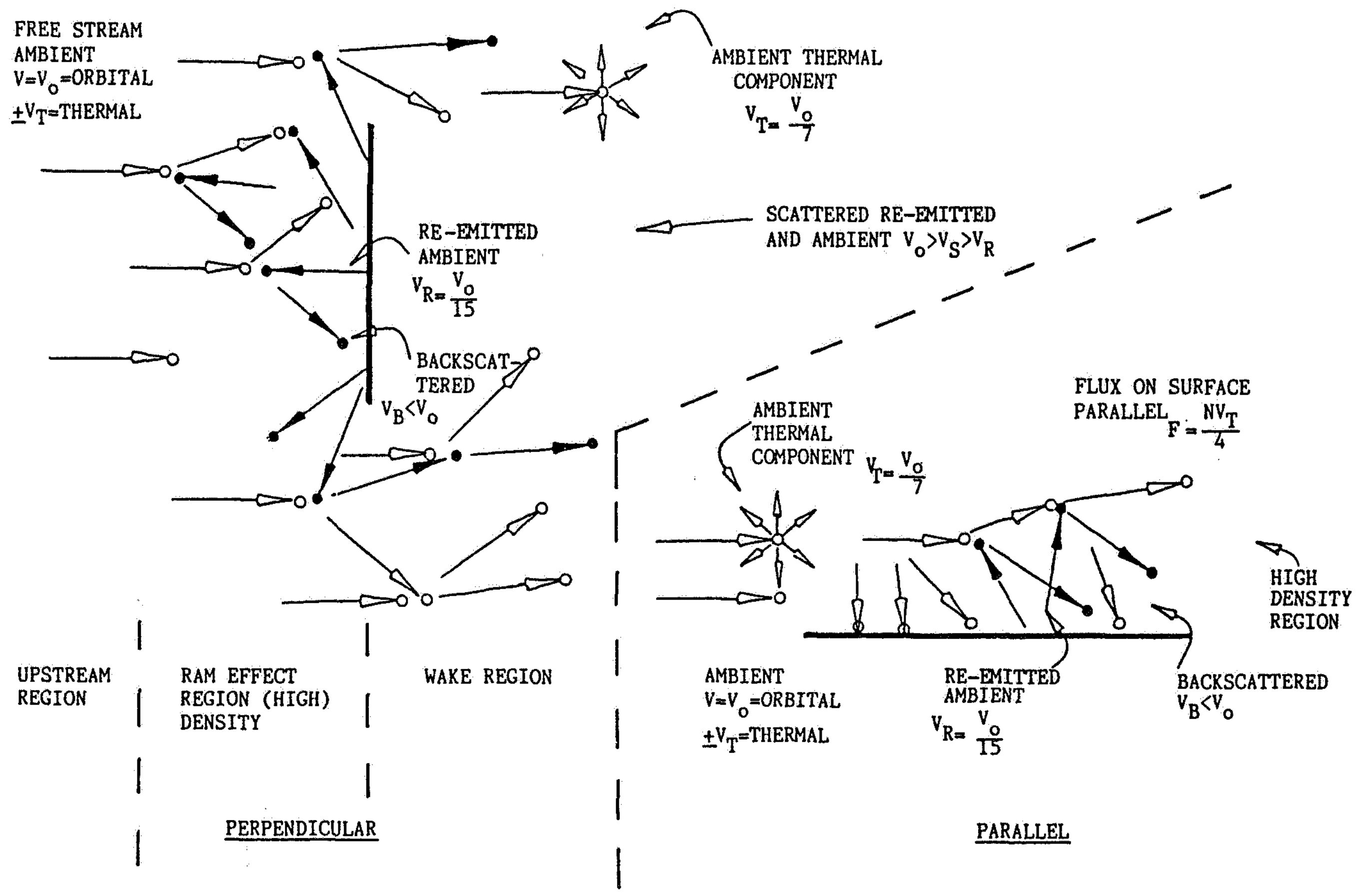

Fig. 1. Physical processes.

