Effects of Free Molecular Heating on the Space Shuttle Active Thermal Control System

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ABSTRACT

During Space Transportation System (STS) flight 121, higher than predicted radiator outlet temperatures were experienced from post insertion and up until nominal correction (NC) burn two. Effects from the higher than predicted heat loads on the radiator panels led to an additional 50 lbm of supply water consumed by the Flash Evaporator System (FES). Post-flight analysis and research revealed that the additional heat loads were due to Free Molecular Heating (FMH) on the radiator panels, which previously had not been considered as a significant environmental factor for the Space Shuttle radiators.

The current Orbiter radiator heat flux models were adapted to incorporate the effects of FMH in addition to solar, earth infrared and albedo sources. Previous STS flights were also examined to find additional flight data on the FMH environment. Results of the model were compared to flight data and verified against results generated by the National Aeronautics and Space Administration (NASA), Johnson Space Center (JSC) Aerosciences group to verify the accuracy of the model.

OVERVIEW OF FREE MOLECULAR HEATING

FMH occurs when free molecules collide onto a surface, and the kinetic energy of the molecule is transferred to thermal energy or heat on the surface. The heat flux generated by FMH is:

$$Q_{FMH} = \alpha\left(\frac{1}{2}\right)\rho V^3 \quad (1)$$

Where α is the accommodation factor represents the efficiency of the conversion of kinetic energy to thermal energy, ρ is the atmospheric density and V is the vehicle velocity. Multiplying the heat flux times the surface area incident to the velocity gives the heat transfer to the surface.

The altitude regime in which FMH is significant is when the atmosphere is rarefied enough such that the molecules no longer act as a fluid, but the density is high enough to produce significant interactions with spacecraft surfaces. The range of altitudes where FMH occurs is variable, but literature[1] suggests that FMH should be assessed when the perigee is less than 100 nautical miles (nm).

STS-121 RADIATOR OUTLET TEMPERATURES

Up until STS-121, FMH was not accounted for in radiator performance predictions. Typically the Space Shuttle radiators are not affected by FMH, either due to high altitudes or the velocity vector not being incident on the radiator. During STS-121, certain factors caused the perigee to be lower than usual and the velocity vector to be incident on the radiators at some points during the orbit.

The first significant factor was the phasing angle required to rendezvous with the International Space Station (ISS). Due to a large phase angle requirement, the insertion altitude was an 85 nm by 120 nm elliptical orbit. This orbit was flown up until nominal correction burn two (NC-2) which occurred at 16 hours Mission Elapsed Time (MET). STS-110 was the only previous shuttle flight to fly in this altitude regime for an extended period of time.

The second factor significant factor was the attitudes flown during STS-121. Two attitudes were flown where the velocity vector was incident on the radiators. The first attitude, the Inertial Measurement Unit (IMU) alignment attitude shown in Figure 1, was flown from post insertion up until 4 hours MET. This is the standard post insertion attitude placing the port wing into the velocity vector.

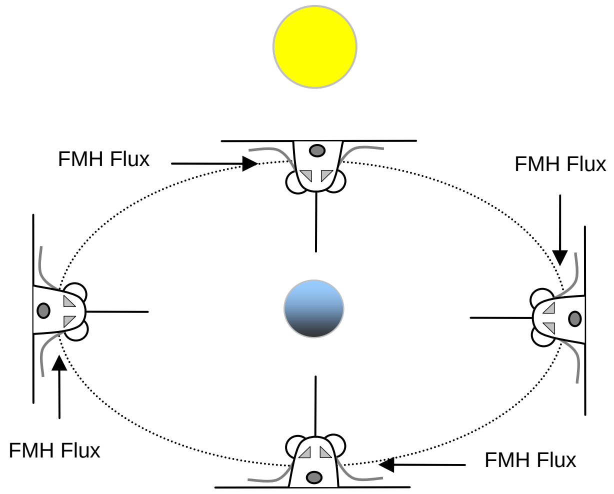

Figure 1 – IMU Alignment Attitude

The second attitude flown, specific to STS-121 was due to a thruster failure that occurred pre-launch. The course of action taken to mitigate freezing risks for the thruster was to fly a port wing to sun solar inertial attitude (-YSI) during crew sleep on Flight Days (FD) 1 and 2, shown in Figure 2.

After post insertion the radiator outlet temperature flight data was observed to be significantly higher than the predicted radiator outlet temperatures, as shown in Figure 3. This trend of higher than predicted radiator outlet temperatures continued throughout the first –YSI attitude At some time periods the difference between the flight data and predictions was as high as 30 °F.

The second –YSI attitude was flown during the next crew sleep period at the end of flight day two. During flight day two, the NC-2 and NC-3 burn were performed raising the orbit to 138 nm by 184 nm. During this period, the flight data for the radiator outlet temperatures agreed with the predicted temperatures.

The radiators are one only one element of the Space Shuttle Active Thermal Control System (ATCS). When the radiators are not able to provide sufficient cooling, they can be supplemented by the Flash Evaporator System (FES). Due to the higher heat loads experienced an additional 50 lbm of water was consumed during the first 16 hours of the mission than predicted.

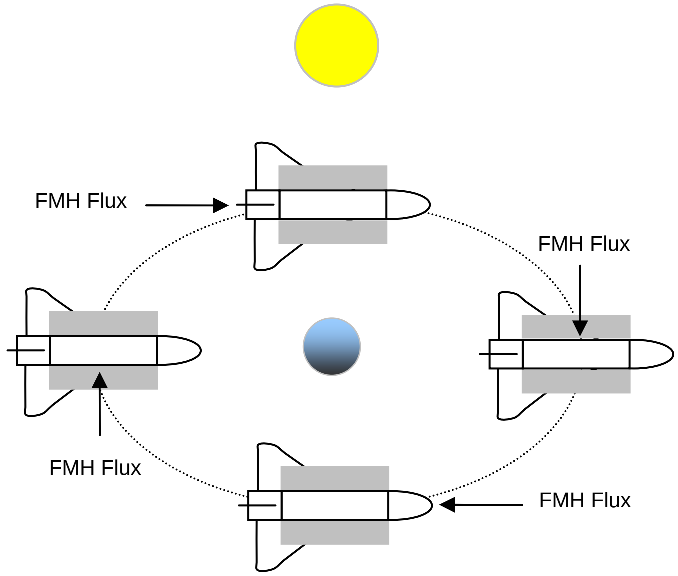

Figure 2 – -YSI Attitude

After STS-121, analysis of the temperature differences between the model predictions and flight data and review of literature on spacecraft thermal control[1] determined that FMH was a likely cause. An effort was then undertaken to incorporate FMH into the orbiter radiator model.