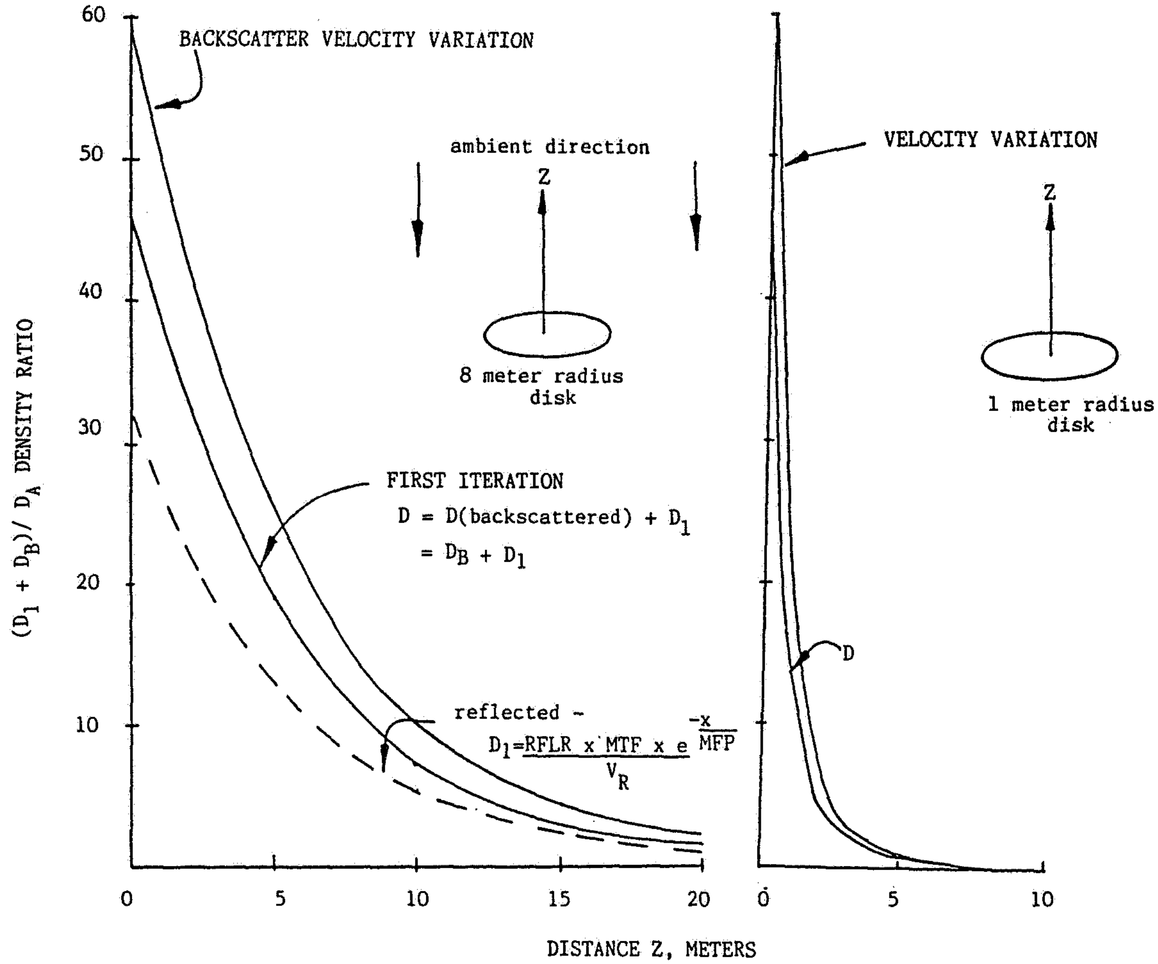

Fig. 2. Ratio of calculated density to ambient free stream density versus distance.

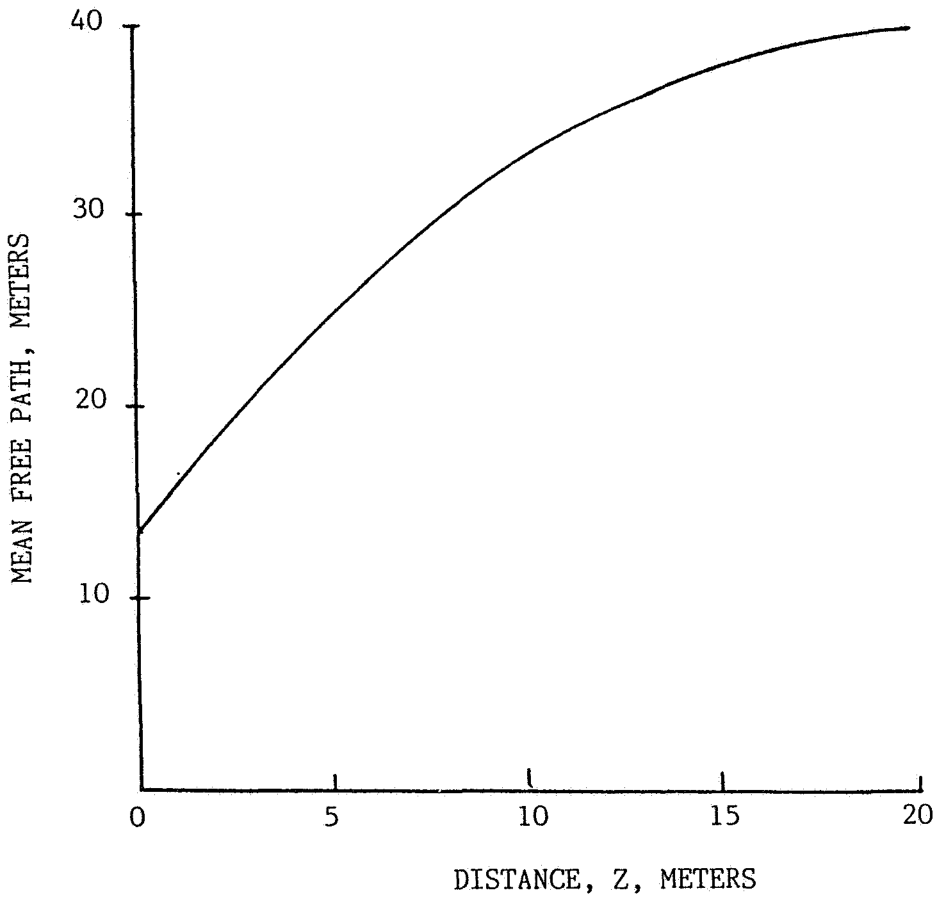

Fig. 3. Adjusted mean free path of surface re-emitted ambient.

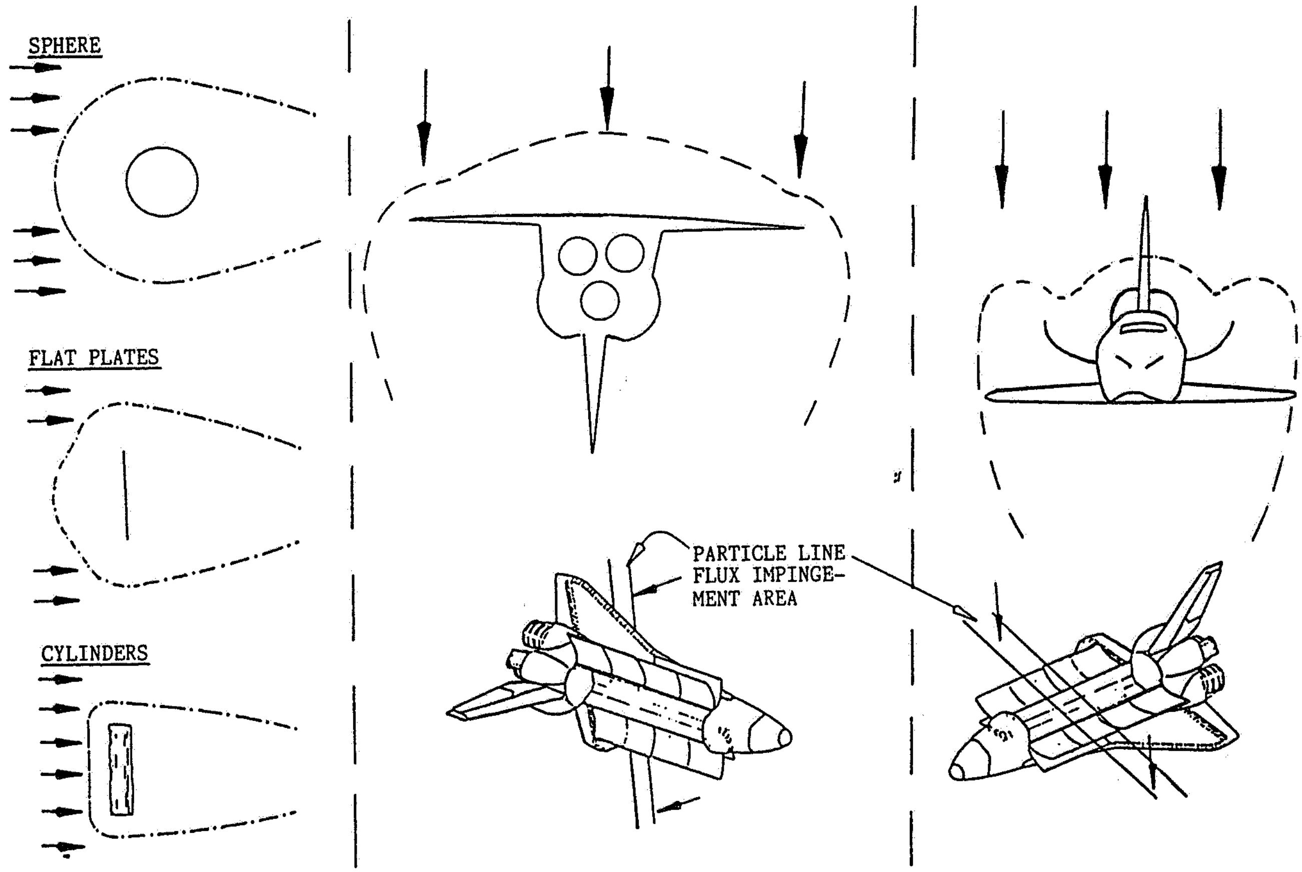

Fig. 4. Density shapes observed in simulation testing.