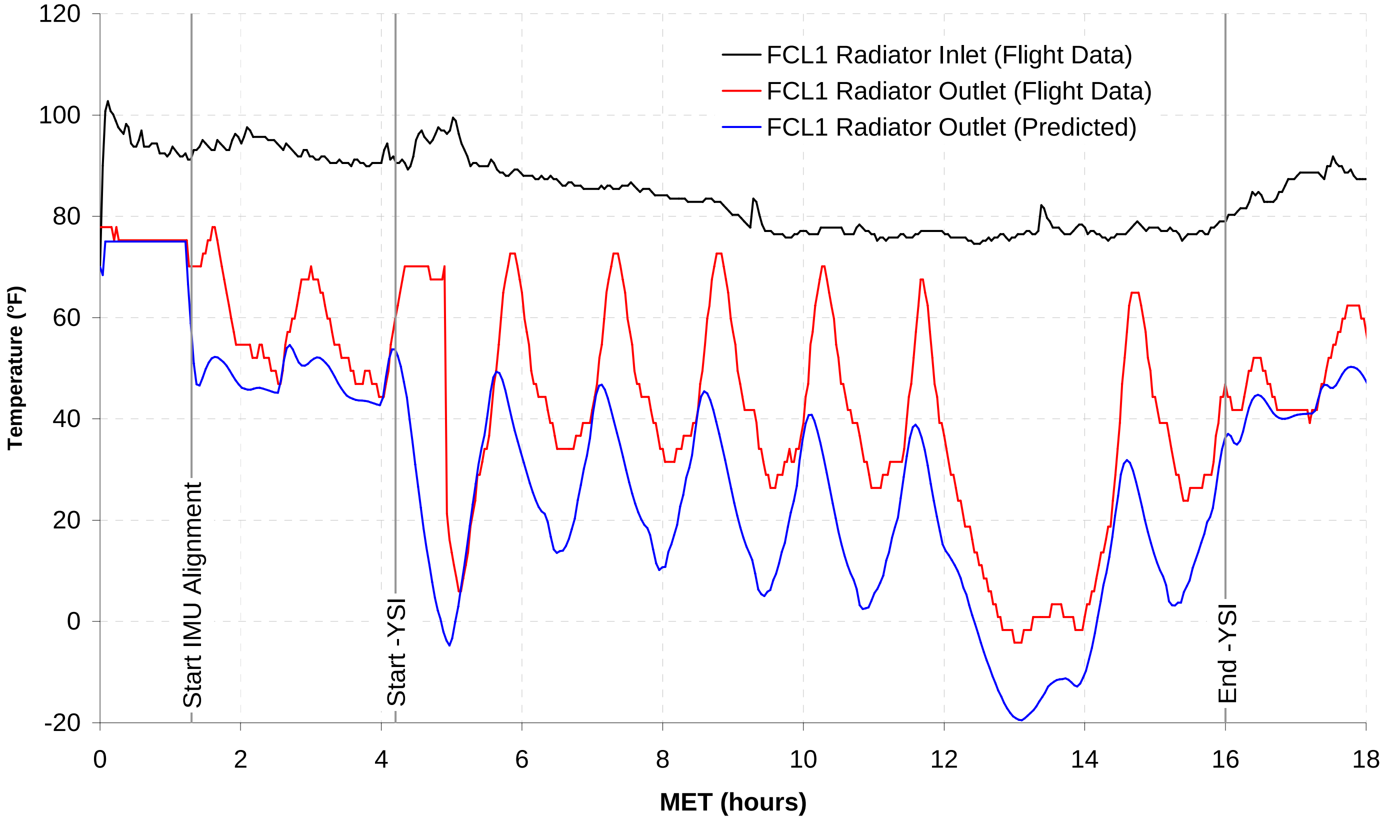

Figure 3 – Freon Coolant Loop (FCL) 1 Radiator Tempeatures for STS-121

UPDATING THE RADIATOR MODELS TO INCORPORATE FMH

The current orbiter radiator model uses an orbiter radiator flux database[2] containing heat fluxes due to solar, earth infrared and albedo sources. The database is expansive, accounting for the beta angle, orbiter attitude, orbiter altitude, day/night shading and other second order factors. The orbiter radiator database also contains fluxes on other areas on the orbiter that are in view of the radiator, such as the wing and radiator door surfaces. A mission timeline of radiator temperatures is predicted utilizing the fluxes from the database. Due to the use of a database, the calculation of a typical twelve day mission timeline using a two minute time step takes a matter of minutes.

To account for all possible combinations of inputs, generating the database was a large scale effort. Expanding the database to account for FMH was not a viable option. Another difficulty in incorporating FMH into the current orbiter radiator model was the complexity of FMH computations. Modeling the interaction of the radiator surface with the incident molecules is not trivial and would have to be computed with every time step. Incorporating a separate model to account for FMH on the orbiter radiators could increase the calculation times drastically.

The solution to the problem of modeling FMH while keeping computer processing time short was utilizing the similarity of the physics between free molecules striking the surface and light striking a surface. For a given point in the orbit, both light and free molecules are assumed to travel along a single vector. Since the orbiter radiator database already contains the solar fluxes for all possible orbiter orientations, the physics of free molecules striking the surface was already essentially modeled. Any effects of free molecules' interactions with other surfaces after the initial collision were assumed to be negligible.

Applying solar flux database values to FMH fluxes was a matter of reading the solar database using velocity vector orientations as inputs and performing some simple algebraic relations to find the radiator area incident to the velocity vector. The total heat rate due to FMH was then found by multiplying the radiator area incident to the velocity vector times the incident FMH flux found using Equation 1.

The parameters needed by the orbiter radiator models to calculate the incident FMH are the vehicle velocity, atmospheric density and the accommodation factor. The vehicle velocity was already available from the orbital mechanics portion of the model. Atmospheric density was found by integrating the Mass Spectrometer, Incoherent Scatter Radar Extended (MSISE)-90[3] model and passing the necessary inputs to MSISE-90 from the orbital mechanics portion of the model. While the solar electromagnetic activity and the geomagnetic index can be input into MSISE-90 to more accurately model the atmosphere, these values would only available post flight. Since the orbiter radiator model is a predictive tool, only the standard values are input into the integrated MSISE-90. The accommodation factor was added as a user defined input with an initial default value of 1.0 to remain conservative[1].

The FMH heat rates are then summed with solar, infrared and albedo heat rates for each model node for use in predicting radiator outlet temperatures. Following these software updates, beta testing was initiated to verify the accuracy of the FMH predictions.

BETA TESTING THE INCORPORATED FMH CALCULATIONS

With the changes to the orbiter radiator model, the first step in beta testing was comparing updated model predictions for the radiator outlet temperatures to the STS-121 radiator outlet temperatures flight data. To obtain the best comparison between model predictions and the flight data, the radiator inlet temperature flight data and radiator flow rate flight data were input into the model. Doing this allows the radiator outlet temperatures to be viewed strictly as a function of the radiator panel heat fluxes.

The final radiator outlet temperature results from the updated orbiter radiator model using an accommodation factor of 0.8 are compared against the STS-121 radiator outlet temperature flight data in Figure 4. The comparisons show that the including FMH calculations greatly improve the accuracy of the orbiter radiator model.

During beta testing, some items of interest were found. In the early stages of development, an accommodation factor of 1.0 was chosen to remain conservative. To provide the best fit between the orbiter radiator model results and flight data, various values of the accommodation factor were tested. Results showed that using a value of 0.8 provided the best fit while remaining conservative. Additional flight data beyond STS-121 may provide further insight into a more accurate value of the accommodation factor.

Early beta versions also did not calculate the heat fluxes due to FMH on the other orbiter surfaces in view of the radiator. Modeling of these other surfaces was found to be important, particularly during the night passes, because of the radiation interaction between the surfaces and the radiator.

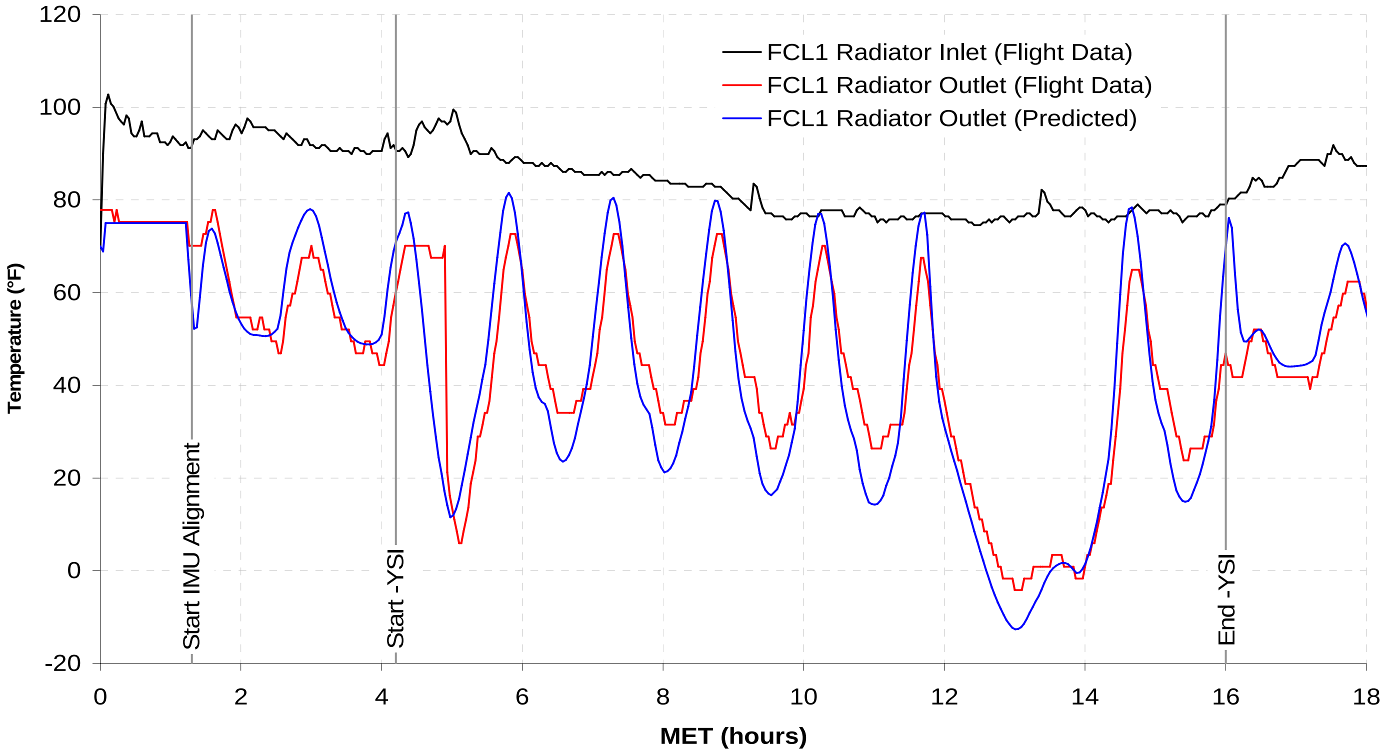

Figure 4 - FCL 1 Radiator Temperature Predictions for STS-121

VERIFICATION OF THE INCORPORATED FMH CALCULATIONS

To obtain independent verification of the FMH calculations, the National Aeronautics and Space Administration (NASA) Johnson Space Center (JSC) Aero-Sciences group was contacted. Using computational fluid dynamics (CFD), an orbiter computer aided drawing (CAD) model of the orbiter, and the FREEMO code developed by the NASA JSC Aero-sciences group, an analysis of the STS-121 radiator heat loads was performed.

To make the comparison between FREEMO and the orbiter radiator model as direct as possible, the same orbiter ephemeris and attitude timelines were used as inputs to both analyses. To keep computer processing time down, the analysis using FREEMO was only performed for times during the mission when FMH was significant. Even taking this step required over twenty hours of processing time.

Results from the updated orbiter radiator model's port-side radiator FMH flux as compared to JSC Aero-Sciences calculations can be seen in Figure 5. Note that FMH heat load values are nearly identical for the two cases, indicating a high degree of correlation between the radiator flux database FMH calculation method and the high-fidelity CFD calculation routine employed by JSC Aero-Sciences.

The biggest discrepancy between the two analyses occurs during perigee at an altitude of 85 nm. The orbiter radiator model predicts a five to ten percent higher heat load on the radiators than the FREEMO code. This over prediction can also be seen at each of the radiator outlet temperature peaks in Figure 4. The likely cause for the orbiter radiator over predicting the heat load is that the atmospheric density at 85 nm has become dense enough for the molecules to start interacting. Since FREEMO relies on CFD, it would account for the molecular interactions. Further study is needed to be conclusive.

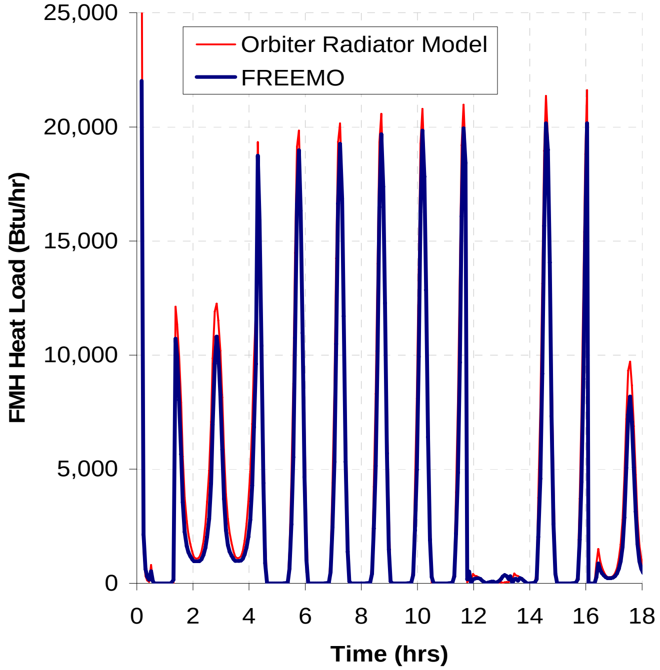

Figure 5 - STS-121 Port Forward Panels (1 & 2) Total Heat load due to FMH

ADDITIONAL SPACE SHUTTLE FMH EVENTS

With the orbiter radiator model FMH calculations verified independently, a review of Space Shuttle flights prior to STS-121 was performed to determine if FMH events had previously occurred. Efforts were concentrated on finding a flight with low post insertion altitudes during the standard IMU alignment attitude. STS-110 was a prime candidate due to the previously mentioned altitude regime flown but sufficiently accurate data was unavailable. Two flights that were identified to have experienced FMH were STS-114 and STS-92. Results from STS-114 are shown in Figure 6.

For both flights, the IMU alignment attitude was flown for only a few hours. After this attitude, the NC-1 burn was performed raising the altitude high enough for FMH to become insignificant. Analyses similar to that conducted for STS-121 and including FMH effects show similar improvements in radiator outlet temperature predictions.

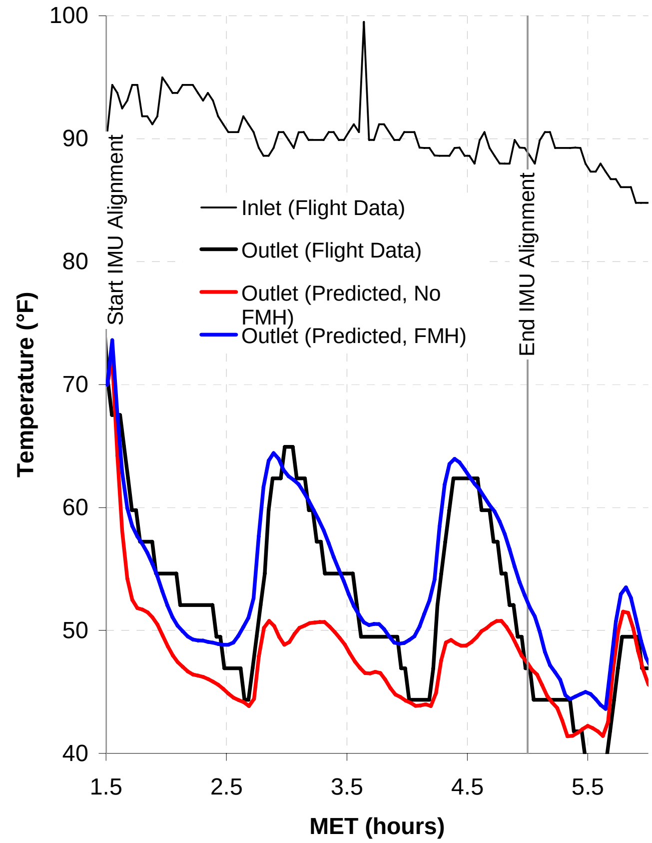

Figure 6 - STS-114 FCL 2 Radiator Temperatures

CONCLUSIONS

Depending on the altitude and attitude flown, FMH can be a significant environmental factor on the Space Shuttle ATCS. The updated orbiter radiator model accurately predicts the heat loads due to FMH and has been independently verified by the NASA JSC Aero-sciences group. When modeling FMH on the space shuttle radiators an accommodation factor of 0.8 was found to fit best the flight data available. FMH is likely to occur again, particularly for the post insertion IMU alignment attitudes.

ACKNOWLEDGMENTS

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DEFINITIONS, ACRONYMS & ABBREVIATIONS

ATCS: Active Thermal Control System
CAD: Computer Aided Drawing
CFD: Computational Fluid Dynamics
FCL: Freon Coolant Loop
FD: Flight Day
FES: Flash Evaporator System
FMH: Free Molecular Heating
FREEMO: Free Molecular Heating Code Developed by the NASA JSC Aero-sciences Group
IMU: Inertial Measurement Unit
ISS: International Space Station
JSC: Johnson Space Center
lbm: pounds (mass)
NC: Nominal Correction
nm: nautical miles
MET: Mission Elapsed Time
MSISE-90: Mass Spectrometer, Incoherent Scatter Radar Extended – 1990; Atmospheric Model
STS: Space Transportation System
NASA: National Aeronautics and Space Administration
Q_{FMH}: Heat Flux due to Free Molecular Heating
V: Vehicle Velocity
-YSI: Port Wing to Sun Solar Inertial Attitude
α: Accommodation Factor
ρ: Atmospheric Density